Three Essays on Network Economics

Incentives for Compatibility Choice, Standard Setting and Infrastructure Investment

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Jan Philipp Bender

Referent:	Prof. Dr. Klaus M. Schmidt
Korreferentin:	Prof. Dr. Monika Schnitzer
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Preface

> *"Many of the effects that drive the new information economy were there in the old industrial economy – you just have to know where to look."*[1]

In the following we present three models that use applied oligopoly theory to research market behavior in network industries. The first two chapters focus on firms' compatibility decisions in the new information economy as exemplified by the software industry. Chapter 1 derives the equilibrium compatibility regime when asymmetric firms compete within an oligopolistic structure. Chapter 2 compares the performance of standards that are established through market competition against those established through cooperative agreements. In Chapter 3 we investigate a network industry which is part of the old industrial economy. By using the example of the railroad industry, we discuss which industry structure and regulatory environment provide the best incentives for infrastructure investments. Before introducing the chapters in more detail, we briefly discuss below what these industries from the old and new economies have in common. In doing so, this preface specifically focuses on the implications of these common elements for market structure, firm strategy and government policy.

Many industries in the old industrial economy are characterized by strong economies of scale in production – i.e. on the supply-side. This applies particularly for network utilities which rely on a physical network infrastructure to provide their services to consumers. These infrastructures involve large, fixed investment costs and thus render utilities the most commonly cited example for natural monopolies. Because of the tendency towards monopolistic structures, these "classical" network industries, such as rail, electricity, gas, telecoms and water are closely monitored by both regulatory agencies as well as competition authorities. Regulatory scrutiny appears to be especially important when recalling that the efficient supply of these services is essential as an input to numerous production processes.

[1] Farrell, Shapiro and Varian (2004), page 12.

New information industries typically also exhibit high fixed and low marginal costs of production. Let us consider the product development and production process in the software industry as an example. A software firm incurs large, up-front investments to develop new software; however, the marginal costs of actually producing and distributing the product tend to zero. Information industries are therefore also subject to economies of scale on the supply-side. However, in addition, these industries also feature demand-side economies of scale that economists usually refer to as network effects or network externalities. A product exhibits network effects if demand – or more precisely the consumers' willingness to pay – depends on how many other consumers also purchase the good. Unlike in old industrial economies, the consumers decisively drive market behavior through the formation of virtual networks on the demand-side. Supply- and demand-side economies of scale in information industries strengthen the tendencies towards monopolization compared to those under network utilities. Thus, control through regulation and competition authorities is indispensable in information markets, especially as their importance is growing rapidly.

This dissertation deals with networks – physical as well as virtual. In the presence of physical networks each firm must incur large fixed costs; hence, larger firms (i.e. those producing more output) have smaller average costs. In the presence of virtual networks larger firms have higher average revenues and demand as their buyers enjoy network effects. In both cases, one firm may be able to drive its competitors out of the market because of these scale economies on the supply- and demand-side. These characteristics will be a dominant feature throughout the three chapters which are discussed next.

The first chapter analyzes the compatibility decisions which firms face in an information economy. To reap the benefits from network effects fully either consumers need to coordinate on buying the same product or products need to be compatible, i.e. interoperability between goods must be established. In reality, however, one can observe that firms deliberately impede interoperability. To understand why firms deny compatibility the existing literature has studied stylized environments where either only two firms decide on compatibility or a dominant firm faces multiple, symmetric rivals. Our model goes one step further in explaining how asymmetries in market shares, which are ubiquitous in information industries, affect firms' compatibility choices. It shows that the presence of multiple, asymmetric firms which decide upon compatibility with each rival in turn, leads to equilibrium compatibility regimes which have not been considered in the literature thus far.

When determining their preferred compatibility alliance, firms trade off two effects. On the one hand, compatibility expands the network base of their customers which directly increases the demand for their products. On the other hand, it also implies that a larger firm loses the advantage as to its network size relative to its rivals. A larger firm thus always has weaker incentives to agree to compatibility. For this reason, a three-firm oligopoly will, in equilibrium, involve less than full compatibility if asymmetries in firms' market shares exist. In particular, we show that when firms can decide upon compatibility with each rival in turn, the smallest firm is always excluded from compatibility. Targeting the smallest rival with incompatibility either magnifies existing asymmetries in market shares or introduces them when small firms are *a priori* symmetric. Incentives for compatibility will only be enhanced if firms offer significantly differentiated products or if perfect symmetry of market shares leads to an agreement amongst equals. Although the fact of allowing firms to exchange cross-payments normally achieves full compatibility, smaller firms are net-givers, i.e. they pay the large firms for compatibility. Interestingly, if asymmetries are very large, firms will have an incentive to pay rivals to remain incompatible. An important policy recommendation is therefore to support small market participants and especially entrants in establishing themselves in the industry as they are otherwise targeted with incompatibility. In this environment an open, mandatory standard might be appealing. However, such an open, mandatory standard also has its adverse effects, especially when considering firms' (long-run) investment incentives in technology – as Chapter 2 shows.

Chapter 2 – a joint piece of work with Klaus M. Schmidt – compares two forms of standardization processes in information technology markets that we observe empirically: cooperative and competitive standard setting. Under competitive standard setting firms refuse to make their products compatible because of the tendency towards monopolization in network industries. One of two firms expects to dominate the market eventually and thereby brings about a *de facto* standard. In contrast, some standards are established early on through a cooperation agreement or a formal standardization process. This may be a very simple agreement that only establishes compatibility between firms' products. Alternatively, it may be more complex, potentially governing large investments in new technologies through an exchange of intellectual property rights, royalty payments, and technology sharing. Despite the empirical observation that some standards are brought about through competition and others through cooperation, the theoretical literature lacks work that aims to understand the relative performance of these standardization processes. Our model allows this comparison by deriving their implications for pricing, technology investment and market structure of the network industry. In doing so, we account for important components of such agreements, in particular royalties and technology sharing.

In our model we show that simple agreements that establish compatibility only *ex post*, i.e. after technology investments have taken place, reduce price competition but have no direct effect on the incentives to invest. If firms can write more complex, *ex ante* contracts on compatibility containing enforceable agreements on linear royalties and technology sharing, they will choose higher prices but invest less in technology. Surprisingly, we find that firms invest even less if the government imposes a royalty-free licensing rule. A recent collaboration agreement between Microsoft and Novell serves as a good example to illustrate some of the points made in this chapter. In 2006, the firms have agreed on a common standard establishing compatibility between their operating systems. Our model suggests that they should always do so, if Microsoft expects that Novell will be a long-term competitor with its Linux technology in the market. As a consequence of the agreement, our model predicts that consumers will certainly gain from the increased compatibility and associated network effects. However, Chapter 2 also points out that they may suffer from higher prices and decreased technology investments in the future.

Finally, Chapter 3 investigates the interplay between market structure and infrastructure investments in network utilities, such as the rail industry. To this end, we compare two conceivable vertical structures – vertical integration and vertical separation. Under vertical integration the monopolistic infrastructure is provided by a firm that is also active in the downstream services segment. In contrast, under vertical separation, the upstream infrastructure is operated by an independent infrastructure firm. A regulator handles the familiar conflict between allowing firms to recover their large sunk infrastructure investments and protecting consumers' interest in low prices. Despite the importance of the infrastructure's quality and cost-effectiveness for the efficient provision of utilities, only few studies have explored the incentives for executing the investments behind it. We contribute to this by explaining how investment incentives change with the regulated access price. Moreover, we investigate which vertical structure provides the best infrastructure investment incentives, for both quality-increasing and cost-reducing investments.

We illustrate that increasing the regulated access price stimulates investments into infrastructure quality but simultaneously reduces investments into cost-reduction, under both vertical integration and vertical separation. In addition, the model predicts that a vertically integrated structure provides stronger incentives for infrastructure investment, both in quality-increases and cost-reduction. Because investments under both vertical structures fall short of the socially optimal levels, our analysis suggests that – despite the advantages related to fostering competition that a vertically separated structure may have – vertical integration may be the superior industry structure, especially if infrastructure investments matter more than competition. These results contribute to the policy debate on restructuring network utilities, such as the rail and energy sector: policy makers should not only assess the consequences for competition, but also investigate the likely impact of different vertical structures on infrastructure investments.

The following three chapters are all self-contained and have their own introduction and appendix. Each chapter can thus be read independently of the other two.

Chapter 1

Compatibility Incentives within an Oligopoly with Asymmetric Firms

1.1 Introduction

In industries displaying network effects[1] compatibility decisions are an important determinant of efficiency. To reach a compatibility agreement, some form of coordination among competitors is required. Nevertheless, firms remain rivals on the final product market. They therefore use compatibility decisions to strategically influence their competitive position on the final goods market. In this chapter we investigate the incentives to deny and/or grant compatibility within an oligopolistic industry structure when firms are asymmetric with respect to their installed network bases.

When forming a compatibility alliance firms trade off two basic effects. Denying compatibility causes a demand reduction because customers' valuation for the product suffers from unrealized network effects. At the same time, firms can – by denying perfect compatibility – retain a vertical differentiation relative to their rivals. While the first effect is negative for all firms and calls in favor of compatibility, the second effect is positive only for larger firms. If it is strong enough, it then causes large firms to deny compatibility to smaller firms. In our analysis we show that, in the interior equilibrium where all firms serve the market, the largest firm generically has an incentive to target some rivals with incompatibility.

Oligopolistic market structures with significant asymmetries of market shares are

[1] Network effects prevail if a consumer's valuation of a good is increasing in the number of other consumers buying the same product.

frequently observed in network industries. The operating systems and the office software market, both subject to direct network effects, are dominated by Microsoft which competes only against a few small rivals.[2] The market for video game consoles where network effects arise indirectly due to larger availability of complementary goods (i.e. gaming software) and services, is shared by three players with asymmetric market shares.[3] Similarly, there are normally only three or four wireless telecommunication providers that share a national market. Here, tariff-mediated network effects stem from differential pricing for on-net and off-net calls.[4]

The formal model considers an industry of three potentially asymmetric firms that first decide on compatibility and then compete à la Cournot in an economic environment characterized by network effects. Each firm's compatibility decision consists of a costless, zero/one compatibility choice towards each of the two rivals. Firms must mutually agree on compatibility. Thus, compatibility strategies of the firms can be non-uniform but cannot be unilaterally enforced.[5] Moreover, we assume transitivity of compatibility, meaning that if a firm is compatible with both rivals, then these rivals are also compatible with each other.[6] In our analysis the compatibility decision only affects the network size and does neither lead to differences in cost nor in performance.

We show that, if network effects are strong, there exist multiple fulfilled-expectations equilibria where tipping in the quantity competition stage may occur under all perceivable compatibility regimes except for full compatibility.[7] The reason why there is no tipping equilibrium under full compatibility is that firms' products are perfect substitutes with identical network size. Therefore, in equilibrium, either all firms remain in the market or none. We then establish that an increase in a firm's own installed-base increases the area where *tipping to* this firm is an equilibrium and decreases the area where *tipping away* from it occurs. However, because there exist multiple expectation-dependent equilibria in the quantity competition stage, little can

[2] In markets with direct network effects, the main concern of potential buyers of a product is the user base of the same product, e.g. because of file-sharing possibilities.

[3] Nintendo Wii (47%), Sony Xbox360 (30%) and MS Playstation 3 (23%); percentage of total sales for past 12 months as of September 16, 2008; see www.vgchartz.com which publishes recent sales data.

[4] See Cabral (2008) for the argument and Bender (2004) for evidence on European market shares.

[5] We do not consider converters or adapters. In this chapter unilateral compatibility would always be desirable for the firms.

[6] This assumption can be justified in a variety of settings but is particularly intuitive when compatibility concerns the technical specification of a product, a code and/or the exchange of IP rights.

[7] *Tipping* describes the equilibrium property that the market structure "*tips*" (meaning turns) into one where only a subgroup of firms or a single firm serves the market. Self-fulfilling expectations may then drive which equilibrium actually comes about. The equilibrium concept itself requires that expectations are fulfilled.

be said about the compatibility choice of firms when network effects are very strong.[8]

If network effects are weak, there exists a unique interior equilibrium under each compatibility regime in which all firms add new customers in the quantity competition stage. By comparing profits under each compatibility regime for each of the three rivals, we then deduce the equilibrium compatibility regime. We confirm the result by Crémer et al. (2000) that the largest firm takes the decisive role in determining equilibrium compatibility and that this firm has the weakest desire for compatibility. The reason is that it has most to lose and least to win in terms of both, vertical differentiation and demand effects. However, the largest firm cannot always enforce its preferred compatibility regime. For example, if the largest firm's market share is very high, it desires no compatibility among firms. But because smaller rivals would then have an incentive to form a compatibility alliance, the market leader in fact offers some compatibility to prevent the rivals' alliance. This shows that asymmetry of market shares crucially impacts equilibrium compatibility. We show that, in equilibrium, the two largest firms jointly target the smallest firm with incompatibility even if compatibility is costless in our model and thus full compatibility socially desirable.

Our analysis therefore strongly supports the restrictive view of competition authorities. Recently, network industries have faced increased scrutiny of both regulators and antitrust authorities. US and European competition authorities were concerned that a large firm may have incentives to deny compatibility and agitated for blocking any mergers that would further corroborate these fears. Prominent cases discussing the impact of compatibility decisions for competition and market structure are the WorldCom/Sprint merger case and the AOL/Time Warner case.[9]

We then investigate the effects of horizontal product differentiation. We show that strong product differentiation leads to a reduction in the set of possible tipping equilibria. Tipping can only occur if differentiated consumer groups remain being served. In this sense, horizontal differentiation, similarly to a larger installed base, serves as a safe harbor against tipping away. Moreover, horizontal differentiation fosters compatibility incentives as competitive effects from the loss in vertical differentiation are weaker. This makes the largest firm become more inclined to grant compatibility.

Finally, we explore the consequences of fixed cross-payments for compatibility. We

[8] This would require further assumptions on the expectations-formation process (compare Farrell and Klemperer (2007)). This is, however, beyond the scope of our study.

[9] As outlined in Malueg and Schwartz (2006) and European Commission (1998, 2000), US Department of Justice (2000) and Faulhaber (2002) and for Microsoft in Bresnahan (2002).

show that, because joint profits under independent pricing are highest under full compatibility, full compatibility can often be achieved.[10] However, the two larger firms both forego the higher profits of their preferred compatibility regime. Thus, they need to be compensated by the smaller firm through fixed cross-payments to agree to grant full compatibility. Hence, it is crucial that complete, contingent contracts specifying the compensation can be written and enforced.

There is a vast literature on the economics of network industries and compatibility choice.[11] Our model builds upon and is closely related to the work by Crémer, Rey and Tirole (2000) and Malueg and Schwartz (2006).

Crémer et al. (2000) adopt the Katz and Shapiro (1985) framework[12] and incorporate old customers that form an installed base. They analyze compatibility strategies of a dominant firm in a duopoly and show that a larger firm prefers less compatibility than its smaller rival. They also explore one very stylized example of targeted incompatibility where they show that a dominant firm may prefer compatibility to just one out of two rivals if these are symmetric. However, in their analysis they do not derive compatibility incentives of the firms explicitly and are not able to formally explain the impact of asymmetry on compatibility.

Our model extends the analysis of Malueg and Schwartz (2002, 2006). Malueg and Schwartz (2006) explore compatibility incentives of a large firm facing multiple, symmetric rivals that are themselves compatible. They also find that under strong network effects and incompatibility of the largest firm to the rivals, *tipping to* or *tipping away* from the largest firm may occur in equilibrium. They then illustrate that the multiple symmetric rivals are subject to an "*intra-network competition effect*". Consumers anticipate that this more competitive network will set lower prices and they therefore penetrate this network more. However, Malueg and Schwartz (2006) do not analyze targeted degradation strategies as they assume uniform compatibility policies. They retain the assumption of compatibility among rivals throughout their analysis

[10] For intermediate network effects sub-coalitions may also have highest joint profits.

[11] For an overview see Farrell and Klemperer (2007) and Koski and Kretschmer (2004); for books see Shy (2001) and Shapiro and Varian (1999).

[12] Katz and Shapiro (1985, 1986) compare the private and social incentives to achieve compatibility in a Cournot model. They show that compatibility can be socially excessive or insufficient under costly compatibility. Moreover, they stress the importance of expectations and expectations formation for the set of equilibria. Both these aspects are outside of our analysis. They then show that firms' (private) decisions will depend crucially on whether they can act unilaterally or whether consensus is required and on the feasibility of side-payments (e.g. royalties). This chapter substantiates these results. Note, however, that because compatibility is assumed costless we are unable to derive welfare implications.

and therefore only compare the regime of full compatibility with that of autarky of the dominant firm. In contrast, we extend their analysis in the following directions: We allow for rivals to be asymmetric and evaluate and explicitly relax their assumption of uniform compatibility policies.[13] We thus do not assume that smaller rivals are compatible among each other but derive compatibility incentives within an oligopoly from first principles. We show that relaxing these assumptions has important implications for the equilibrium compatibility outcome. Targeting is the predominant equilibrium outcome and splintering among rivals is frequently observed.[14] Finally, we also allow for the possibility of cross-payments or royalties in exchange for compatibility.

The chapter is organized as follows: Section 1.2 introduces the model and illustrates the feasible compatibility regimes. We then solve the model by backward induction in Section 1.3. We first explore possible types of equilibria in the quantity stage. We then derive the equilibrium compatibility regimes for weak network effects and illustrate the associated comparative statics. In Section 1.4 we allow for cross-payments and explore their implications for equilibrium. We discuss how this instrument may be able to achieve the efficient outcome and when it fails to do so. Section 1.5 concludes.

1.2 The Model

To analyze the competitive effects of mixed compatibility regimes we adapt the framework of Crémer et al. (2000) and Malueg and Schwartz (2006). In our model, three firms first decide on compatibility and then compete à la Cournot in an industry that is subject to network effects. In this section we introduce the model in its simplest form and illustrate basic implications of different compatibility regimes.[15]

[13] Malueg and Schwartz (2006) admit themselves that in reality uniform compatibility among rivals is hardly observed. In addition to the evidence given at the outset of this chapter, theoretical work predicts the emergence of asymmetric market structures in network industries (e.g. Cabral (2008)). Recently, the importance of learning more about the incentives for compatibility in asymmetric settings has therefore been stressed.

[14] Following Kretschmer (2008) and Farrell and Klemperer (2007) *splintering* describes that the competitive landscape becomes fragmented, e.g. it typically describes the existence of incompatible software systems.

[15] We introduce horizontal product differentiation in Section 1.3.3 and in Appendix, Section 1.6.1. The case of homogeneous products discussed here is nested within that more general framework.

1.2.1 Setup

Demand

The three firms differ only in their locked-in, installed bases of customers. These customers are bound to previously signed contracts that are outside the scope of the model and the terms of these cannot be changed.[16] Each firm i has an installed base of β_i of these passive customers.[17] The total installed base is the sum of firm-specific installed bases and assumed to equal unity: $\beta = \sum_{i=1}^{3} \beta_i = 1$. This normalization implies that the individual shares may also be interpreted as the respective firm's market share. For ease of notation and without loss of generality we label the largest firm with installed base β_1 firm 1. Firm 2 holds an installed base of β_2 with $\beta_1 \geqslant \beta_2 \geqslant \beta_3$. To save on parameters we write $\beta_2 = x(1-\beta_1)$ and $\beta_3 = (1-x)(1-\beta_1)$ with $x \in [\frac{1}{2}, 1)$. Besides pinning down the mere size of the installed bases β_2 and β_3, the parameter x also characterizes the asymmetry between firms 2 and 3.

The competition between the three firms is for *new* consumers. In the basic framework of our model, we borrow the linear inverse demand functions with network effects as derived in Crémer et al. (2000) and Malueg and Schwartz (2006) so that each firm faces[18]:

$$p_i = \alpha + \nu L_i - \delta \sum_{k=1}^{3} q_k \tag{1.1}$$

where we assume throughout the chapter that $\alpha = 1$, $\delta = 1$ and we restrict the strength of network effects ν to $0 < \nu < 1$ to ensure downward-sloping demand.[19] The parameter ν thus measures the importance of network effects for consumers and therefore also governs the social desirability of compatibility between the products supplied by the three firms. L_i measures the size or quality of the compatibility network of firm i and will be discussed at length in the next subsection. Given q_i is the number of new customers added by each firm i that adds customers in a consistent-expectations equilibrium, the above prices satisfy market-clearing.

[16] This assumption is standard in the literature. Compare, for example, Crémer et al. (2000), Malueg and Schwartz (2006) and Cabral (2008).

[17] Although passive, these consumers could be important for welfare – e.g. if they suffer from being stranded when their provider does not serve the market for new consumers.

[18] Both, Crémer et al. (2000) and Malueg and Schwartz (2006), provide an excellent discussion of how these are derived from standard consumers' utility functions. A consumer of type τ receives a net benefit of $\tau + \nu L_i - p_i$ when buying the good. In equilibrium, network-quality-adjusted prices of firms must be the same. Equation 1.1 must be satisfied in any consistent-expectations equilibrium.

[19] For simplicity, assume that $p_i \geq 0$ for now. We will discuss implications of $p_i < 0$ at length in Section 1.3.1. More general demand shifters and shapers α, δ and $\nu > 1$ have less interesting implications.

Supply

There are three firms that supply the network good. Firms differ in their installed bases of old customers, β_i, but are otherwise fully symmetric. They have identical marginal costs of production that we normalize to zero.[20] The asymmetry of installed-bases can be interpreted as a quality or vertical differentiation component.[21]

Timing

In stage zero each firm is endowed with an installed base β_i from competition in the past. Neither competition in this stage nor the buying behavior of consumers that make up the installed base are modeled explicitly. At stage 1/2 firms undergo compatibility agreements and potentially bargain about the distribution of surplus achieved from compatibility (fixed cross-payments). The compatibility decision is based upon firms' and consumers' beliefs about stage 1 of the game. We elaborate on the details of the compatibility formation process in the next subsection (Section 1.2.2). Finally, at stage 1, quantity competition determines firms' equilibrium profits and consumers' utility. The equilibrium outcome of stage 1 will critically depend on the expectations of firms and consumers which we require to be consistent in equilibrium. Competition for *new* consumers thus occurs after the compatibility regime is determined.

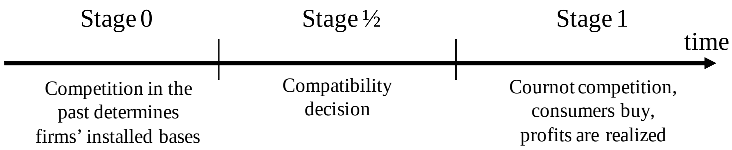

Figure 1.1: Time Structure of the Model

We solve the game by backward induction in Section 1.3. We consider stage 1 in Section 1.3.1 of the chapter and the compatibility decision (stage 1/2) in Section 1.3.2.

[20] In fact, results would be qualitatively unchanged under positive and symmetric marginal costs c as long as $c < 1$ (compare Malueg and Schwartz (2006)). For asymmetric costs, there are implications for optimal pricing and thus the expected quantity of new consumers. However, as shown in Section 1.6.2 of the Appendix, it is not the cost asymmetry that matters for the largest firm when competing à la Cournot but solely its effect on installed bases and asymmetries therein.

[21] Firms may be asymmetric in their installed bases for different reasons. Alluding to the earlier examples, asymmetries could stem from past technological leadership of one of the firms, e.g. protected through patents or secrecy. Similarly, successive entry, for example due to past regulatory or government policy as in the auctioning of frequency bands in wireless telecommunications, or simply differences in historic competitive performance represent further reasons. In many of the above examples marginal costs nevertheless converge across competitors after this initial phase of competition.

1.2.2 Network Sizes and Compatibility

The network quality or network size, L_i, of each product is characterized by three components. The first component stems from the already installed number of consumers β_i that are exogenously given. Secondly, the own new consumers, q_i, join the network as an outcome of quantity competition. Network quality is therefore only imperfectly determined by installed-bases. In addition, each firm i can agree on compatibility with rival j to expand its network further. If it does so, its customers enjoy the additional benefit from interacting perfectly with customers of firm j and vice versa. The compatibility decisions and the compatibility regime are characterized by a number of binary compatibility choice variables $\theta_{ij} \in \{0,1\}$. A value of $\theta_{ij} = 1$ implies that firms i and j are compatible and that their customers enjoy equally good network access to respective customers of the other network. In contrast, $\theta_{ij} = 0$ means that firms' products are incompatible and customers of firm i have no access to customers of firm j and vice versa. The total network benefit from buying a product from firm i, L_i , is then given by:

$$L_i = \underbrace{\beta_i}_{\text{installed base}} + \underbrace{q_i}_{\text{new consumers}} + \underbrace{\textstyle\sum_{k\neq i}^{3} \theta_{ik}(\beta_k + q_k)}_{\text{compatibility}}. \tag{1.2}$$

We make several assumptions on compatibility. First, we assume that compatibility is either perfect or not at all ($\theta_{ij} \in \{0,1\}$). Further, these decisions for or against compatibility are assumed to imply equal costs that we normalize to zero.[22] Although compatibility may – in reality – sometimes cause cost differences, it is not *a priori* clear whether compatibility or no compatibility is more costly.[23] Moreover, we assume that compatibility decisions cannot be achieved unilaterally but must be mutually agreed upon (i.e. $\theta_{ij} = \theta_{ji}$). Furthermore, compatibility decisions are transitive in our model which implies that if a firm is compatible with both of the rivals, then these rivals must also be compatible with each other. For example, if $\theta_{12} = \theta_{13} = 1$, then (by transitivity) it follows that: $\theta_{23} = 1$.[24] This assumption is particularly intuitive when

[22] Crémer et al. (2000) show for a setting with two firms and continuous compatibility choice (i.e. $\theta_{ij} \in [0,1]$) that if different levels of compatibility are of equal costs, then indeed compatibility choice will involve either $\theta_{ij} = 0$ or $\theta_{ij} = 1$.

[23] Malueg and Schwartz (2006) reason that compatibility might involve adjustment costs but might also be cheaper (when adopting a common, off-the shelf standard). Incompatibility might involve no costs but could also be costly, e.g. if development of an own proprietary standard is necessary. Because we omit costs of (in-)compatibility we are unable to make welfare statements. We thereby also avoid possible hold-up problems associated with compatibility decisions.

[24] Due to mutual agreement we can also deduce that $\theta_{21} = \theta_{31} = \theta_{32} = 1$. Thus, here all firms are compatible with each other.

thinking about technical norms or standards that are required for interoperability of products.

In contrast to Malueg and Schwartz (2006), we do not assume that compatibility decisions must be uniform. Each firm can independently decide whether to grant compatibility to just one rival, both rivals or none of them. We also do not assume *a priori* that smaller rivals always offer compatibility. Under these assumptions there exist five feasible compatibility regimes:

1. *Full Compatibility:* $\theta_{12} = \theta_{13} = \theta_{23} = 1$
2. *Full Autarky:* $\theta_{12} = \theta_{13} = \theta_{23} = 0$
3. *Coalition of the Small (Autarky by Firm 1):* $\theta_{12} = \theta_{13} = 0$; $\theta_{23} = 1$
4. *Targeting of Firm 2 (Autarky by Firm 2):* $\theta_{12} = \theta_{23} = 0$; $\theta_{13} = 1$
5. *Targeting of Firm 3 (Autarky by Firm 3):* $\theta_{13} = \theta_{23} = 0$; $\theta_{12} = 1$

Under "Full Compatibility" all firms supply perfectly compatible products – resembling a scenario with a common industry standard. In fact, because all binary compatibility variables are equal to one the products are perfect substitutes. They are not only homogeneous but also provide the same network benefit. Full Compatibility requires all firms agreeing to provide products compatible with both rivals. Absent pricing considerations, this is the most desirable regime for consumers who seek to be compatible with as many other users as possible. The size of the network under an agreement of case 1 is the entire customer base, i.e. $L_i^{FC} = \beta_i + q_i + \sum_{k \neq i}^{3} (\beta_k + q_k) = (\beta_1 + \beta_2 + \beta_3) + (q_1 + q_2 + q_3)$.

In contrast, there is no compatibility under the "Full Autarky" regime. Here, the vertical differentiation between firms is strongest and network size only comprises of own customers: i.e. $L_i^{FA} = \beta_i + q_i$.

Besides these most extreme agreements of an all-or-nothing type, "mixed compatibility regimes" are possible. The "Coalition of the Small" involves compatibility between firms 2 and 3 – which implies that firm 1 remains autarkic. Note that this agreement can arise for two fundamentally different reasons: either firm 1 denies firms 2 and 3 access to its customer base or each of firms 2 and 3 denies firm 1 compatibility because they prefer a "Coalition of the Small". This logic translates similarly to the cases of "Targeting of Firm 2" and "Targeting of Firm 3".

To determine what agreement firms reach in equilibrium we employ the following mechanism. Each firm determines its preferred complete order of compatibility regimes. We then match the preferred choices so that they fulfill the requirement of mutual agreement. In addition, the compatibility strategy should be the best response to the other firms' optimal compatibility choice. This mechanism best resembles the different ways that compatibility standards can come about in reality.[25] Finally, note that the compatibility decision has no further implications for product market competition except for the adjustment in network sizes. Firms remain competitors – no collusion is allowed.[26]

Substituting the respective network size (equation (1.2)) into the inverse demand (equation (1.1)), we obtain the following inverse demand function, which depends directly on the firm's compatibility decisions and the strength of network effects:

$$p_i = 1 + \nu(\beta_i + q_i + \textstyle\sum_{k\neq i}^{3} \theta_{ik}(\beta_k + q_k)) - \textstyle\sum_{k=1}^{3} q_k. \tag{1.3}$$

1.3 Equilibrium Analysis

We now analyze the game by backward induction. We first derive equilibrium quantities taking the compatibility regime as given and characterize the different types of equilibria that may occur depending on the strength of network effects in Section 1.3.1. We then derive the equilibrium compatibility regimes in Section 1.3.2.

1.3.1 Cournot Equilibria

We start by illustrating competition under Full Compatibility. With Full Compatibility, firms have same network sizes. Each firm maximizes profits given the inverse demand function. As there are no costs of producing the output, the profit function – when substituting the inverse demand equation (1.3) under Full Compatibility – takes the following form:

$$\begin{aligned} \pi_i &= p_i \cdot q_i = (1 + \nu(\textstyle\sum_{k=1}^{3}(\beta_k + q_k)) - \textstyle\sum_{k=1}^{3} q_k) \cdot q_i \\ \pi_i &= (1 + \nu\beta - (1-\nu)\textstyle\sum_{k=1}^{3} q_k) \cdot q_i. \end{aligned} \tag{1.4}$$

[25] Chapter 2 discusses alternative standardization processes in detail.

[26] We maintain this assumption throughout this chapter, also in Section 1.4, where we explicitly allow for fixed payments between firms.

The three firms' best response functions are symmetric:

$$q_i = \frac{1 + \nu\beta - (1-\nu)\sum_{k\neq i}^{3} q_k}{2(1-\nu)}.$$

By solving the system of three equations simultaneously, we find the following equilibrium outputs under Full Compatibility:

$$q_1^{FC} = q_2^{FC} = q_3^{FC} = \frac{(1+\nu)}{4(1-\nu)}. \tag{1.5}$$

Note that, as one would expect, all firms' equilibrium outputs and the industry output increase in the strength of network effects:

$$\frac{\partial q_i^{FC}}{\partial \nu} = \frac{1}{2(1-\nu)^2} > 0; \; \frac{\partial Q^{FC}}{\partial \nu} = \frac{3}{2(1-\nu)^2} > 0.$$

Under Full Compatibility products are perfect substitutes, network sizes (independent of the split of actual production) are the same and thus firms' equilibrium quantities are the same. Because there is no vertical differentiation between products in equilibrium, tipping – i.e. one or more firms being excluded from the market – cannot be a consistent-expectations equilibrium under Full Compatibility. Either all firms make positive profits and serve the market or no firm serves the market in equilibrium. The symmetric interior equilibrium is thus indeed the unique equilibrium of the quantity competition stage under Full Compatibility.[27]

That all firms remain in the market is beneficial for consumers as the number of firms and the intensity of competition tend to drive down equilibrium prices. Also, full compatibility ensures that no consumers are left behind stranded. However, if there are costs involved in setting up the compatibility or fixed costs of supplying the market, this may also be detrimental from a social point of view.

For compatibility regimes involving less than full compatibility, i.e. when network effects imply vertical differentiation between products of the different firms, there are indeed tipping equilibria possible for strong enough network effects. In the following section we derive the necessary parameter constellations for this to happen under each of the other four compatibility regimes and illustrate their characteristics.

[27] As part of Proposition 1.1 we provide the formal argument behind the proof.

Tipping Equilibria

In a tipping equilibrium new consumers expect that a particular firm or a group of firms will not serve the market. For these expectations to be consistent in equilibrium, this firm or group of firms must indeed find it profitable to provide zero output in equilibrium. The following proposition summarizes the sufficient condition for existence of tipping equilibria under the possible compatibility regimes:

Proposition 1.1 *Tipping equilibria exist under all feasible compatibility regimes except for Full Compatibility iff network effects are strong enough ($\nu \geq \frac{1}{\sqrt{2}}$). For strong network effects multiple equilibria exist under these compatibility regimes.*

Proof. See Appendix, Section 1.6.3. ■

Thus, the existence of tipping equilibria requires sufficiently strong network effects. In addition, expectations and the expectations-formation process play an important role in determining the market outcome. These equilibria are typically not unique so that that multiple equilibria exist. To make more exact predictions about equilibrium selection we would need a more detailed theory on the underlying expectations-formation process.[28] As this is, however, not the focus of our study we abstract from further refinements. To illustrate the derivation of conditions for existence of tipping equilibria and to gain some general insights consider the following example:

Example 1 *Suppose that Full Autarky is the compatibility regime agreed on at stage 1/2 of the game (i.e. $L_i = \beta_i + q_i$). Suppose further that each new consumer expects all other new consumers to buy from firm 1. Then, given these expectations, firm 1 maximizes the profit expression:*

$$\pi_1 = p_1 q_1 = (1 + \nu(\beta_1 + q_1) - q_1)q_1$$

and adds the monopoly quantity of new consumers:

$$q_1^{FA}(q_2 = q_3 = 0) = \frac{1 + \nu\beta_1}{2(1-\nu)}.$$

[28] According to Farrell and Klemperer (2007) expectations may respond in various ways to price or "quality" differences. They could, for example, track quality or surplus but consumers could also stubbornly favor one firm. Existence of tipping equilibria changes dramatically depending on the underlying expectations formation process.

Given firm 1 adds $q_1^{FA}(q_2 = q_3 = 0)$ it is indeed not profitable for firms 2 and 3 to serve the market if the following condition holds on price (inverse demand) p_2 for all $q_2 > 0$ (note that the corresponding condition of $p_3 < 0$ is implied by $p_2 < 0$):

$$p_2 = 1 + \nu\beta_2 - \frac{1 + \nu\beta_1}{2(1-\nu)} < 0.$$

If this inequality holds, firms 2 and 3 do indeed not produce and thus there exists a tipping equilibrium with firm 1 producing the monopoly output. The respective parameter space is bounded by:

$$\beta_1 > \frac{2(1-\nu)(1+x\nu) - 1}{\nu + 2\nu x(1-\nu)}$$

which implies a negatively-sloped boundary line in the (ν, β_1)-space (as $\frac{\partial}{\partial \nu}\left(\frac{2(1-\nu)(1+x\nu)-1}{\nu+2\nu x(1-\nu)}\right) = \frac{-6x\nu^2+4x\nu-2x-1}{\nu^2(2x(1-\nu)+1)^2} < 0$) with $\nu(RHS = 1) = \overline{\nu} = \frac{1}{3}$ and $\nu(RHS = 0) = \underline{\nu} = \frac{x-1+\sqrt{x^2+1}}{2x} > \overline{\nu}$ for $x \in [\frac{1}{2}, 1)$. Thus, for large enough network effects ν there exists a consistent-expectations equilibrium in which there is tipping to firm 1 ($q_1 = \frac{1+\nu\beta_1}{2(1-\nu)}, q_2 = 0, q_3 = 0$). Note, that under Full Autarky other types of tipping equilibria are also possible (see proof of Proposition 1.1 in Appendix 1.6.3). Tipping may be to firm 2 only, to firm 3 only or to subgroups of firms 1 and 2, firms 1 and 3 and firms 2 and 3 – depending on expectations. For larger network effects multiple equilibria exist depending on the expectations that consumers have.

The above example reveals the following basic insights which can be generalized. First, tipping may occur if network effects are significantly weaker than required in Proposition 1.1. The parameter regions for existence differ depending on the compatibility regime chosen at stage 1/2 and the market structure (in particular the asymmetries in β_is). Second, the boundary in (ν, β_1)-space of where these equilibria exist is negatively sloped if it involves equilibria of *tipping to* firm 1 (i.e. a higher β_1 implies tipping also at lower levels of network effects) and positively if it involves *tipping from* firm 1. Third, under Full Autarky we may observe a variety of market structures in equilibrium. With a higher degree of compatibility, i.e. a regime of a "Coalition of the Small" or "Targeting of either Firm 2" or "Firm 3", multiplicity of tipping is reduced. In that case tipping can only occur to the compatibility alliance or away from it.[29] Finally, expectation-dependent multiple equilibria exist for a large region of the parameter space.

[29] The intuition is similar to why there is no tipping under full compatibility. Products of the coalition are perfect substitutes – so either both firms of the coalition serve the market or none of them do so in equilibrium.

The following corollary summarizes the general comparative statics results of tipping equilibria:

Corollary 1.1 *In any tipping equilibrium* ***(a)*** *an increase in a firm's own installed base increases ceteris paribus the parameter region where* tipping to *it is an equilibrium,* ***(b)*** *an increase in a firm's own installed base reduces ceteris paribus the parameter region where* tipping away *from it is an equilibrium,* ***(c)*** *larger asymmetry of rivals acts like an increase in the installed base of firm 2 and thus increases regions of* tipping to *a coalition that includes firm 2 and reduces regions where* tipping away *from a coalition that includes firm 2 is an equilibrium,* ***(d)*** *sufficiently strong network effects are needed.*

Proof. See Appendix, Section 1.6.3. ■

Therefore, when compatibility regimes are of less than Full Compatibility, tipping occurs for strong network effects. Installed-bases then act as a safe-harbor against *tipping away* or potentially make *tipping to* a firm an equilibrium. Imperfect compatibility introduces a vertical differentiation component which, if it has sufficient weight in consumers' utility functions through strong network effects, leads to some firms not producing in equilibrium.

The following figure summarizes the existence of tipping equilibria for different compatibility regimes in (ν, β_1)-space:

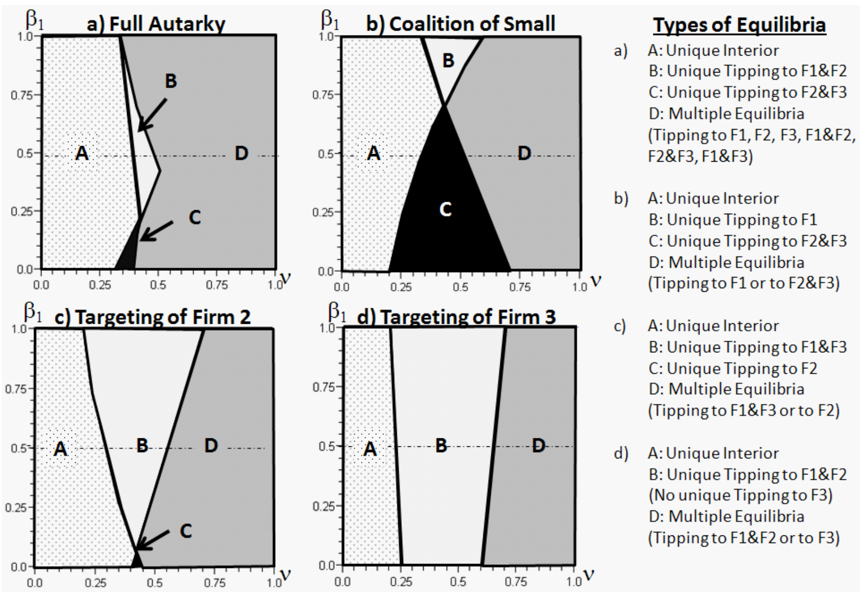

Figure 1.2: Possible Equilibria under Different Compatibility Regimes

The horizontal axes capture the strength of network effects, the vertical axes firm 1's market share β_1. Note that market shares of firms 2 and 3 can also be deduced from firm 1's market share. Firm 2's share is $\beta_2 = x \cdot (1 - \beta_1)$ and firm 3's share is $\beta_3 = (1 - x) \cdot (1 - \beta_1)$ where for the above figure x is fixed to $x = 0.75$.

The figure graphically confirms the prediction that tipping equilibria exist as network effects increase. Moreover, there are multiple equilibria under all compatibility regimes for large network effects (Area D as $\nu \to 1$). Picture **a)** reveals that out of the different tipping equilibria those involving competition between two firms out of which one is the market leader span the largest parameter region. In area B of graph **a)**, for example, firm 1 is largest, while it is firm 2 when firm 1's market share β_1 becomes very small (as in area C of graph **a)**). Competition between the two firms entails a competitive effect similar to the "*intra-network competition effect*" of Malueg and Schwartz (2006). Compared to prices in a tipping equilibrium with just one firm, competition reduces prices and increases adoption. Therefore tipping to two firms is more likely than tipping to a monopoly. This is also the intuition behind figure **b)**. Area C is larger than area B in this figure because intra-network competition drives prices down and makes *tipping to* the Coalition of the Small more likely. Figures **c)** and **d)** show that targeting firms 2 or 3 protects firm 1 against *tipping away* for a large region in parameter space. In particular, under Targeting of Firm 3 in graph **d)** tipping to firms 1 and 2 is the unique equilibrium for area B. When expectations are such that this equilibrium will obtain, firms 1 and 2 can exclude firm 3 from serving the market.

Through its compatibility decision in stage 1/2 a firm can critically influence whether and what kind of tipping will be feasible in equilibrium. However, this decision requires full insights into expectations of new consumers. Because of the multiplicity of equilibria, it is difficult to compare firms' incentives for compatibility. For compatibility incentives we therefore focus exclusively on the unique interior equilibria in the quantity game that result under weaker network effects. These equilibria exist under every compatibility regime – also under Full Compatibility which was not depicted in Figure 1.2 and will be discussed next.

Interior Equilibrium

In an interior equilibrium all three firms are active in the industry and supply their products to new consumers. As depicted in Figure 1.2 the interior equilibrium is the unique equilibrium under each compatibility regime for weak network effects. A sufficient condition for their existence is given by the following proposition:

Proposition 1.2 *For low strength of network effects ($\nu \leq \frac{1}{5}$) there exists a unique interior equilibrium under each compatibility regime in which all firms add new customers.*

Proof. See Appendix, Section 1.6.3. ■

To derive conditions for existence of the interior equilibria we maximize firms' profit functions given the compatibility regime and derive the optimal quantities (analogously to the derivation for Full Compatibility in Section 1.3.1, equations (1.4) to (1.5)). We must also ensure that profit expressions are non-negative. In the interior equilibria of the subgame firms' profits are as given in the following table[30]:

Regime	Firm 1 (π_1)	Firm 2 (π_2)	Firm 3 (π_3)
FC	$\frac{1}{16}\frac{(\nu+1)}{(1-\nu)}$	$\frac{1}{16}\frac{(\nu+1)}{(1-\nu)}$	$\frac{1}{16}\frac{(\nu+1)}{(1-\nu)}$
FA	$\frac{1-3\nu+\nu\beta_1(4-2\nu)}{2(\nu-2)(2\nu-1)}$	$\frac{1-3\nu+\nu x(1-\beta_1)(4-2\nu)}{2(\nu-2)(2\nu-1)}$	$\frac{1-3\nu+\nu(1-x)(1-\beta_1)(4-2\nu)}{2(\nu-2)(2\nu-1)}$
CS/AF1	$\frac{1+\nu\beta_1(5-3\nu)-5\nu}{6\nu^2-12\nu+4}$	$\frac{1-\nu\beta_1(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1-\nu\beta_1(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$
TF2	$\frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1+x\nu(5-3\nu)(1-\beta_1)-5\nu}{6\nu^2-12\nu+4}$	$\frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$
TF3	$\frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1+(5-3\nu)\nu(1-x)(1-\beta_1)-5\nu}{6\nu^2-12\nu+4}$

By comparing the expressions for profits we can deduce that a larger firm can leverage the installed-base advantage into a higher number of new consumers for most compatibility regimes. The reason is that customers perceive the larger network size as a quality advantage and value the product more than that of competitors. As long as compatibility is less than perfect, larger firms therefore benefit from this relative advantage in the quantity competition game and they can also leverage this comparative advantage into compatibility decisions as we will see later. In contrast, smaller competitors suffer from the same effect and for them compatibility becomes crucial to diminish the relative disadvantage.

The analysis in conjunction with Figure 1.2 also shows that the unique interior equilibrium may exist for values of network effects which significantly exceed the threshold

[30] Note that quantities in equilibrium can be deduced by dividing by $(1-\nu)$ and then taking the square root. Equilibrium price is given by multiplying the equilibrium quantity by $(1-\nu)$. We abbreviate as follows: FC=Full Compatibility; FA=Full Autarky; CS=Coalition of the Small; TFi=Targeting of Firm i.

for sufficiency (i.e. for $\nu > \frac{1}{5}$). In fact, for the Full Compatibility regime, the symmetric interior equilibrium is the unique equilibrium for the entire parameter space. In the proof for uniqueness of Proposition 1.2 we show that tipping equilibria and interior equilibrium are in fact mutually exclusive. When tipping is a possible equilibrium, the interior equilibrium does not exist.

By focusing on interior equilibria only ($\nu \leq \frac{1}{5}$) and comparing profits across compatibility regimes, we can make predictions about the preferred compatibility regime of firms as well as the equilibrium compatibility regime. It will be interesting to see whether and when firm 1, the largest firm, has an incentive to share its installed base with its competitors. The incentives to do so are reflected in the firm's equilibrium profits under the different regimes and will be illuminated in the next section.

1.3.2 Compatibility Choice ($\nu \leq \frac{1}{5}$)

The equilibrium compatibility regime results from firms' desired compatibility choices at stage 1/2 under the requirement of mutual agreement. As the number and form of profit expressions in the above table already indicates, multiple compatibility regimes are feasible. The following remark facilitates comparisons:

Remark 1 *In any equilibrium – tipping or interior – profits of firm i are*

$$\pi_i^* = (1-\nu)(q_i^*)^2 \tag{1.6}$$

where q_i^* denotes the quantity of firm i in this equilibrium.

Proof. See Appendix, Section 1.6.3. ■

The above observation which is also valid in a standard Cournot model carries over to the augmented versions with network effects (and even horizontal product differentiation) considered here. It states that we can base equilibrium profit comparisons across compatibility regimes purely on the equilibrium quantities as there is a simple mapping from quantities to profits (which is positive and monotone). As the expressions for equilibrium quantities are a lot simpler, we thus usually argue using equilibrium quantities even if intuition would suggest a comparison of profits. Until we investigate cross-payments in Section 1.4 we make statements on quantities and profits interchangeably.

Let us first understand firm 1's preferred compatibility policy by ranking compatibility regimes. Comparing equilibrium profits, one can easily observe that firm 1 always prefers "Targeting of Firm 3" over "Targeting of Firm 2" if $x > \frac{1}{2}$. Clearly, the only difference for firm 1 between those two regimes lies in firm 2 bringing a larger installed base into the coalition. Thus, firm 1 prefers firm 2 as a partner over firm 3. Moreover, firm 1 always prefers "Full Autarky" over a "Coalition of the Small". Both regimes leave firm 1 incompatible with rivals. Under this presumption firm 1 would opt for competitors remaining incompatible as well, so that their networks are not merged to a larger network. For the three compatibility regimes that are not directly revealed preferred to by others, we can show that firm 1's compatibility choice looks like the following for $x = 0.75$:

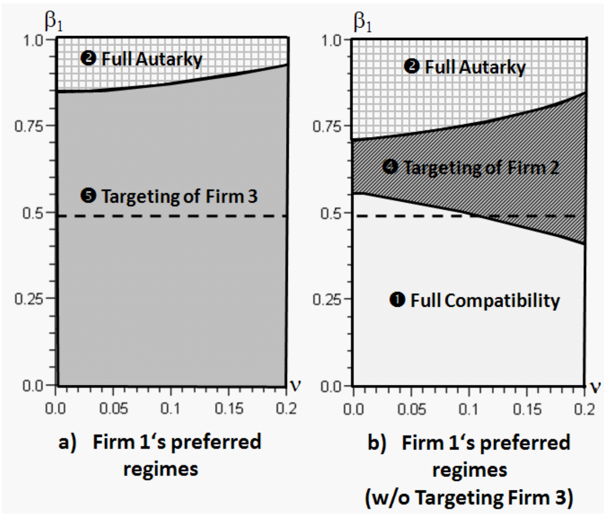

Figure 1.3: Firm 1's Preferred Compatibility Regimes

The left figure **a)** shows firm 1's preferred regimes. Firm 1 desires "Targeting of Firm 3" for most of the parameter space. Only if its market share becomes extremely large, firm 1 opts for Full Autarky and against sharing its installed base with its rivals. The right figure **b)** discusses firm 1's ranking of compatibility regimes if regulation or antitrust policies were to forbid targeting the smallest firm, firm 3. In that case, firm 1 would prefer "Targeting of Firm 2" for intermediate own market shares. For a high market share, Full Autarky again yields the highest profits for firm 1. For low values of β_1, which may also imply that firm 1 is no longer the largest firm, firm 1 prefers Full Compatibility.[31] Figure 1.3 therefore highlights the relevance of mixed compatibility

[31] Firm 1 will be smaller than firm 2 if $\beta_1 < x(1-\beta_1) \Leftrightarrow \beta_1 < \frac{x}{1+x} \approx .43$ for $x = 0.75$. However, here we assume that $\beta_1 \geq \beta_2 \geq \beta_3$.

regimes. Firm 1 will generally seek just one partner so that one firm will not partake in the sharing of network effects.

However, firm 1 cannot set the compatibility agreement at own will. Firms must mutually agree. Therefore, the compatibility incentives of firms 2 and 3 are important which we determine by similar logic. Ranking the preferred compatibility regimes for both firms we can first show that firm 2 always prefers "Targeting of Firm 3" over the "Coalition of the Small". Again the intuition is that when picking just one partner, firm 2 chooses the larger one. Also, firm 2 always prefers "Full Autarky" over "Targeting of firm 2" where it would be left outside a rivals' alliance. Whether and when firm 2 favors the compatibility regimes of "Targeting of Firm 3", "Full Autarky" or "Full Compatibility" depends on the distribution of market shares. In fact, one can show that firm 2 prefers "Targeting of Firm 3" for the entire parameter space where $\beta_1 \geq \beta_2 \geq \beta_3$ holds. Because both parties that need to sign the "Targeting of Firm 3" compatibility agreement indeed have this as their preferred alliance, they will mutually agree on it. Therefore, firm 3's compatibility choice is irrelevant (we show that this is similar in logic to firm 2's).

Let us briefly consider what happens for extremely large values of market shares of firm 1. We have shown in Figure 1.3 that firm 1 would then desire Full Autarky. However, this would require firms 2 and 3 not wanting to form an alliance. The incentives of firms 2 and 3 are different – they would form an alliance. Because firm 1 anticipates this, it will, for this parameter region, propose its second-best compatibility regime, "Targeting of Firm 3". This is accepted by firm 2. We can summarize the findings in the following proposition:

Proposition 1.3 *If $\beta_1 > \beta_2 > \beta_3$ and $\nu \leq \frac{1}{5}$, the equilibrium compatibility choice among the three firms is "Targeting of Firm 3" and thus involves less than full compatibility even if compatibility is costless. Firms produce the following quantities:* $(q_1^{TF3} = q_2^{TF3}, q_3^{TF3}) = (\frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}, \frac{1+(5-3\nu)\nu(1-x)(1-\beta_1)-5\nu}{6\nu^2-12\nu+4})$.

Proof. See Appendix, Section 1.6.3. ■

The above result is based on the following basic insights. First, maintaining the assumption that firm 1 is the largest firm, firms 2 and 3 seek alliances with firm 1. They would therefore generally want to agree to proposals of compatibility made by the market leader. Therefore, firm 1 *de facto* determines the equilibrium compatibility of the industry. As long as firm 1 is the largest firm (so that we can exclude the area of small market shares of firm 1) firm 1 always finds its proposal accepted by the partner. Only when firm 1 opts for Full Autarky for very large market shares the proposal is rejected as firms 2 and 3 have an incentive to form an alliance. Anticipating this, firm 1 proposes its second best compatibility regime of "Targeting of Firm 3" to firm 2 – as this gives it higher profits than a "Coalition of the Small".

Because firm 1's decision is of highest importance in determining the equilibrium compatibility regime we now explore the effects that influence firm 1's decision. Firm 1 trades off the two effects already noted in Crémer et al. (2000) which are also at the heart of firm 2's and 3's decision:

- *Demand effect:* Agreeing on compatibility with one or two partners increases demand of all firms within that alliance as consumers' willingness to pay increases. The larger the prospective partner, the more the firm seeks an alliance. Smaller firms therefore generally seek compatibility strongest.

- *Vertical Differentiation effect:* Compatibility implies that the network quality of partners is equalized. The larger firm will therefore lose its vertical differentiation advantage. If network qualities are very asymmetric and hence vertical differentiation plays an important role, this second effect becomes decisive. It points in favor of compatibility for small firms but is the reason why a large firm may opt against compatibility.

This trade-off implies that very symmetric firms have little to lose from compatibility as the vertical differentiation effect is small. However, for large firms, such as firm 1 in our model, agreeing on compatibility has a countervailing effect. It loses its vertical product differentiation advantage. Incentives for full compatibility are therefore reduced if significant asymmetries exist. The same effects also determine the incentives of firm 2 towards compatibility with firm 3. Firm 2's incentives are always smaller than firm 3's and when the market shares are very asymmetric, firm 2 might not want to undergo compatibility with firm 3.

The above effects also illustrate that one-sided compatibility through adapters or converters which we have excluded by assumption are always desirable as there would be no negative vertical differentiation effect but only the beneficial demand effect.

It is now interesting to examine the robustness of Proposition 1.3. In the following proposition we examine firm 1's compatibility strategy if we add additional competitors to the market. We can generalize the above result as follows.

Proposition 1.4 *Targeting by firm 1, i.e. excluding at least a positive fraction of symmetric competitors from the compatibility agreement, is always profitable for the dominant firm, firm 1.*

Proof. See Appendix, Section 1.6.3. ■

To generalize the result of Proposition 1.3 we analyze a situation where firm 1 with the installed base β_1 faces n *a priori* identical and symmetric rivals. We then investigate the compatibility incentives of firm 1. We assume that a compatibility offer of firm 1 is never rejected (which we have shown to be true if firm 1 is the largest firm) so that firm 1 can essentially choose the number of firms to be compatible with. For the fraction of firms that does not receive a compatibility offer of firm 1, we assume that they form their own compatibility network.[32] In the appendix we prove the above statement by showing that firm 1 – starting from Full Compatibility – has an incentive to reduce compatibility at the margin. The result would be further reinforced if market shares of rivals were asymmetric and competitors were not to form their own compatibility network.

In summary, this section has shown that under non-uniform compatibility choice with asymmetric rivals mixed compatibility regimes are predominantly chosen. Therefore, neither Full Compatibility nor Full Autarky result in equilibrium. Thus, if the socially efficient regime is indeed Full Compatibility regulatory intervention may be desirable.[33] In the next section we want to investigate the comparative statics of different parameters on firm 1's compatibility incentives and on equilibrium. In Section 1.4 we then ask whether and how it will be possible to achieve full compatibility using different measures. For this purpose we investigate the possibility of fixed cross-payments between firms.

1.3.3 Comparative Statics

The aim of this section is to understand the effects of changes in market structure or the market environment on firm 1's compatibility incentives and the equilibrium compatibility regime.

[32] This tends to bias results towards firm 1 offering more compatibility. As it was our aim to show that full compatibility is never achieved, this bias further reconfirms our hypothesis. The same is true for the symmetry of rivals. As long as rivals are symmetric they would indeed always form a compatibility regime.

[33] This depends on the associated transaction and setup costs of compatibility or the costs of incompatibility (e.g. in the case of quality degradation).

Strength of network effects (ν)

The strength of network effects influences firm 1's incentives to grant compatibility. The demand and the vertical differentiation effect both increase in network effects. Therefore the overall effect is ambiguous and depends on the relative size of the effects and the underlying market share of firm 1. As can be inferred from Figure 1.3a) stronger network effects generally result in an expanding parameter region for which "Targeting of Firm 3" is desirable. The critical market share required for firm 1 to desire Full Autarky is increased. Thus, the equilibrium compatibility regime of "Targeting of Firm 3" remains the equilibrium compatibility regime as long as $\nu \leq \frac{1}{5}$. In addition, as shown in Section 1.3.1, very strong network effects cause tipping. In summary:

Corollary 1.2 *With stronger network effects, there may be tipping and multiplicity of equilibria. Also, as the strength of network effects increases, firm 1 seeks mixed compatibility (Targeting of Firm 3) for a larger parameter region implying that profits under this regime increase faster in network effects than under Full Autarky. The equilibrium compatibility regime remains unchanged.*

Proof. See Appendix, Section 1.6.3. ■

Dominance of the market leader (β_1)

The distribution of market shares plays the predominant role in determining equilibrium compatibility. The market leader *de facto* determines equilibrium compatibility. While firm 1 prefers "Targeting of Firm 3" as the compatibility regime, it can be seen from Figure 1.3b) that firm 1's desire for compatibility hinges on the dominance the market leader has over its rivals. A firm seeks less compatibility the larger its market share. For very small shares it may desire Full Compatibility, for intermediate shares it desires mixed compatibility regimes while for high market shares it desires Full Autarky. The reason is that with increasing market share, the firm's vertical differentiation advantage increases. If that is large enough, the firm wants to deny compatibility. In equilibrium the compatibility regime is then generically targeting of the smallest of the three firms.

Corollary 1.3 *With increasing dominance (i.e. larger β_1) the market leader, firm 1, seeks less compatibility. The equilibrium compatibility regime is, however, not influenced.*

Proof. See Appendix, Section 1.6.3. ■

The equilibrium compatibility regime is thus robust to changes in both network effects and installed base shares of the market leader (as reflected in Figure 1.3).

Asymmetry of rivals' market shares (x)

Previous research has either focused on all rivals being fully symmetric or on very special cases of asymmetry.[34] Our framework allows to formally analyze the impact of asymmetries of installed bases on the equilibrium compatibility regime as well as equilibrium quantities. Besides varying the market share of firm 1 (relative to the sum of firms 2 and 3), we can introduce different degrees of asymmetries between rivals by changing the parameter of asymmetry x. The following figure shows how firm 1's compatibility incentives change if asymmetry between rivals increases from perfect symmetry (i.e. $x = 0.5$) to significant asymmetry ($x = 0.75$):

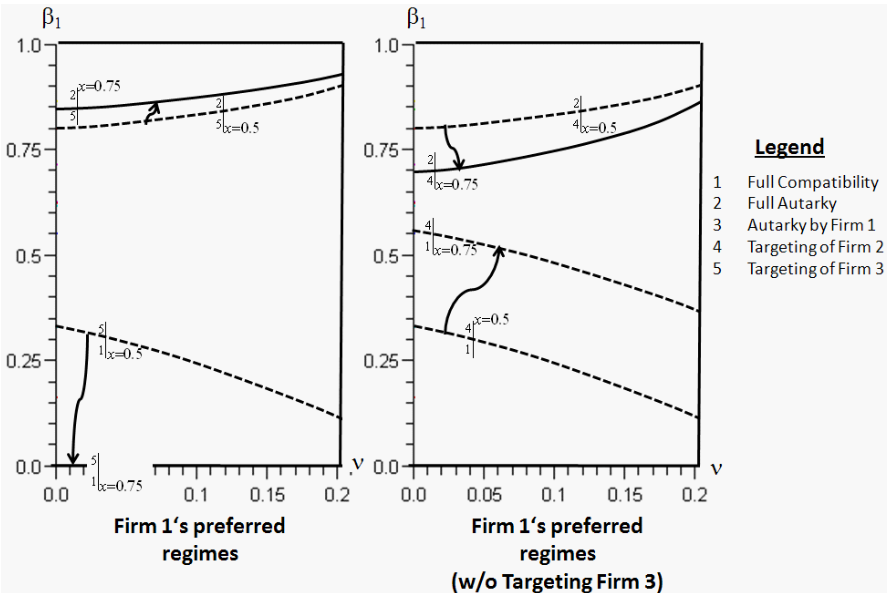

Figure 1.4: Comparative Statics in Asymmetry of Rivals

Proposition 1.5 *With increasing asymmetry between rivals' market shares, firm 1 seeks mixed compatibility for a larger parameter space. The equilibrium compatibility regime remains unchanged unless all firms are symmetric ($\beta_1 = \frac{1}{3}$, $x = \frac{1}{2}$); in that case Full Compatibility obtains.*

Proof. See Appendix, Section 1.6.3. ■

[34] Both, Malueg and Schwartz (2006) and Crémer et al. (2000) assume symmetric rivals.

Again, the intuition can be traced back to the interplay between demand and vertical differentiation effects. If all firms are very symmetric (consider e.g. $\beta_i = \frac{1}{3}\ \forall i$), no firm wants to opt for incompatibility – Full Compatibility obtains. The reason is that a firm that opts for incompatibility with an equally-sized firm will not gain a competitive advantage over this firm and the quality or network size of it relative to the other two firms even deteriorates. However, as soon as there is one firm with a larger market share Full Compatibility does not result in equilibrium. With increasing asymmetry the vertical differentiation effect gains increasing importance. Firms deny compatibility to safeguard their vertical differentiation advantage.

Consider now the compatibility choice of firm 1. From Figure 1.4 we can deduce that with greater symmetry of rivals' shares firm 1 seeks less compatibility for a larger parameter region. Consider, for example, the "Targeting of Firm 3" versus "Full Autarky" choice that firm 1 faces for high own market shares. The "Full Autarky" regime has the same attractiveness, no matter whether rivals are symmetric or asymmetric as long as their joint market share is unchanged. However, the "Targeting of Firm 3" regime becomes more attractive the larger the asymmetry in rivals, i.e. the larger x.

While a rival in a standard Cournot model without network effects does not care about asymmetries of rivals, asymmetries in this model do play an important role for equilibrium. As we show in Appendix, Section 1.6.2, a firm designs its quantity choice in a regular Cournot model only by accounting for the *average* cost efficiency of rivals (i.e. optimal quantities depend on the sum of marginal costs). Cost asymmetries have no direct effect on the shape of the reaction function. However, when asymmetries in marginal costs lead to firms building different installed-bases, this has important implications for equilibrium compatibility.

Horizontal Differentiation

We now generalize the model to capture horizontal product differentiation in addition. We introduce horizontal product differentiation of firm 1 vis-à-vis its rivals and assume that there are two equally-sized groups of consumers and each group prefers *ceteris paribus* one of two varieties on the market. We further assume that variety a is offered by firm 1 only and variety b is provided by firms 2 and 3 in competition.[35] As the price of the preferred variety increases, more and more consumers switch to buy the

[35] Though the industry structure is stylized it is most important here to understand firm 1's incentives of compatibility depending on horizontal differentiation. Results can be readily transferred to a setting were all firms are differentiated.

less preferred variety at a cheaper price.[36] The industry structure therefore looks as follows:

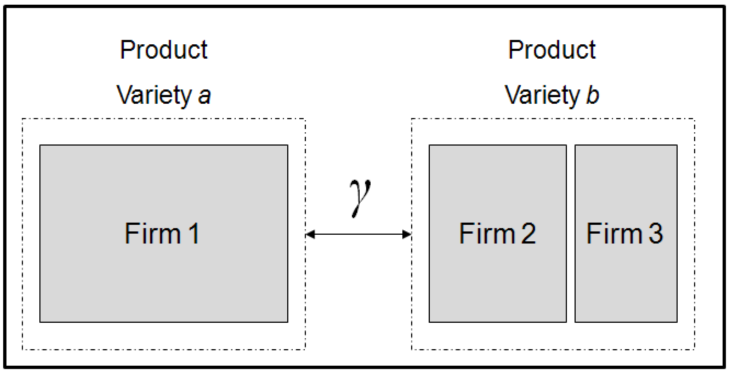

Figure 1.5: Industry Configuration with Horizontal Product Differentiation

From the utility functions we derive linear inverse demand functions that are very similar to the ones under homogeneous products:

$$p_1 = a + \nu L_1 - \delta q_1 - \gamma q_2 - \gamma q_3 \tag{1.7}$$

$$p_2 = a + \nu L_2 - \gamma q_1 - \delta q_2 - \delta q_3 \tag{1.8}$$

$$p_3 = a + \nu L_3 - \gamma q_1 - \delta q_2 - \delta q_3 \tag{1.9}$$

where $0 \leq \nu \leq \gamma \leq \delta$[37] and:

$$L_i = \beta_i + q_i + \sum_{j \neq i}^{3} \theta_{ij} \cdot (\beta_j + q_j). \tag{1.10}$$

These expressions have, abstracting from the term stemming from network benefits, similarity to the linear inverse demand functions as used in Bowley (1924) or Spence (1976) and Dixit (1979). We again ensure that inverse demand functions are downward sloping in own quantity by restricting $\delta > \nu$. Product varieties a and b are imperfect substitutes as long as the product differentiation parameter, γ, takes a value of $0 < \gamma < \delta$. Thus, the other variety's price and quantity matter for a firm's own inverse demand, its profit maximization and its compatibility choice. The strength of the effect through product competition is, as in any other model of horizontal product

[36] A specification of utility functions and a detailed derivation of the general demand system is given in the Appendix, Section 1.6.1.

[37] We again assume for exposition that $\alpha = \delta = 1$ when stating our results.

differentiation, governed by the parameter measuring the substitutability of product varieties, γ. Note that as $\gamma \rightarrow \delta$ products become perfect substitutes. As $\gamma \rightarrow 0$ varieties become less and less substitutable and finally when $\gamma = 0$, demands of the two product varieties are independent. We assume that $\gamma \nless 0$ and thereby exclude the analysis of complementary variety demands.[38]

Observe that the homogeneous products' case is completely nested in the above demand system. By setting $\gamma = \delta$ we are back to the demand system considered in Section 1.2. Note that we assume that network effects are not influenced through horizontal differentiation, i.e. the desire for compatibility remains, even if products become more and more differentiated. In addition the network effects are modeled to be firm-specific so that even if firms 2 and 3 produce homogeneous products network effects only accrue at a product, not at the variety level. We do so because neither homogeneity nor heterogeneity of products governs the technical compatibility and interoperability. Firms can therefore independently decide on compatibility as in previous sections.

To compare compatibility incentives we proceed as in Section 1.3 by again making use of the equivalence of equilibrium quantities and profits (Remark 1 also holds for differentiated products). We can summarize the impact of product differentiation in the following proposition:

Proposition 1.6 *With a higher degree of horizontal product differentiation between firm 1 and its rivals, firm 1 desires more compatibility. In the extreme, where product demands are almost independent, Full Compatibility is firm 1's preferred compatibility regime. At the same time product differentiation reduces the set of feasible tipping equilibria.*

Proof. See Appendix, Section 1.6.3. ■

The figure on the next page summarizes the results graphically by comparing the case of homogeneous products ($\gamma = \delta = 1$) with that of significant horizontal differentiation ($\gamma = 0.5$) for $x = 0.75$.

[38] In fact "complementarities" could also arise through the existence of network effects, resembling the idea of indirect network effects. Because we assume that $\nu \leq \gamma \nless 0$, the potentially positive demand-boosting effect under compatibility through network effects is always offset through the competitive effect in our model.

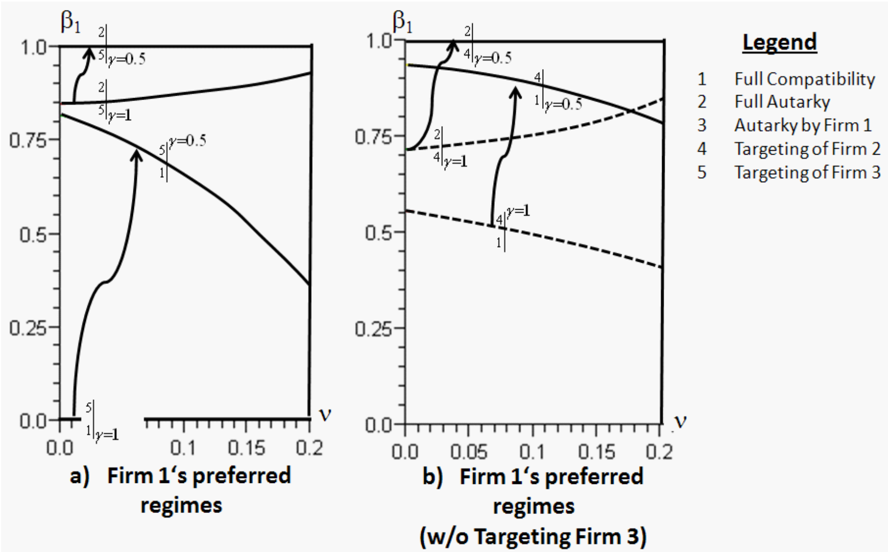

Figure 1.6: Comparative Statics in Degree of Product Differentiation

The above figure shows that with increasing product differentiation, firm 1 prefers more compatibility. In particular, the region where full compatibility is optimal for firm 1 expands significantly whereas the region of Full Autarky contracts fully. As horizontal product differentiation becomes very strong ($\gamma \to 0$) firm 1 always opts for Full Compatibility because sharing the vertical differentiation advantage loses importance with increasing product differentiation whereas the demand effect remains. However, when firms 2 and 3 are sufficiently asymmetric it may now be firm 2 that refuses full compatibility. The reason is that this firm still trades off the demand effect against the deterioration of relative quality advantages with respect to firm 3.

An application where product differentiation and compatibility are jointly important is the software applications and the operating systems market. Whereas Microsoft and Linux are imperfect substitutes their compatibility is of great importance for users. Some authors have even argued that operating systems could also be complements to some degree.[39] This discussion only shows that understanding the impact of horizontal product differentiation on compatibility choice is relevant. The result that compatibility typically increases towards those products that are weaker substitutes is not only intuitive but also observed in reality. Microsoft has just launched a new "compatibility initiative" in 2007 which aims at establishing compatibility with many other products. This initiative is targeted at imperfect substitutes that do not truly threaten Microsoft's demand but rather foster benefits through realization of network effects.

[39] For an empirical study investigating this, see Kretschmer (2004).

Some financial analysts, for example, argue that Microsoft is in fact fostering compatibility to increase own demand through virtualization allowing a broader set of services and software to interact.

Besides the above results which hold for interior equilibria, there are also important implications of horizontal product differentiation for the set of possible tipping equilibria. In fact, the set of possible equilibria reduces. Because there are two consumer groups with preferences for one of the varieties, both of these have to be served in equilibrium as horizontal differentiation becomes strong. Thus, those tipping equilibria that do not allow serving both customer groups no longer exist.

Example 2 *Suppose that Full Autarky is again the compatibility regime agreed on at stage 1/2 of the game (as in Section 1.3.1). We now again derive the equivalent condition required for firm 1 to indeed supply the market as a monopoly (i.e. profits of firms 2 and 3 being negative):*

$$p_2 = 1 + \nu\beta_2 - (\gamma - \nu)\frac{1 + \nu\beta_1}{2(1-\nu)} < 0.$$

Although the inequality may hold for values of γ close to δ, it no longer holds for low values of γ. Converting the first inequality by isolating γ:

$$\gamma > \frac{\nu\,(1 + \nu\beta_1) + 2\,(1 + \nu\beta_2)\,(1 - \nu)}{1 + \nu\beta_1},$$

it is readily observed that as $\gamma \to 0$ the inequality fails to hold. Thus, this tipping equilibrium no longer exists for strong horizontal differentiation. The set of tipping equilibria for strong network effects reduces to tipping to firms 1&3 and tipping to firms 1&2 only.

1.4 Efficient Bargaining

When compatibility decisions are costless, Full Compatibility is the socially desirable regime. However, the analysis of Section 1.3 has shown that, except for the case where there is symmetry among competitors and/or sufficient product differentiation in the market, full compatibility is not achieved. In this section we investigate whether cross-payments may serve as an instrument to establish full compatibility as the equilibrium outcome.

We now assume that firms can draw up a contract that specifies fixed cross-payments between the firms in addition to the compatibility agreement. The terms of the contract are observable and verifiable in court so that renegotiation, hold-up and incompleteness do not play a role here. The bargaining process on royalties may take different forms. However, because there are three parties involved and the threat points are endogenously determined the usual economic approaches of Nash Bargaining and the Shapley value are difficult to apply here.[40] To approach the problem, we first derive expressions for the sum of profits of the three firms under the different compatibility regimes. We assume that firms may agree on the type of compatibility regime jointly but are not allowed to collude on prices. The following proposition summarizes the results:

Proposition 1.7 *Joint profits are highest under Full Compatibility for small network effects. However, for intermediate network effects profits are higher under mixed compatibility regimes if market shares are very asymmetric.*

Proof. See Appendix, Section 1.6.3. ■

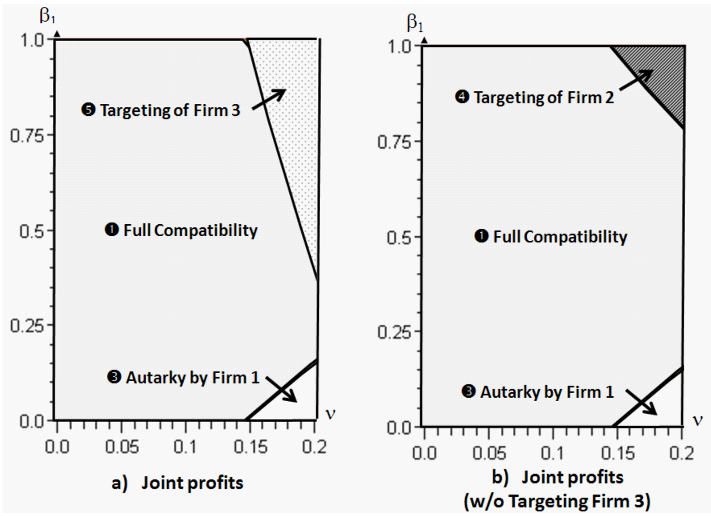

Figure 1.7: Compatibility Regimes with Highest Joint Profits

When comparing the above figure (again $x = 0.75$) against that of equilibrium compatibility regimes as discussed in Section 1.3, it becomes apparent that it is possible

[40] Under Shapley values the firms are paid their respective marginal contributions to the coalition. For that one would need a clearly defined "non-cooperative" regime. Similarly, it is difficult to define one threat point needed to calculated outcomes under Nash Bargaining. Compare Thomson (1994) and Winter (2002).

to use fixed cross-payments between firms to achieve a higher degree of compatibility. Because the outcome without bargaining would involve "Targeting of Firm 3", achieving full compatibility with cross-payments must imply granting firms 1 and 2 at least the profits that they would make under their outside option of "Targeting of Firm 3". Clearly, therefore, they must be net-receivers in the bargaining game. Firm 3 will have to compensate firms 1 and 2 and pay for compatibility. Cross-payments which achieve this outcome exist because joint profits are higher under Full Compatibility than under "Targeting of Firm 3".

Nevertheless, there are also insights from the above figure that should make us cautious. For intermediate network effects, full compatibility cannot be achieved through fixed cross-payments because joint profits are higher under mixed compatibility regimes if market shares are very asymmetric. Consider, for example, a large firm 1 and sufficiently strong network effects. "Targeting of Firm 3" is then the regime with highest joint profits. Firm 3's profits are so small that firms 1 and 2 in fact almost act as a duopoly because their vertical differentiation advantage relative to firm 3 is so large. Therefore, this regime is more profitable for sufficiently large asymmetries in market shares, i.e. for very small β_3. Firms 1 and 2 can mutually agree on it.[41]

Even in an environment where all firms must jointly agree on compatibility, no full compatibility would be achieved. Firms 1 and 2 would be willing to pay firm 3 to not become compatible. There exists a payment that is so large that firm 3 would agree to the mixed compatibility regime although it would not be part of the compatibility network. In equilibrium it can therefore happen that firms are paid to remain incompatible.

Note that looking at fixed cross-payments implies that there is no additional marginal effect on prices except for that resulting from the network expansion due to a change in the equilibrium compatibility regime. If firms were allowed to apply linear royalties to achieve compatibility, they would have an incentive to use these so as to set monopoly prices and sustain a collusionary outcome.[42]

In summary, we would expect that with fixed cross-payments full compatibility is achieved for weak network effects. In any such agreement, the smallest firm will need to bribe the larger firms to provide compatibility. In essence, the small firm has to buy

[41] For small market shares of firm 1 autarky by firm 1 ($\approxeq$ Coalition of the Small) has highest profits. We term it "Autarky by Firm 1" because for that range firm 1 is no longer the large firm, making the term "coalition of the small" odd.

[42] Compare, for example, Chapter 2 of this dissertation.

itself into receiving the benefits of the larger installed base. The idea reinforces the importance of installed base customers for profitability in a network industry and at the same time the importance that switching costs play to secure rents, especially in durable goods markets. At the same time, the importance of market share asymmetries and mixed compatibility regimes is further reinforced as they may obtain in equilibrium for intermediate network effects – even if fixed cross-payments are allowed.

1.5 Conclusions

We have used a model of quantity competition in the spirit of Crémer et al. (2000) and Malueg and Schwartz (2006) to analyze compatibility choice in an industry exhibiting network effects. To consider non-uniform compatibility choices of asymmetric rivals, we have focused on an oligopoly consisting of three firms with potentially asymmetric market shares. We have shown that for strong network effects there are multiple expectation-dependent equilibria in the quantity game. A tipping equilibrium, however, requires significant asymmetries in network sizes. Thus, under Full Compatibility, when products are perfect substitutes, no tipping can occur. Similarly, when an imperfect compatibility alliance is formed *tipping* is either *to* or *away* from both members of the alliance. We establish that an increase in a firm's own installed-base increases the area where *tipping to* this firm is an equilibrium and decreases the area where *tipping away* from it occurs. However, because there exist multiple expectation-dependent equilibria, little can be said about the compatibility choice of firms when network effects are very strong.

When network effects are weak, there exists a unique interior equilibrium in the quantity subgame under each compatibility regime. All three firms serve the market. Deriving the equilibrium compatibility regime by comparing profit expressions for each firm and analyzing the ranking of preferred compatibility choices, reveals that full compatibility is generically not achieved. Despite Full Compatibility being the socially desirable outcome as compatibility decisions are costless in our model, the equilibrium compatibility regime involves targeting of the smallest firm for the entire parameter space as long as there are some asymmetries in installed bases. Therefore, our model also provides an explanation for why splintering of smaller rivals competing against a large dominant firm can result in equilibrium. Our finding is further reinforced as rivals become more asymmetric. However, when introducing horizontal product differentiation, incentives for full compatibility are increased.

Last, we explored the impact of allowing fixed cross-payments between firms. We have shown that full compatibility can be achieved for low network effects because joint profits are highest under Full Compatibility. The smallest firm will then have to compensate its rivals with fixed payments. However, for intermediate network effects firms may again have an incentive to agree on compatibility regimes that involve imperfect compatibility.

In our model there are no costs of (in-)compatibility. Absent pricing considerations, full compatibility is therefore the socially efficient regime. In such an economic environment, the government should enforce a mandatory and/or open standard to achieve full compatibility. However, there are some caveats as to this conclusion. First, costs of (in-)compatibility may render this result obsolete. Also, as we will discuss in the next chapter of this dissertation, such an open standard may have negative implications for (long-run) investment incentives. Only if there is no strong negative feedback of full compatibility on technology investments and/or if compatibility is not excessively costly, full compatibility will indeed be socially efficient.

1.6 Appendix

1.6.1 Derivation of Demand System in General Form

Following Martin (2002), we assume that there are two product varieties l offered on the market, variety a and variety b. Furthermore, there are two equally-sized groups of consumers, with group A and B each consisting of a mass of z consumers. The consumers are uniformly distributed over a $[0, 1]$ interval. Consumers in group A regard variety a as being of higher quality than variety b. At the same time, each consumer purchasing a particular variety l, obtains additional utility from more consumers buying the same good. The exact form of network effects νL_l is introduced in the main part, Section 1.2.1.[43] A consumer of group A located at $j \in [0, 1]$ when purchasing variety l gets utility

$$U_{jl}^{A} = \begin{cases} e - fj + \nu L_a - p_a & \text{when buying variety } a \\ g - j + \nu L_b - p_b & \text{when buying variety } b \\ 0 & \text{when not buying} \end{cases} \tag{1.11}$$

where $e > g$, $f > 1$. Consumers in group B have preferences of the same functional form as consumers of group A, but group B consumers regard variety b as being of higher quality than variety a. Producers cannot price discriminate between members of the two groups. Thus, as opposed to the model by Malueg and Schwartz (2006), consumers have a binary stand-alone valuation of the product (either e or g). Nevertheless, the resulting linear inverse demand function of Malueg and Schwartz (2006) is nested in the demand system that we subsequently derive from the above utility specification.

Consider w.l.o.g. a consumer in group A. A consumer located close to $j = 0$ is likely to buy a product of variety a as long as benefits from network effects or a relatively large g or f are not favoring variety b. We can then derive a condition of indifference under which a consumer from group A is just indifferent between buying variety a or b. Also, there exists a corresponding condition where a group A consumer would just opt not to buy at all. As j increases, consumers of group A change buying behavior in a monotonic fashion: for low values of j, consumers buy variety a. As j increases, they then switch to buying variety b and as j increases further, they opt not to buy at

[43] We undertake the standard assumption that utility is increasing in the network size of the firm that the consumer buys from and, in a complementary fashion, in network size of compatible networks.

all, as the outside option of not buying ($\overline{U_i} = 0$) gives more utility than buying any of the two varieties at offer. By argument of symmetry, we get analogous expressions for consumer behavior in group B, as long as network effects are not solely determining buyer behavior, consumer groups are similar in size and prices are roughly the same.

These points of indifference are illustrated in the following figure:

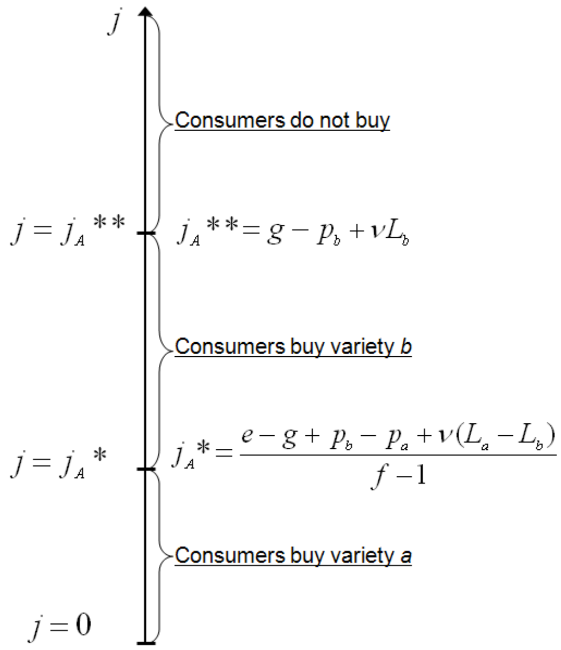

Figure 1.8: Group A Consumer Buying Behavior

The full demand for variety a is thus derived as the sum of consumers from group A and group B buying variety a:

$$q_a = z \cdot \frac{e - g + p_b - p_a + \nu(L_a - L_b)}{f - 1} + z \cdot (g - p_a + \nu L_a - \frac{e - g + p_a - p_b + \nu(L_b - L_a)}{f - 1}).$$

Here, the first term is the fraction of consumers from group A buying variety a and the second term is contributed by consumers from group B. Note that there may well be consumers that decide not to buy at all, namely all those for which the utility from buying lies below their outside utility from not buying at all ($\overline{U_i} = 0$). Similarly, we find for demand of variety b:

$$q_b = z \cdot \frac{e - g + p_a - p_b + \nu(L_b - L_a)}{f - 1} + z \cdot (g - p_b + \nu L_b - \frac{e - g + p_b - p_a + \nu(L_a - L_b)}{f - 1}).$$

The demand functions simplify to give the following expressions:

$$
\begin{aligned}
q_a &= \frac{2z}{f-1}p_b - \frac{z(1+f)}{f-1}p_a - \frac{z(1-f)}{f-1}g + \frac{\nu z(1+f)}{f-1}L_a - \frac{2\nu z}{f-1}L_b \\
q_b &= \frac{2z}{f-1}p_a - \frac{z(1+f)}{f-1}p_b - \frac{z(1-f)}{f-1}g + \frac{\nu z(1+f)}{f-1}L_b - \frac{2\nu z}{f-1}L_a.
\end{aligned}
$$

Solving for inverse demand one gets:

$$
\begin{aligned}
p_a &= g + \nu L_a - \frac{(1+f)}{z(3+f)}q_a - \frac{2}{z(3+f)}q_b \\
p_b &= g + \nu L_b - \frac{(1+f)}{z(3+f)}q_b - \frac{2}{z(3+f)}q_a.
\end{aligned}
$$

These expressions have – abstracting from the term stemming from network benefits νL_l – the same form as the linear inverse demand functions used in Bowley (1924), Spence (1976) or Dixit (1979). By reparameterizing we get:

$$
\begin{aligned}
p_a &= \alpha + \nu L_a - \delta q_a - \gamma q_b \qquad (1.12)\\
p_b &= \alpha + \nu L_b - \delta q_b - \gamma q_a
\end{aligned}
$$

where $\alpha = g > 0$, $\delta = \frac{(1+f)}{z(3+f)} > 0$, $\gamma > 0$ with $\gamma = \frac{(1+f)}{z(3+f)}\frac{2}{1+f} < \delta$. The model with aspects of vertical product differentiation between both consumer groups thus turns into a model of horizontal product differentiation at the aggregate level, also when accounting for network effects.

1.6.2 Competition in Semi-Differentiated Cournot

Equations (1.12) from Appendix 1.6.1, simplify to the following inverse product variety demands in absence of network effects ($\nu = 0$):

$$
\begin{aligned}
p_a &= \alpha - \delta q_a - \gamma q_b \\
p_b &= \alpha - \delta q_b - \gamma q_a .
\end{aligned}
$$

The following illustrates competition in a semi-differentiated Cournot model, i.e. in a set-up where the product varieties offered by firms may be either homogeneous to rivals' products or differentiated horizontally. We consider the three firms framework as proposed in Section 1.2. There is a duopoly offering variety b (firms 2 and 3) and a monopoly (firm 1) offering product variety a. We assume positive and constant but asymmetric marginal costs of production c_i. The profit function of firm 1 producing variety a is then:

$$\pi_1 = (p_1 - c_1)q_1 = (\alpha - c_1 - \delta q_1 - \gamma q_2 - \gamma q_3)q_1,$$

leading to the standard best response functions for the three firms:

$$
\begin{aligned}
q_1 &= \frac{\alpha - c_1 - \gamma q_2 - \gamma q_3}{2\delta} \\
q_2 &= \frac{\alpha - c_2 - \delta q_3 - \gamma q_1}{2\delta} \\
q_3 &= \frac{\alpha - c_3 - \delta q_2 - \gamma q_1}{2\delta} .
\end{aligned}
$$

The difference in best responses stems from the shape of inverse demand functions. Whereas the competitive effect of a rival supplying a homogeneous product variety with respect to one's own product can have a large effect on own demand (δ), the competitive effect of a rival acting in the differentiated market is weaker ($\gamma < \delta$). Thus, a firm active in the product variety market supplied by the duopoly faces fiercer competition and this is reflected in the best responses as well as the equilibrium demands of the firms. Combining the best response functions to find the equilibrium quantities, one gets:

$$\begin{aligned} q_1 &= \frac{\alpha(3\delta - 2\gamma) - 3\delta c_1 + \gamma(c_2 + c_3)}{2(3\delta^2 - \gamma^2)} \\ q_2 &= \frac{\alpha\delta(2\delta - \gamma) + \delta\gamma c_1 - (4\delta^2 - \gamma^2)c_2 + (2\delta^2 - \gamma^2)c_3}{2\delta(3\delta^2 - \gamma^2)} \\ q_3 &= \frac{\alpha\delta(2\delta - \gamma) + \delta\gamma c_1 - (4\delta^2 - \gamma^2)c_3 + (2\delta^2 - \gamma^2)c_2}{2\delta(3\delta^2 - \gamma^2)}. \end{aligned}$$

It is then easy to show that if marginal costs are symmetric, variety b is provided in larger quantity because of the fiercer competition on that variety market. This result vanishes as marginal costs of firm 1 become increasingly competitive compared to rivals or as product differentiation becomes smaller.

The important effect that should be taken away from this analysis is that firm 1 does not care about the distribution of marginal costs and quantities between firms 2 and 3. As long as cost asymmetries are small, firm 1 only cares about the sum of the marginal costs of firms 2 and 3. Thus, firm 1 cares only about the efficiency with which the rivalrous product variety is offered. Hence, competitive effects stemming from the quantity competition between firms 2 and 3 affect firm 1 only at the aggregate level. Asymmetries in costs – if not very large – do not really matter for an outside competitor. Hence, we assume symmetric costs between all firms and focus on differences in network size and their impact on competition in the main part of this chapter.

1.6.3 Proofs

Proof of Proposition 1.1:
We consider each feasible compatibility regime in turn and derive conditions for existence of tipping equilibria.
Full Compatibility: Here, $L_i = \beta_i + q_i + \sum_{j=1}^{3} \theta_{ij}(\beta_j + q_j) = \sum_{j=1}^{3} \beta_j + q_j$ which implies equal installed bases and as a result equal quantities of the firms. Equal quantities imply equal profits. Hence if $q_i > 0$ all firms offer the same positive quantity and make the same profits. In turn, if $q_i < 0$ all firms make negative profits and would not offer at all. Therefore tipping to a constellation where a subfraction of firms survives is not feasible. Tipping cannot be an equilibrium under Full Compatibility.
Full Autarky: Under Full Autarky, network effects are firm-specific. This leads to different tipping equilibria depending on the parameter constellations. To derive the

conditions, we follow the logic of Example 1 on page 17 of this dissertation. The following types can occur for the stated parameter regions:

- Firm 1 supplies market ($q_1^* > 0$, $q_2^* = q_3^* = 0$):
  if $\beta_1 > \frac{2(1-\nu)(1+x\nu)-1}{\nu+2\nu x(1-\nu)}$
- Firm 2 supplies market ($q_2^* > 0$, $q_1^* = q_3^* = 0$):
  if $\beta_1 < \frac{2\nu+x\nu-1}{2\nu+x\nu-2\nu^2}$ for $\beta_1 > \frac{1-x}{2-x}$; $\beta_1 < \frac{1+x\nu-2(1-\nu)(1+\nu-x\nu)}{2(1-\nu)\nu(x-1)+x\nu}$ for $\beta_1 < \frac{1-x}{2-x}$
- Firm 3 supplies market ($q_3^* > 0$, $q_1^* = q_2^* = 0$):
  if $\beta_1 < \frac{1+\nu(1-x)-2(1-\nu)}{\nu(1-x)+2(1-\nu)\nu}$ for $\beta_1 > \frac{x}{1+x}$; $\beta_1 < \frac{1+\nu(1-x)-2(1-\nu)(1+x\nu)}{\nu(1-x)-2(1-\nu)\nu x}$ for $\beta_1 < \frac{x}{1+x}$
- Firms 1 and 2 supply market ($q_1^* > 0, q_2^* > 0$, $q_3^* = 0$):
  if $\beta_1 > \frac{\nu-4x\nu-2\nu^2+2x\nu^2+1}{4\nu-4x\nu-2\nu^2+2x\nu^2}$
- Firms 1 and 3 supply market ($q_1^* > 0, q_2^* = 0, q_3^* > 0$):
  if $\beta_1 > \frac{1-3\nu+4x\nu-2x\nu^2}{4x\nu-2x\nu^2}$
- Firms 2 and 3 supply market ($q_1^* = 0, q_2^* > 0, q_3^* > 0$):
  if $\beta_1 < \frac{3\nu-1}{4\nu-2\nu^2}$

Example 3 *Firms 2 and 3 supply the market ($q_1^* = 0, q_2^* > 0, q_3^* > 0$): Assume that consumers expect all new consumers to buy from firms 2 and 3 only. The optimal quantities are then derived from a Cournot duopoly game with firm 1 providing nothing and firms 2 and 3 providing the optimal quantity depending on their installed bases. We then require:*

$p_1 = 1 + \nu\beta_1 - \frac{(1-2\nu)-\nu\beta_3+2\nu(1-\nu)\beta_2}{3-8\nu+4\nu^2} - \frac{(1-2\nu)-\nu\beta_2+2\nu(1-\nu)\beta_3}{3-8\nu+4\nu^2} < 0$

$\Leftrightarrow p_1 = \frac{3\nu-4\nu\beta_1+2\nu^2\beta_1-1}{2\nu-3} < 0$

$\Leftrightarrow \beta_1 < \frac{3\nu-1}{4\nu-2\nu^2}$

Existence of this tipping equilibrium requires a sufficiently low market share of firm 1 and strong enough network effects. As $\beta_1 \in (0,1)$, we can describe the RHS of the inequality. The threshold values at boundary values $\beta_1 \in \{0,1\}$ are as follows:

$\frac{3\nu-1}{4\nu-2\nu^2} = 1$ *at* $\overline{\nu} = 1$ *and* $\frac{3\nu-1}{4\nu-2\nu^2} = 0$ *at* $\underline{\nu} = \frac{1}{3}$

with $\frac{\partial}{\partial\nu}(\frac{3\nu-1}{4\nu-2\nu^2}) = \frac{3\nu^2-2\nu+2}{2\nu^2(\nu-2)^2} > 0$ *if* $3\nu^2 - 2\nu + 2 > 0$.

This holds for $\nu \in [0,1)$; the tipping equilibrium condition is thus increasing in network effects. This also pins down the minimum level of network effects required: $\underline{\nu} = \frac{1}{3}$.

Autarky by Firm 1:

- Firm 1 supplies market ($q_1^* > 0$, $q_2^* = 0$, $q_3^* = 0$):
  if $\beta_1 > \frac{1-2\nu^2}{3\nu-2\nu^2}$
- Firms 2 and 3 supply market ($q_1^* = 0$, $q_2^* > 0$, $q_3^* > 0$):
  if $\beta_1 < \frac{5\nu-1}{5\nu-3\nu^2}$

Targeting of Firm 2:

- Firm 2 supplies market ($q_1^* = 0$, $q_2^* > 0$, $q_3^* = 0$):
  if $\beta_1 < \frac{3x\nu+2\nu^2-2x\nu^2-1}{3x\nu-2x\nu^2}$
- Firms 1 and 3 supply market ($q_1^* > 0$, $q_2^* = 0$, $q_3^* > 0$):
  if $\beta_1 > -\frac{5\nu-5x\nu+3x\nu^2-1}{5x\nu-3x\nu^2}$

Targeting of Firm 3:

- Firm 3 supplies market ($q_1^* = 0$, $q_2^* = 0$, $q_3^* > 0$):
  if $\beta_1 < \frac{3\nu-3x\nu+2x\nu^2-1}{3\nu-3x\nu-2\nu^2+2x\nu^2}$
- Firms 1 and 2 supply market ($q_1^* > 0$, $q_2^* > 0$, $q_3^* = 0$):
  if $\beta_1 > -\frac{5x\nu+3\nu^2-3x\nu^2-1}{5\nu-5x\nu-3\nu^2+3x\nu^2}$

For the above conditions to be fulfilled we require strong network effects, ν. Generally multiple of these expectation-dependent equilibria exist. The toughest condition for tipping to exist is the one under Targeting of Firm 3 – *tipping to* firm 3. We require the following strength of network effects to guarantee tipping under all feasible compatibility regimes – except Full Compatibility: $\beta_1 < \frac{3\nu-3x\nu+2x\nu^2-1}{3\nu-3x\nu-2\nu^2+2x\nu^2}$ implying $\nu|_{\beta_1=0} = \underline{\nu} = \frac{3x+\sqrt{-10x+9x^2+9}-3}{4x}$ and $\nu|_{\beta_1=1} = \overline{\nu} = \frac{1}{\sqrt{2}} \approx 0.707$.

<u>Proof of Corollary 1.1</u>:
(a) For each tipping equilibrium there exists a corresponding parameter restriction as derived in Proposition 1.1. These conditions directly imply that an increase in a firm's installed base increases the region of *tipping to* this firm (for all tipping equilibria that involve *tipping to* this firm). For illustration, consider the case of the compatibility regime of Full Autarky and the parameter region for which *tipping to* firm 1 exists as

an equilibrium:

$$\beta_1 > \frac{2(1-\nu)(1+x\nu)-1}{\nu+2\nu x(1-\nu)}.$$

Ceteris paribus, as β_1 increases, the inequality is more likely to be satisfied implying that the parameter region of where this equilibrium exists expands. Similar conditions can be derived for all compatibility regimes, all types of tipping equilibria and all firms.
(b) Similarly to the argument in (a), the reverse argument holds for tipping equilibria that imply *tipping away* from a firm. A larger installed base implies that the parameter region for these equilibria reduces. For illustration, consider firm 1. An increase in firm 1's installed base implies that equilibria involving *tipping to* firms 2 and 3 or a subgroup of these (i.e. *tipping away* from a subgroup involving firm 1) now only exist for a smaller parameter set. Under Full Autarky, for example, *tipping to* firms 2 and 3 can occur if $\beta_1 < \frac{3\nu-1}{4\nu-2\nu^2}$. As β_1 increases, this inequality is satisfied for a smaller parameter set.
(c) Increasing asymmetry x implies a larger installed base share of firm 2 and a smaller one for firm 3 for any given β_1. From (a) and (b) it thus follows that *tipping to* firm 2 or any coalition including firm 2 is more likely and *tipping away* from 2 or any coalition containing firm 2 less likely. If a coalition includes both, firms 2 and 3, there is no effect through a change in x.
(d) This follows directly from the proof for Proposition 1.1. Tipping occurs only with sufficient strength of network effects. It is easily shown that when taking $\nu \to 0$ no tipping can occur. With $\nu \to 1$ all tipping equilibria mentioned above exist.

Proof of Proposition 1.2:
The equilibrium quantities in an interior equilibrium under the different compatibility regimes are given by:

Case	Firm 1	Firm 2	Firm 3
FC:	$\frac{1}{4}\frac{(\nu+1)}{(1-\nu)}$	$\frac{1}{4}\frac{(\nu+1)}{(1-\nu)}$	$\frac{1}{4}\frac{(\nu+1)}{(1-\nu)}$
FA:	$\frac{1-3\nu+\nu\beta_1(4-2\nu)}{2(\nu-2)(2\nu-1)}$	$\frac{1-3\nu+\nu x(1-\beta_1)(4-2\nu)}{2(\nu-2)(2\nu-1)}$	$\frac{1-3\nu+\nu(1-x)(1-\beta_1)(4-2\nu)}{2(\nu-2)(2\nu-1)}$
AF1:	$\frac{1+\nu\beta_1(5-3\nu)-5\nu}{6\nu^2-12\nu+4}$	$\frac{1-\nu\beta_1(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1-\nu\beta_1(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$
TF2:	$\frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1+x\nu(5-3\nu)(1-\beta_1)-5\nu}{6\nu^2-12\nu+4}$	$\frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$
TF3:	$\frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$	$\frac{1+(5-3\nu)\nu(1-x)(1-\beta_1)-5\nu}{6\nu^2-12\nu+4}$

For the equilibrium to exist, we require non-negative outputs (and thus profits, see Remark 1) for all firms in any interior equilibrium. We therefore get the following

conditions under the compatibility regimes:
Full Compatibility: the interior equilibrium exists for any $\nu < 1$. There are no tipping equilibria under Full Compatibility (compare Proposition 1.1) which makes the interior equilibrium also the unique equilibrium.
Full Autarky: the interior equilibrium exists as long as the smallest competitor makes non-negative profits. Normally this will be firm 3, but it may, for very small β_1 also be firm 1. Thus, non-negativity of profits requires:
$\frac{1-3\nu+\nu(1-x)(1-\beta_1)(4-2\nu)}{2(\nu-2)(2\nu-1)} \geq 0$ and $\frac{1-3\nu+\nu\beta_1(4-2\nu)}{2(\nu-2)(2\nu-1)} \geq 0$ which translate into $\beta_1 < \frac{1-3\nu+\nu(2\nu-4)(x-1)}{\nu(2\nu-4)(x-1)}$ and $\beta_1 > \frac{3\nu-1}{4\nu-2\nu^2}$. Note that these are equivalent to the conditions on tipping derived in Proposition 1.1. Hence, if there exists an interior equilibrium, it is indeed unique.
Autarky by Firm 1: Non-negativity constraints are given by:
$\frac{1+\nu\beta_1(5-3\nu)-5\nu}{6\nu^2-12\nu+4} > 0 \wedge \frac{1-\nu\beta_1(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4} > 0$ which again translate into the conditions $\beta_1 > \frac{5\nu-1}{5\nu-3\nu^2} \wedge \beta_1 < \frac{1-2\nu^2}{3\nu-2\nu^2}$ derived for tipping in Proposition 1.1. Thus, again uniqueness upholds.
Targeting of Firm 2: Similarly, we find the conditions $\beta_1 < \frac{3x\nu+2\nu^2-2x\nu^2-1}{3x\nu-2x\nu^2} \wedge \beta_1 > \frac{5\nu-5x\nu+3x\nu^2-1}{5x\nu-3x\nu^2}$. Thus, again uniqueness obtains for the region where the interior equilibrium exists.
Targeting of Firm 3: Similarly, we find the conditions $\beta_1 > \frac{3\nu-3x\nu+2x\nu^2-1}{3\nu-3x\nu-2\nu^2+2x\nu^2} \wedge \beta_1 < -\frac{5x\nu+3\nu^2-3x\nu^2-1}{5\nu-5x\nu-3\nu^2+3x\nu^2}$ which again guarantee both existence and uniqueness of the interior equilibrium.
To derive the condition that guarantees existence across all compatibility regimes, we compare the above restrictions. In fact, the condition of profitability on firm 3 under Targeting of Firm 3 is the one that determines existence across regimes: $\beta_1 > -\frac{5x\nu+3\nu^2-3x\nu^2-1}{5\nu-5x\nu-3\nu^2+3x\nu^2}$; thus, existence of the unique interior equilibrium is fulfilled under all compatibility regimes if:
$\lim_{x\to 1}(\nu|_{\beta_1=0}) = \frac{\sqrt{25x^2-12x+12}-5x}{6(1-x)} = \frac{1}{5}$ and $\nu|_{\beta_1=1} = \frac{1}{5}$.

Proof of Remark 1:
Here we prove the equivalence of quantities and profits when deciding on the optimal compatibility regime. We do so in the most general case, namely for the case with horizontal product differentiation (as considered in Section 1.3.3). The proof follows the derivation of Malueg and Schwartz (2006) and can be replicated for other nested Cournot models, for example the case without network effects ($\nu = 0$) and the case of homogeneous products ($\delta = \gamma$).
Without loss of generality the proof below is for firm 1. The same statements follow by similar argument for firms 2 and 3.

Let $A(\theta_{12},\theta_{13}) = \alpha + \nu(\beta_1 + \theta_{12}\beta_2 + \theta_{13}\beta_3) - (\gamma - \theta_{12}\nu)q_2 - (\gamma - \theta_{13}\nu)q_3$ and write firm 1's inverse demand $p_1 = \alpha + \nu L_1 - \delta q_1 - \gamma q_2 - \gamma q_3$ as $p_1 = A(\theta_{12},\theta_{13}) - (\delta - \nu)q_1$. Hence, profits are:

$\pi_1 = (p_1)q_1 = (A(\theta_{12},\theta_{13}) - (\delta - \nu)q_1)q_1$. In any equilibrium where firm 1's output is positive, firm 1's output is given by the first order condition:

$0 = A(\theta_{12},\theta_{13}) - 2(\delta - \nu)q_1$, implying $(\delta - \nu)q_1 = A(\theta_{12},\theta_{13}) - (\delta - \nu)q_1 = p_1$. Substituting $p_1 = (\delta - \nu)q_1$ gives:

$$\pi_1^* = (\delta - \nu)(q_1^*)^2.$$

As explained, we can replicate the above argument for any other firm, such that we find:

$$\pi_i^* = (\delta - \nu)(q_i^*)^2.$$

Clearly, $\frac{\partial \pi_1^*}{\partial q_1^*} > 0$ as $\delta > \nu$ confirming the intuition that larger equilibrium quantities imply larger equilibrium profit.

Proof of Proposition 1.3:

We proceed as follows: First, we determine the preferred order of compatibility regimes for each firm in turn (by comparing their profits under each regime). Second, we check whether the preferred order can be matched to the mutual agreement criterion needed for a compatibility agreement.

1) Firm 1's optimal compatibility regime:

(a) Full Compatibility is preferred to Full Autarky if:
$\frac{1}{4}\frac{(\nu+1)}{(1-\nu)} > \frac{1-3\nu+\nu\beta_1(4-2\nu)}{2(\nu-2)(2\nu-1)}$, i.e. if $\beta_1 < \frac{-9\nu+2\nu^2+5}{-12\nu+4\nu^2+8}$

(b) Full Compatibility is preferred to Autarky by Firm 1 if:
$\frac{1}{4}\frac{(\nu+1)}{(1-\nu)} > \frac{1+\nu\beta_1(5-3\nu)-5\nu}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 < \frac{-13\nu+3\nu^2+8}{-16\nu+6\nu^2+10}$

(c) Full Compatibility is preferred to Targeting of Firm 2 if:
$\frac{1}{4}\frac{(\nu+1)}{(1-\nu)} > \frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 < \frac{6x+\nu-10x\nu-\nu^2+4x\nu^2-2}{6x-10x\nu+4x\nu^2}$

(d) Full Compatibility is preferred to Targeting of Firm 3 if:
$\frac{1}{4}\frac{(\nu+1)}{(1-\nu)} > \frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 < \frac{6x+9\nu-10x\nu-3\nu^2+4x\nu^2-4}{6x+10\nu-10x\nu-4\nu^2+4x\nu^2-6}$

(e) Full Autarky is preferred over Autarky by Firm 1 if:
$\frac{1-3\nu+\nu\beta_1(4-2\nu)}{2(\nu-2)(2\nu-1)} > \frac{1+\nu\beta_1(5-3\nu)-5\nu}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 > \frac{-6\nu+\nu^2+3}{-3\nu+\nu^2+2}$ which holds for all relevant ν.

(f) Full Autarky is preferred over Targeting of Firm 2 if:
$\frac{1-3\nu+\nu\beta_1(4-2\nu)}{2(\nu-2)(2\nu-1)} > \frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 > \frac{6x+23\nu-19x\nu-19\nu^2+4\nu^3+16x\nu^2-4x\nu^3-7}{6x+28\nu-19x\nu-24\nu^2+6\nu^3+16x\nu^2-4x\nu^3-8}$

(g) Full Autarky is preferred over Targeting of Firm 3 if:
$\frac{1-3\nu+\nu\beta_1(4-2\nu)}{2(\nu-2)(2\nu-1)} > \frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 > -\frac{6x-4\nu-19x\nu+3\nu^2+16x\nu^2-4x\nu^3+1}{-6x+9\nu+19x\nu-8\nu^2+2\nu^3-16x\nu^2+4x\nu^3-2}$

(h) Autarky by Firm 1 is preferred over Targeting of Firm 2 if:
$\frac{1+\nu\beta_1(5-3\nu)-5\nu}{6\nu^2-12\nu+4} > \frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 > \frac{3x+2\nu-2x\nu-5}{3x+3\nu-2x\nu-5}$, never for $\beta_1 \in (0,1)$.
(i) Autarky by Firm 1 is preferred over Targeting of Firm 3 if:
$\frac{1+\nu\beta_1(5-3\nu)-5\nu}{6\nu^2-12\nu+4} > \frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$, i.e. if $\beta_1 > -\frac{3x-2x\nu+2}{-3x+\nu+2x\nu-2}$, never for $\beta_1 \in (0,1)$.
(j) Targeting of Firm 2 is preferred over Targeting of Firm 3 if:
$\frac{1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2}{6\nu^2-12\nu+4} > \frac{1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2}{6\nu^2-12\nu+4}$, i.e. if $x < \frac{1}{2}$; $\Rightarrow$ never by assumption.
We can then partition the relevant (ν, β_1)-area into regions of preferred compatibility regimes for firm 1.
Area 1: Full Autarky is preferred by firm 1 for high β_1,
i.e. if $\beta_1 > -\frac{6x-4\nu-19x\nu+3\nu^2+16x\nu^2-4x\nu^3+1}{-6x+9\nu+19x\nu-8\nu^2+2\nu^3-16x\nu^2+4x\nu^3-2}$.
Area 2: Targeting of Firm 3 is preferred by firm 1 for low and intermediate β_1,
i.e. if $0 < \beta_1 < -\frac{6x-4\nu-19x\nu+3\nu^2+16x\nu^2-4x\nu^3+1}{-6x+9\nu+19x\nu-8\nu^2+2\nu^3-16x\nu^2+4x\nu^3-2}$.

Firm 2's optimal compatibility regime:

Proceeding similarly for firm 2, we find that – for the range of interest, i.e. for $\beta_1 > \beta_2 > \beta_3$ – firm 2 always prefers Targeting of Firm 3 over Full Compatibility. Only when firm 1's market share becomes very small, i.e. smaller than that of firm 3, firm 2 will now prefer Autarky of Firm 1.[44]

Firm 3's optimal compatibility regime:

Firm 3 prefers Targeting of Firm 2 to any other compatibility regime for any $\beta_1 > \beta_2 > \beta_3$. If firm 1 becomes smaller than firm 2 (for low β_1) it will prefer Autarky of Firm 1.

2) Equilibrium compatibility regime:

Firms have to mutually agree on the compatibility. As firm 1 is the most desired partner in any alliance because of its large installed base ($\beta_1 > \beta_2 > \beta_3$), it will be able to strongly influence the equilibrium compatibility regime. The most preferred regime of Targeting of Firm 3 can be implemented through firm 1's and 2's alliance (it is the most preferred regime for both of them). However, the wish for Full Autarky (for large β_1) will be prevented as in the range where this is optimal, firms 2 and 3 would rather be compatible with each other than stay autarkic. Taking this into consideration, firm 1 will also opt for Targeting of Firm 3 in this range as this is firm 1's second preference after Full Autarky in that parameter range. Therefore, firm 3 will always be excluded from the compatibility in equilibrium if $\beta_1 > \beta_2 > \beta_3$.

[44] This would violate the original assumption of the size of installed bases. Nevertheless, for completeness, firm 1's share is smaller if $\beta_1 < (1-x)(1-\beta_1)$, i.e. if $\beta_1 < \frac{1-x}{2-x}$.

Proof of Proposition 1.4:

In this proposition we analyze firm 1's compatibility policy under the following presumptions. Firm 1 faces n *a priori* symmetric competitors. We explore firm 1's compatibility policy under the assumption that if a competitor i is not in the alliance of firm 1, it will group its own alliance of competitors. Note that this will bias our result towards firm 1 desiring more compatibility with the competitors as their alliance poses a stronger competitive threat to it than if competitors were not to exhaustively form a compatibility agreement. There are therefore two groups with compatible members: the alliance of firm 1 and the alliance of those firms that firm 1 refuses to be compatible with. We use the continuous choice variable y to characterize firm 1's desired degree of compatibility:

$$y = \begin{cases} 0 & \text{under Autarky by Firm 1} \\ y \in (0,1) & \text{if a fraction of } y \text{ competitors is compatible with firm 1} \\ 1 & \text{under Full Compatibility} \end{cases}$$

The proof of this proposition proceeds as follows:
1) We derive the equilibrium quantities of firm 1 and its n *a priori* symmetric competitors by profit maximization conditional on y.
2) We examine the equilibrium quantity of firm 1 for different degrees of compatibility. In particular, we show that
(a) the quantities at the extreme values $y \in \{0, 1\}$ correspond to the values derived in Malueg and Schwartz (2006) for Autarky by Firm 1 and Full Compatibility.
(b) quantities (and thus profits) generally rise as we marginally increase the degree of compatibility at the point of Autarky by Firm 1 (i.e. $\lim_{y\to 0}(\frac{\partial q_1}{\partial y}) = \frac{\partial q_1}{\partial y}|_{y=0} > 0$).
(c) quantities fall in the degree of compatibility (y) in the point of full compatibility, i.e. at $y = 1$, so that decreasing the degree of compatibility is profitable (i.e. $\lim_{y\to 1}(\frac{\partial q_1}{\partial y}) = \frac{\partial q_1}{\partial y}|_{y=1} < 0$).
We can therefore argue that there is at least one level of compatibility that is strictly between 0 and 1 which delivers higher profits for firm 1 than one of the two extremes. Therefore, mixed compatibility regimes, in the sense that a fraction will be compatible with the dominant firm and a fraction will not be, are important!

1) Derivation of equilibrium quantities:

Best responses are given by:
$q_1 = \frac{(1+\nu(\beta_1+y(\beta-\beta_1)))-(1-y)n(q_j)}{(1-\nu)(2+yn)}$ and $q_j = \frac{(1+\nu(1-y)(\beta-\beta_1))-(xn+1)q_1}{(1-\nu)(1+(1-y)n)}$ for each rival j not

compatible with firm 1.

Thus: $q_1 = \frac{(1+\nu(\beta_1+y(\beta-\beta_1)))(1-\nu)+(1-y)n((1+\nu(\beta_1+y(\beta-\beta_1)))(1-\nu)-(1+\nu((1-y)(\beta-\beta_1))))}{(1-\nu)^2(2+yn)+(1-y)n((1-\nu)^2(2+yn)-(1+yn))}$

2) (a) Equivalence to values of Malueg and Schwartz (2006):

$\lim_{y\to 0}(q_1) = \frac{1-\nu(n+1)+(n+(n+1)(1-\nu))\nu\beta_1-\nu n\beta}{2(n+1)(1-\nu)^2-n}$

$\lim_{y\to 1}(q_1) = \frac{1+\nu\beta}{(n+2)(1-\nu)}$

Thus, expressions for $y = 0$ and $y = 1$ correspond to the expressions derived in Malueg and Schwartz (2006).

(b) Marginal behavior at $y = 0$:

$\lim_{y\to 1}(\frac{\partial q_1}{\partial y}) = \nu(X + Y + Z)$

where

$X = \frac{\beta\left(7n-6\nu+9n^2\nu^2-2n^2\nu^3+n^3\nu^2-19n\nu+6\nu^2-2\nu^3+16n\nu^2-11n^2\nu-4n\nu^3-2n^3\nu+3n^2+2\right)}{(n-4\nu-4n\nu+2\nu^2+2n\nu^2+2)^2}$

$Y = \frac{\beta_1\left(-9n+6\nu-15n^2\nu^2+4n^2\nu^3-4n^3\nu^2+n^3\nu^3+23n\nu-6\nu^2+2\nu^3-19n\nu^2+16n^2\nu+5n\nu^3+4n^3\nu-4n^2-2\right)}{(n-4\nu-4n\nu+2\nu^2+2n\nu^2+2)^2}$

$Z = \frac{n\left(3n-\nu-5n\nu+(n^2+1)\nu^2-2n\nu(n-\nu)\right)}{(n-4\nu-4n\nu+2\nu^2+2n\nu^2+2)^2}$

and for small ν and small n these terms as well as their common denominator are always positive. Therefore, for small ν and n, firm 1 would seek some compatibility (i.e. $y > 0$) with competitors.

(c) Marginal behavior at $y = 1$:

$\lim_{y\to 1}(\frac{\partial q_1}{\partial y}) = \frac{\nu\left(-\beta_1(1-\nu)^2(n+2)-\beta(n(1+n)-2+2\nu(2-\nu))-n\nu-n^2\right)}{(1-\nu)^3(n+2)^2} < 0$

Thus, reducing the degree of compatibility to values $y < 1$ will always be profitable for firm 1. Full compatibility is never optimal for firm 1. Thus, targeting of some form will result in equilibrium which corroborates the importance of mixed compatibility regimes.

Proof of Corollary 1.2:

Corollary 1.1 shows that stronger network effects are needed for tipping. Proposition 1.1 shows that this may lead to multiplicity of equilibria. Firm 1's compatibility choice depends on the inequality that states relative preference of the regimes Full Autarky and Targeting of Firm 3: $\beta_1 > -\frac{6x-4\nu-19x\nu+3\nu^2+16x\nu^2-4x\nu^3+1}{-6x+9\nu+19x\nu-8\nu^2+2\nu^3-16x\nu^2+4x\nu^3-2}$. This boundary is increasing in network effects for the relevant range. Thus, as network effects increase firm 1 relatively seeks Targeting of Firm 3 more as compared to Full Autarky.

Proof of Corollary 1.3:

From Proposition 1.3 we deduce that as the installed base of firm 1 increases, it desires less compatibility. The condition for Targeting of Firm 3 is less likely to hold and firm 1's desire for Full Autarky increases. Note that this result holds more generally. The smaller the installed base of a firm the more compatibility it seeks and vice versa. Although the smallest firm, firm 3, prefers mixed compatibility by means of Targeting of Firm 2 over Full Compatibility, it prefers any kind of compatibility over either Full Autarky or Targeting of Firm 3 (i.e. staying autarkic). The formal proof proceeds by comparing expressions as given in Proposition 1.3.

Proof of Proposition 1.5:

As we have shown in Proposition 1.3, the relevant threshold line is given by the following expression:

Area 1: Full Autarky is preferred by F1 for high β_1,
i.e. if $\beta_1 > -\frac{6x-4\nu-19x\nu+3\nu^2+16x\nu^2-4x\nu^3+1}{-6x+9\nu+19x\nu-8\nu^2+2\nu^3-16x\nu^2+4x\nu^3-2}$.

Area 2: Targeting of firm 3 is preferred by F1 for low and intermediate β_1,
i.e. if $0 < \beta_1 < -\frac{6x-4\nu-19x\nu+3\nu^2+16x\nu^2-4x\nu^3+1}{-6x+9\nu+19x\nu-8\nu^2+2\nu^3-16x\nu^2+4x\nu^3-2}$.

We can now show that as asymmetry x increases, this threshold line shifts up (for relevant values of ν):

$\frac{\partial}{\partial x}(-\frac{6x-4\nu-19x\nu+3\nu^2+16x\nu^2-4x\nu^3+1}{-6x+9\nu+19x\nu-8\nu^2+2\nu^3-16x\nu^2+4x\nu^3-2}) = \frac{8\nu^5-36\nu^4+66\nu^3-59\nu^2+23\nu-3}{(\nu-2)(3x-4\nu-8x\nu+2\nu^2+4x\nu^2+1)^2} > 0$

Both, numerator and denominator are negative for ν in the relevant range. Thus, asymmetry reinforces the importance of mixed compatibility regimes for firm 1's preferred regime. However, this has no influence on the equilibrium compatibility regime.

Proof of Proposition 1.6:

1) Following the derivation of the general demand system in Section 1.6.1 of the Appendix, we can derive the equilibrium quantities in the interior equilibrium straightaway.

Case	Firm 1
FC:	$\frac{(\alpha+\beta\nu)(3\delta-2\gamma-\nu)}{6(\delta-\nu)^2-2(\gamma-\nu)^2}$
FA:	$\frac{\alpha(3\delta-2\gamma-2\nu)+\nu\beta_1(3\delta-2\nu)-\nu\gamma(\beta_2+\beta_3)}{2(3\delta^2-\gamma^2)-2\nu(5\delta-2\nu)}$
AF1:	$\frac{\alpha(3\delta-3\nu-2\gamma)+3\nu(\delta-\nu)\beta_1-2\gamma\nu(\beta_2+\beta_3)}{6(\delta-\nu)^2-2\gamma^2}$
TF2:	$\frac{\alpha(2\gamma(-\delta+2\nu)-7\delta\nu+3\delta^2+2\nu^2)+\nu(\beta_1+\beta_3)(\gamma(-\delta+2\nu)+2\nu^2-6\delta\nu+3\delta^2)+\nu\beta_2(\gamma(-\delta+2\nu)-\delta\nu)}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$
TF3:	$\frac{\alpha(2\gamma(-\delta+2\nu)-7\delta\nu+3\delta^2+2\nu^2)+\nu(\beta_1+\beta_2)(\gamma(-\delta+2\nu)+2\nu^2-6\delta\nu+3\delta^2)+\nu\beta_3(\gamma(-\delta+2\nu)-\delta\nu)}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$

Case	Firm 2
FC:	$\frac{(\alpha+\beta\nu)(2\delta-\gamma-\nu)}{6(\delta-\nu)^2-2(\gamma-\nu)^2}$
FA:	$\frac{\alpha((\gamma-2(\delta-\nu))(\delta-2\nu))+\nu\gamma\beta_1(\delta-2\nu)+\nu\beta_2((\gamma+2(\delta-\nu))(\gamma-2(\delta-\nu)))+\nu\beta_3(2\delta(\delta-\nu)-\gamma^2)}{2(\delta-2\nu)\left(\gamma^2-3\delta^2+5\delta\nu-2\nu^2\right)}$
AF1:	$\frac{\alpha(2\delta-2\nu-\gamma)-\gamma\nu\beta_1+2\nu(\delta-\nu)(\beta_2+\beta_3)}{6(\delta-\nu)^2-2\gamma^2}$
TF2:	$\frac{\alpha(\gamma(3\nu-\delta)-7\delta\nu+2\delta^2+3\nu^2)+\nu(\beta_1+\beta_3)(\gamma(\nu-\delta+\gamma)+\delta(\nu-2\delta))+\nu\beta_2(\gamma(2\nu-\gamma)+3\nu^2-8\delta\nu+4\delta^2)}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$
TF3:	$\frac{\alpha(\delta-\nu)(2(\delta-\nu)-\gamma)+\nu(\beta_1+\beta_2)(\gamma(-\delta+2\nu-\gamma)-6\delta\nu+4\delta^2+2\nu^2)+\nu\beta_3(\gamma(-\nu+\gamma)+2\delta(\nu-\delta))}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$

Case	Firm 3
FC:	$\frac{(\alpha+\beta\nu)(2\delta-\gamma-\nu)}{6(\delta-\nu)^2-2(\gamma-\nu)^2}$
FA:	$\frac{\alpha(\gamma(\delta-2\nu)+6\delta\nu-2\delta^2-4\nu^2)+\nu\gamma\beta_1(\delta-2\nu)+\nu\beta_2(-\gamma^2-2\delta\nu+2\delta^2)+\nu\beta_3(\gamma^2+8\delta\nu-4\delta^2-4\nu^2)}{2(\delta-2\nu)\left(\gamma^2-3\delta^2+5\delta\nu-2\nu^2\right)}$
AF1:	$\frac{\alpha(2\delta-2\nu-\gamma)-\gamma\nu\beta_1+2\nu(\delta-\nu)(\beta_2+\beta_3)}{6(\delta-\nu)^2-2\gamma^2}$
TF2:	$\frac{\alpha(\delta-\nu)(2(\delta-\nu)-\gamma)+\nu(\beta_1+\beta_3)(\gamma(-\delta+2\nu-\gamma)+2(\nu^2-3\delta\nu+2\delta^2))+\nu\beta_2(\gamma(-\nu+\gamma)+2\delta(\nu-\delta))}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$
TF3:	$\frac{\alpha(\gamma(-\delta+3\nu)-7\delta\nu+2\delta^2+3\nu^2)+\nu(\beta_1+\beta_2)(\gamma(-\delta+\nu+\gamma)+\delta(\nu-2\delta))+\nu\beta_3(\gamma(2\nu-\gamma)+3\nu^2-8\delta\nu+4\delta^2)}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$

We now examine the comparative statics as we move away from a scenario of homogeneous products ($\gamma = \delta$) to one where $\gamma < \delta$. From Proposition 1.3 we know that the relevant threshold line for firm 1 is given by the change from Targeting of Firm 3 to Full Autarky. In addition, we will now also consider the threshold line between Targeting of Firm 3 and Full Compatibility (which becomes attractive for firm 1 for low values of β_1). As the expressions for differentiated products nest the case of homogeneity ($\gamma = \delta$), it suffices to look at the comparative statics of the mentioned threshold lines for the case of differentiated products. We proceed as follows: First, we compare firm 1's profits under the two compatibility regimes and derive the threshold condition as a restriction on β_1. We then check the comparative statics in γ of this condition.
$q_1^{FC} > q_1^{TF3}$ if $\frac{(\alpha+\beta\nu)(3\delta-2\gamma-\nu)}{6(\delta-\nu)^2-2(\gamma-\nu)^2} >$
$\frac{\alpha(2\gamma(-\delta+2\nu)-7\delta\nu+3\delta^2+2\nu^2)+\nu(\beta_1+x(1-\beta_1))(\gamma(-\delta+2\nu)+2\nu^2-6\delta\nu+3\delta^2)+\nu(1-x)(1-\beta_1)(\gamma(-\delta+2\nu)-\delta\nu)}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$ which can be solved for an upper bound on β_1. Taking the derivative of this bound with respect to γ yields:
$\frac{\gamma^4(-2\nu+1)+4\nu\gamma^3(2\nu-1)+\gamma^2(12\nu^3-29\nu^2+12\nu-1)+\gamma(2\nu^4+6\nu^3-48\nu^2+62\nu-18)-2\nu^5+20\nu^4-78\nu^3+137\nu^2-102\nu+24}{(x-1)(2\nu^2-5\nu+3)(-\gamma^2+2\gamma\nu+2\nu^2-6\nu+3)^2}$
Thus, $\lim_{\gamma\to 1}(\frac{\partial(RHS)}{\partial\gamma}) = -\frac{\left(2\nu^5-22\nu^4+60\nu^3-68\nu^2+34\nu-6\right)}{(x-1)(2\nu^2-4\nu+2)^2(2\nu^2-5\nu+3)}$ which implies:
$\lim_{\nu\to 0}(\lim_{\gamma\to 1}(\frac{\partial(RHS)}{\partial\gamma})) = \frac{1}{2(x-1)} < 0.$
Although we only prove the case where values of γ are close to $\delta = 1$ and ν is close enough to zero, the result holds more generally. In particular, taking $\nu \to 0$ is not necessary. We only require that $v < 4 - \sqrt{13} \approx 0.39445$. This is always the case for the interior equilibria that we are focusing on. We have thus shown that as γ falls (i.e. product differentiation *increases*), the RHS increases. This implies that the inequality on β_1 is more likely to be satisfied, i.e. Full Compatibility spans a larger parameter region relative to Targeting of Firm 3. Thus, more product differentiation is conducive to more compatibility.
Similarly, we can show that the area of Targeting of Firm 3 expands up into the region

where firm 1 finds Full Autarky to be optimal, i.e. becomes more attractive relative to Full Autarky. We proceed similarly:

$q_1^{FA} > q_1^{TF3}$ if $\frac{\alpha(3\delta-2\gamma-2\nu)+\nu\beta_1(3\delta-2\nu)-\nu\gamma(\beta_2+\beta_3)}{2(3\delta^2-\gamma^2)-2\nu(5\delta-2\nu)} >$
$\frac{\alpha(2\gamma(-\delta+2\nu)-7\delta\nu+3\delta^2+2\nu^2)+\nu(\beta_1+x(1-\beta_1))(\gamma(-\delta+2\nu)+2\nu^2-6\delta\nu+3\delta^2)+\nu(1-x)(1-\beta_1)(\gamma(-\delta+2\nu)-\delta\nu)}{2\gamma(\nu-\gamma)(\delta-2\nu)+2(\delta-\nu)\left(3\delta^2-8\delta\nu+3\nu^2\right)}$

Thus, if $\beta_1 >$
$-\frac{-9x+11\nu+30x\nu-12\nu^2+4\nu^3-37x\nu^2+20x\nu^3-4x\nu^4-3+(-\gamma^2+2\nu^2+3x+2x\nu^2-5x\nu)+\gamma(3-6\nu+3\nu^2-\nu^3)}{9x-9\nu-30x\nu+18\nu^2-11\nu^3+2\nu^4+37x\nu^2-20x\nu^3+4x\nu^4+\gamma^3(2\nu-1)+\gamma^2(5x\nu-4\nu^2-3x+4\nu-2x\nu^2)+\gamma(3-8\nu+3\nu^2+\nu^3)}$

The comparative statics of the RHS around $\gamma = 1$ are:
$\lim_{\gamma\to 1}(\frac{\partial(RHS)}{\partial\gamma}) = -\frac{1}{\nu-1}\frac{-12x+15\nu+59x\nu-47\nu^2+76\nu^3-58\nu^4+19\nu^5-2\nu^6-112x\nu^2+124x\nu^3-72x\nu^4+16x\nu^5-2}{(\nu-2)^2(3x-4\nu-8x\nu+2\nu^2+4x\nu^2+1)^2}$
which implies:
$\lim_{\nu\to 0}(\lim_{\gamma\to 1}(\frac{\partial(RHS)}{\partial\gamma})) = -\frac{1}{4(3x+1)^2}(12x+2) < 0.$

As γ falls with greater horizontal product differentiation, the threshold therefore increases. This holds not only for $\nu \to 0$ but more generally in the interior equilibria that we compare as long as $v < \frac{1}{4x+2}\left(4x - \sqrt{2}\sqrt{(2x+1)(x+1)} + 2\right)$. Again this holds for the interior equilibria and the parameter space that we consider here.

2) A second important implication of increasing horizontal product differentiation is that it may reduce the multiplicity of tipping equilibria. Firm 1 which is the only firm offering product variety a may even be fully protected against *tipping away* from it.

Example 4 *This can be seen from the condition that would need to be satisfied under tipping, e.g. tipping to firms 2 and 3 under Full Autarky:*
$p_1 = \alpha + \nu\beta_1 - \gamma\frac{\alpha(\delta-2\nu)-\delta\nu\beta_3+2\nu(\delta-\nu)\beta_2}{3\delta^2-8\delta\nu+4\nu^2} - \gamma\frac{\alpha(\delta-2\nu)-\delta\nu\beta_2+2\nu(\delta-\nu)\beta_3}{3\delta^2-8\delta\nu+4\nu^2} < 0$
However, with $\gamma \to 0$, we have $p_1 = \alpha + \nu\beta_1 < 0$ which never holds.
Thus, tipping away from firm 1 cannot occur. Therefore, for $\gamma \to 0$ the intuitive result obtains. At least one firm offering each variety must be present in the market.

Hence, only the following tipping equilibria are possible:
Full Compatibility: no tipping can occur
Full Autarky: Tipping to firms 1 and 2; tipping to firms 2 and 3
Coalition of the Small: no tipping can occur
Targeting of Firm 2: tipping to firms 1 and 3 only
Targeting of Firm 3: tipping to firms 1 and 2 only
This result may also hold for intermediate levels of horizontal product differentiation. Firms may take this into account when network effects are so strong that tipping may occur. Hence, compatibility for firm 1 becomes particularly desirable – not only because strong horizontal product differentiation weakens competition and compatibility increases profitability through the realization of network effects but also because the set of tipping equilibria is influenced.

Proof of Proposition 1.7:

Case	Joint Profits
FC:	$\frac{3}{16}\frac{(\nu+1)^2}{(1-\nu)}$
FA:	$\frac{(1-\nu)\{[1-3\nu+\nu\beta_1(4-2\nu)]^2+[1-3\nu+\nu x(1-\beta_1)(4-2\nu)]^2+[1-3\nu+\nu(1-x)(1-\beta_1)(4-2\nu)]^2\}}{[2(\nu-2)(2\nu-1)]^2}$
CS/AF1:	$\frac{(1-\nu)\{[1+\nu\beta_1(5-3\nu)-5\nu]^2+[1-\nu\beta_1(3-2\nu)-2\nu^2]^2+[1-\nu\beta_1(3-2\nu)-2\nu^2]^2\}}{[6\nu^2-12\nu+4]^2}$
TF2:	$\frac{(1-\nu)\{[1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2]^2+[1+x\nu(5-3\nu)(1-\beta_1)-5\nu]^2+[1-\nu x(1-\beta_1)(3-2\nu)-2\nu^2]^2\}}{[6\nu^2-12\nu+4]^2}$
TF3:	$\frac{(1-\nu)\{[1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2]^2+[1-(3-2\nu)(1-\beta_1)\nu(1-x)-2\nu^2]^2+[1+(5-3\nu)\nu(1-x)(1-\beta_1)-5\nu]^2\}}{[6\nu^2-12\nu+4]^2}$

Comparing the profit expressions, we can define areas in the parameter space where the joint profitability of a particular compatibility regime is highest. In fact, Full Compatibility has highest joint profits for weak network effects. However, when network effects are stronger and the installed base share β_1 of firm 1 is very small $\pi^{\mathrm{AF1}}_{\mathrm{joint}} > \pi^{\mathrm{FC}}_{\mathrm{joint}}$. Similarly, for very large values of β_1 $\pi^{\mathrm{TF3}}_{\mathrm{joint}} > \pi^{\mathrm{FC}}_{\mathrm{joint}}$ if network effects are strong enough.

For low values of network effects ($\nu < \frac{1}{5}$), we can partition the parameter space into the following areas that each implicitly define values of β_1 depicted in the figure 1.7 in Section 1.4 of the chapter[45]:

Area 1: Targeting of Firm 3 is most profitable: $\pi^{\mathrm{TF3}}_{\mathrm{joint}} > \pi^{\mathrm{FC}}_{\mathrm{joint}}$

Area 2: Full Compatibility is most profitable: $\pi^{\mathrm{FC}}_{\mathrm{joint}} > \pi^{\mathrm{TF3}}_{\mathrm{joint}} \wedge \pi^{\mathrm{FC}}_{\mathrm{joint}} > \pi^{\mathrm{AF1}}_{\mathrm{joint}}$

Area 3: Autarky of Firm 1 is most profitable: $\pi^{\mathrm{AF1}}_{\mathrm{joint}} > \pi^{\mathrm{FC}}_{\mathrm{joint}}$

Note that when Targeting of Firm 3 is not allowed (e.g. for competitive reasons) there is a corresponding area where Targeting of Firm 2 gives highest joint profits if $\pi^{\mathrm{TF2}}_{\mathrm{joint}} > \pi^{\mathrm{FC}}_{\mathrm{joint}}$.

[45] The explicit expressions are lengthy and thus omitted here for clarity of exposition. Unfortunately, because of Jensen's inequality and squaring using binomials, Remark 1 does not hold when comparing joint profits.

Chapter 2

Cooperative versus Competitive Standard Setting*

2.1 Introduction

In many industries compatibility standards are important for consumers to reap the benefits of direct or indirect network externalities. In some cases firms refuse to make their products compatible because at least one of them hopes to eventually dominate the market and establish a *de facto* standard. In other cases firms cooperate and agree to a joint standard. This may be a very simple agreement, just making sure that both firms adhere to the same technical norms. Or it may be more complex, involving an exchange of intellectual property rights, royalty payments, and potentially large investments in new technologies that are going to be jointly used. What are the incentives to form such agreements and what are the implications for competition, investments and market structure?

A prominent recent case is the agreement of Microsoft and Novell to make the Windows and Linux operating systems interoperable. This agreement came as a surprise to many industry observers. For years Microsoft and Novell had sued each other for the violation of intellectual property rights rendering any attempt to make the two operating systems compatible impossible. According to the new agreement Microsoft and Novell will work together to provide "virtualization" and "document format compatibility" allowing customers to run Linux applications on Windows and Windows applications on Linux. Furthermore, they provide patent coverage for each others'

*This chapter is joint work with Klaus M. Schmidt from the University of Munich.

customers so that patent infringements are no longer an issue.

Compatibility standards benefit consumers – either directly because there are more people they can interact with or indirectly because there is a larger market for complementary products and services. However, a compatibility standard also affects how firms compete and it may alter their incentives to invest in the quality of their goods. We show that a compatibility standard reduces price competition. If firms agree to the standard after their products are fully developed and their investment costs are sunk, the expectation of a standard does not affect investment incentives. But if firms can agree to compatibility *ex ante*, i.e. before investing in the quality of their goods and the potential standard, and if they can contract on royalties and technology sharing, there is a strong effect on investments. We show that firms can use linear royalties and technology sharing agreements to reduce their investment incentives and to further curb price competition. In this case imposing a royalty-free licensing rule makes matters worse because it further reduces investment incentives. However, it may be optimal to forbid *ex ante* agreements on compatibility and technology sharing altogether. Finally, we analyze the incentives to agree on compatibility and show that a common standard is more likely if horizontal product differentiation is large, if investment costs are high and if the investment process is risky.

To better understand the intuition behind these results consider two firms that can form a common standard at no cost if both of them agree to do so. We model competition between these firms by a simple Hotelling model with horizontal and vertical product differentiation and network externalities. If network effects are so strong that without compatibility the market will eventually tip and only one firm will serve the entire market as a monopolist a compatibility standard will not be formed. Each firm will try to become the monopolist in which case it can prevent market entry more effectively if other firms cannot offer compatible products. However, if network effects are less strong so that even without a compatibility standard both firms will survive and serve the market, the firms are better off with a common standard. The reason is that if the two goods are compatible firms do not have to increase their customer base to raise the willingness to pay of their consumers. Therefore, with a common standard they will compete less aggressively and charge higher prices in equilibrium.

These effects may explain why Microsoft and Novell changed their minds. As long as at least one firm was hoping to be able to drive the other firm out of the market, there was no incentive to form a joint compatibility standard. However, when it became clear that both operating systems are going to stay, a common standard was more profitable.

Then we consider an extended model in which firms may sign a more elaborate compatibility agreement at an *ex ante* stage, i.e. before they take their investment decisions. Firms may agree to adopt the superior product as the standard, they may agree to fixed and/or linear royalties, and they may agree to share technologies, in which case investments increase not only the quality of their own good but also the quality of their competitor's product. For example, in the Microsoft/Novell case the standard may allow users of one operating system to use superior features or applications of the other system. We assume that both parties invest individually and non-cooperatively in the development of such a standard and that the standards are substitutes, i.e. only one standard will be adopted.

We show that firms are more likely to make their products compatible if the degree of horizontal product differentiation is large and if investment costs are high. Furthermore, an *ex ante* compatibility agreement with technology sharing and linear royalties becomes more attractive the more uncertainty there is in the investment process. If the uncertainty about the outcome of the R&D process is large, for example because the technology to be developed is very innovative, the parties will not agree to share their technologies. Instead, each firm wants to vertically differentiate itself by striving for higher quality. If, however, the development of the technology is fairly predictable and the uncertainty involved is small, the parties will agree on full technology sharing. In this case they set a strictly positive linear royalty to be paid by the firm with the inferior standard to the firm with the superior standard and a fixed royalty equal to zero. The linear royalty increases the perceived marginal cost of each firm and thus raises the output price. If this was the only effect, the parties would use the linear royalty to implement the monopoly price. On the other hand, however, the linear royalty induces firms to invest too much (from the perspective of joint profits), because they strive to receive rather than to pay royalties by developing the superior standard. The optimal royalty trades off these two effects. From a social welfare point of view the optimal royalty rate will be set too low and induce too little investment. This implies that the government should not impose a free licensing rule on a standard setting agreement. However, it may be optimal to forbid *ex ante* agreements on compatibility and technology sharing altogether.

In this chapter we restrict attention to the case where technologies are substitutes, i.e. only one of the technologies is required for the standard. This is not to say that cases where complementary patents are owned by different firms are not important – to the contrary. But complementary patents raise a different set of issues that are not dealt with here. If patents are complements, each firm that controls an essential patent has monopoly power because it can block the other firms from using the standard. Thus, if all firms charge royalties independently, total royalties will induce an output price that is higher than the monopoly price. In this case cooperation in a patent pool is socially desirable because it reduces total royalties.[46]

Furthermore, we do not consider possible inefficiencies that may arise due to the dynamic process of standard setting.[47] Again, these problems are important, but they are orthogonal to the main questions addressed in this chapter. Therefore we abstract from these problems by assuming that the process of standard setting is instantaneous and efficient and that all firms are *ex ante* symmetric.

The formal literature on standard setting started in the 1980s.[48] In a seminal paper, Katz and Shapiro (1985) compare the private and social incentives to achieve compatibility in a Cournot model with network externalities. In their model the private incentives to achieve compatibility are always too low. In a companion paper, Katz and Shapiro (1986) consider a dynamic model in which firms may choose compatibility too often in order to reduce the degree of competition early on. Farrell and Saloner (1986) also show that standardization may be excessive because it may reduce the variety of products on the market. However, none of these papers considers the incentives to invest in the standard, and they take the number of firms in the market as exogenously given.

Another strand of the literature focuses on the competitive process to establish a standard in the market. Farrell (1996) and Bulow and Klemperer (1999) model this as a "war of attrition" between standards and show that the better standard will be selected, but that delay is a function of the vested interests of the technology-sponsoring parties. In Farrell and Saloner (1988) standard setting organizations (SSOs) outperform markets with respect to the quality of the standard, but markets reach a decision more quickly. Simcoe (2005) models the conflicts of interest within a standard setting organization and shows that there may be delay in reaching an agreement even if all parties are symmetrically informed. He uses this model to explain the slowdown of the standards production of the Internet Engineering Task Force in the 1990s. Other

[46] See Lerner and Tirole (2004) and Schmidt (2006).

[47] If standards compete with each other it may happen that some consumers get stranded if another technology becomes the industry standard. Similarly, it may happen that a dominant firm manages to establish its technology as the industry standard even though this technology is inferior (see Farrell and Klemperer (2007)).

[48] An extensive overview is provided in Farrell and Klemperer (2007).

interesting case studies of the standard setting process are provided in DeLacey et al. (2006).

Finally, this chapter is related to Lerner and Tirole (2004, 2006). Their first paper considers the effects of patent pools on competition. It is more general than our approach in that it is not restricted to patents that are substitutes. However, they do not consider investment incentives. Lerner and Tirole (2006) study SSOs, but focus on the role of standards to certify quality while we are interested in their role to achieve compatibility.

The remainder of the chapter is organized as follows. Section 2.2 sets up the basic model. Section 2.3 analyzes the impact of an *ex post* compatibility standard on price competition and on the incentives of the parties to invest in the quality of their products, and compares the private and social incentives to form a standard. In Section 2.4 we develop an extended model in which parties invest in the quality of the technology/standard and may share technological improvements. Furthermore, they may agree on royalties. We show how the parties will use these instruments to affect product market competition and the incentives to innovate. Section 2.5 compares the private and social incentives to form an *ex ante* compatibility agreement and discusses some policy instruments to improve social welfare. Section 2.6 discusses possible extensions of our model and concludes. Most proofs are relegated to the Appendix, Section 2.7.

2.2 The Model

We need a model that captures horizontal and vertical product differentiation, compatibility choices and network effects, that allows firms to invest in the quality of their products, to share their technologies, and to agree to fixed and/or linear royalties. The following Hotelling model is the simplest model that does the job. There is a continuum of consumers with mass one, distributed uniformly on $[0,1]$. Two firms, A and B, are located at the end points of the unit interval. They offer products of quality θ_i and compete in prices p_i, $i \in \{A, B\}$. Each consumer buys at most one unit of the good. A consumer located at point $x \in [0,1]$ who buys from firm i receives utility

$$U(x,i) = \begin{cases} \nu + \theta_A - t \cdot x + \alpha \cdot n_A - p_A & \text{if } i = A \\ \nu + \theta_B - t \cdot (1-x) + \alpha \cdot n_B - p_B & \text{if } i = B. \end{cases}$$

To avoid uninteresting case distinctions we assume that the base utility ν is sufficiently high that each consumer always buys one unit of the good. Goods are vertically differentiated because of the potentially different quality levels θ_A and θ_B that are determined up to a random element at the first stage of the game. Horizontal product differentiation is captured by a "transportation" cost that is linear in the distance between each consumer's most preferred point x and the location of the firm he buys from. The degree of horizontal product differentiation is reflected by the parameter $t > 0$. Furthermore, consumers benefit from direct and/or indirect network externalities that arise if their good is compatible with the goods purchased by other consumers. For simplicity, this effect is assumed to be linear in the number of customers n_i using a good that is compatible with good i. Note that if goods A and B are not compatible, then n_A and n_B are simply the market shares of firms A and B with $n_A + n_B = 1$. However, if the two firms agreed to a compatibility standard, then $n_A = n_B = 1$ is the sum of the market shares of A and B. We assume that network effects are weak as compared to the degree of horizontal product differentiation, i.e. $0 < \alpha < t$ [49]. Firms produce with constant and identical marginal costs that are normalized to 0.

Throughout this chapter we assume that a firm cannot unilaterally make its product compatible with the product of the other firm. If this was possible it would be a dominant strategy for each firm to achieve compatibility. We assume that both firms have to agree to make their products compatible, either because each firm can block compatibility by technical means or by refusing to reveal trade secrets or to license intellectual property rights that are required for compatibility.

The time structure of the model is as follows:

- At date 1 the two firms may collaborate in a standard setting organization and agree to a common standard that makes their products compatible with each other. Furthermore, they may agree to share technologies that improve the qualities of both of their products and they may agree to fixed and/or linear royalty payments. This will be explained in more detail in Section 2.4.
- At date 2 each firm i, $i \in \{A, B\}$, can make an investment $\overline{\theta}_i$ at cost $\frac{K}{2}\overline{\theta}_i^2$ that improves the expected quality of its good. The final quality of each good is stochastic and given by $\theta_i = \overline{\theta_i} + \widetilde{\Delta}$ where $\widetilde{\Delta_i} \in [-\Delta, \Delta]$ is uniformly distributed with mean 0, variance Δ^2 and covariance $cov(\Delta_A, \Delta_B) = 0$. To avoid complex case distinctions we assume that the uncertainty in the investment process is not

[49] If network effects are strong, i.e. $\alpha > t$, there are two asymmetric pure strategy equilibria in each of which only one firm supplies the entire market. In this case a *de facto* standard always prevails.

too large in the sense that $\Delta < \frac{3}{2}(t-\alpha)$. The realized quality levels are commonly observed by both firms before date 3.

- At date 3 firms may agree to make their products compatible if they did not agree to a common standard *ex ante*, i.e. at date 1, already.
- At date 4 firms choose their prices p_i, $i \in \{A, B\}$, simultaneously, consumers decide which firm to buy from, and payoffs are realized.

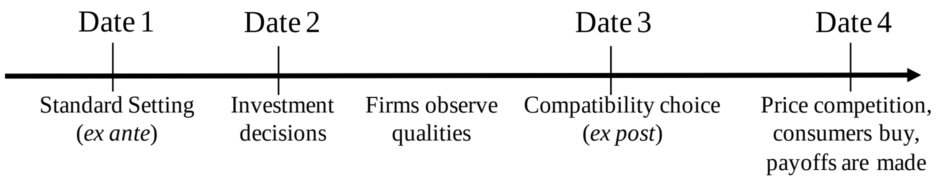

Figure 2.1: Time Structure of the Model

In the next two sections we solve the game by backward induction and focus on symmetric pure strategy subgame perfect equilibria.

2.3 Ex Post Compatibility, Price Competition and Investment Incentives

In this section we analyze the incentives of the firms to form a standard *ex post*, i.e. after their investment decisions have been taken. Thus, we consider the model that starts at date 2 with no *ex ante* standard in place. Furthermore, we assume that IP rights are not required to achieve compatibility, so royalties are not an issue. Section 2.4 considers the effects of *ex ante* standard setting, technology sharing and royalties.

2.3.1 Price Competition with and without Compatibility

Consider the subgame starting at date 4 when investment costs are sunk and the two firms know the realized quality levels θ_A and θ_B. Before setting their prices they may agree to make their products compatible with each other.[50] Suppose that both firms

[50] We assume that there is no cost to achieve compatibility. Introducing such a cost would affect our results in a straightforward manner.

have positive market shares. If products are not compatible the marginal customer $\overline{x}$ who is just indifferent between buying good A or B satisfies:

$$\nu + \theta_A - t \cdot \overline{x} + \alpha \cdot \overline{x} - p_A = \nu + \theta_B - t \cdot (1 - \overline{x}) + \alpha \cdot (1 - \overline{x}) - p_B.$$

Similarly, if products are compatible, the marginal customer is characterized by

$$\nu + \theta_A - t \cdot \overline{x} + \alpha - p_A = \nu + \theta_B - t \cdot (1 - \overline{x}) + \alpha - p_B.$$

Thus,

$$\overline{x} = \frac{1}{2} + \frac{\theta_A - \theta_B - p_A + p_B}{2 \cdot \widehat{t}} \text{ with } \widehat{t} = \begin{cases} t & \text{if goods are compatible} \\ t - \alpha & \text{if goods are not compatible} \end{cases}$$

and the profit functions are given by

$$\pi_A = p_A \cdot \overline{x}(\theta_A, \theta_B, p_A, p_B) - \frac{K}{2}\overline{\theta}_A^2 \text{ and } \pi_B = p_B \cdot (1 - \overline{x}(\theta_A, \theta_B, p_A, p_B)) - \frac{K}{2}\overline{\theta}_B^2,$$

respectively.

Lemma 2.1 *Suppose that* $\widehat{t} > \left|\frac{\theta_A - \theta_B}{3}\right|$. *Then there exists a unique symmetric Nash equilibrium of the pricing subgame with*

$$p_A = \frac{\theta_A - \theta_B}{3} + \widehat{t} \textit{ and } p_B = \frac{\theta_B - \theta_A}{3} + \widehat{t}.$$

The marginal consumer is given by $\overline{x} = \frac{1}{2} + \frac{\theta_A - \theta_B}{6\widehat{t}}$ *and firms' profits are*

$$\pi_A = \frac{(\theta_A - \theta_B + 3\widehat{t})^2}{18\widehat{t}} - \frac{K}{2}\overline{\theta}_A^2 \textit{ and } \pi_B = \frac{(\theta_A - \theta_B + 3\widehat{t})^2}{18\widehat{t}} - \frac{K}{2}\overline{\theta}_B^2.$$

Proof. See Appendix, Section 2.7.1. ■

Note that the market sustains two firms if and only if

$$\widehat{t} > \left|\frac{\theta_A - \theta_B}{3}\right|.$$

If this condition is violated the quality difference between the two firms is so large that only the firm with the superior product can make positive profits. Note also that this condition implies that profits are strictly increasing in $\widehat{t}$.

Proposition 2.1 *If both firms serve the market, prices and profits are higher if firms agreed on compatibility ($\widehat{t} = t$) than if they did not agree on compatibility ($\widehat{t} = t - \alpha$).*

Proof. See Appendix, Section 2.7.1. ■

At first glance this proposition may be surprising. One might have suspected that if goods obey a common standard, they are closer substitutes and that, therefore, price competition should be more intense. However, the exact opposite is the case. To see the intuition for this result note that without a common standard ($n_A = \overline{x}$, $n_B = 1 - \overline{x}$), consumers are interested in buying a good that many other consumers buy as well. Thus, in order to attract customers firms have to offer a large market share which forces them to compete more aggressively. The larger the network benefit α the more important market share is for consumers and the more intense competition is. On the other hand, if firms agree to a common standard ($n_A = n_B = 1$) each consumer gets the full network benefit α no matter which good he buys. Therefore, consumers do not care about market shares, and firms will compete less aggressively.

A different way to see this is to look at the marginal customer $\overline{x}$. He benefits from network externalities in proportion to the market share of firm i, but he also suffers from transportation cost in proportion to the market share of firm i (because he is – by definition – the most distant customer of this firm). Therefore, without a common standard a decrease of the network externality α has the same effect as an increase of the transportation cost t: they make the demand of each firm less price elastic and reduce the degree of competition.[51] If a common standard is introduced the network externality no longer affects the decision of the marginal customer where to buy. Thus, introducing a common standard has the same effect as an increase of transportation cost by α.

Consider now the case where $\widehat{t} < \left|\frac{\theta_A - \theta_B}{3}\right|$. In this case only one firm will serve the market. We assume that consumers manage to coordinate to all buy from the firm with the superior quality.[52] Note that this firm is still constrained in its pricing decision by

[51] Navon et al. (1995) also show that an increase in the network externality α has a similar effect on competition as a reduction of transportation costs, but they do not consider compatibility standards.

[52] Thus, we abstract from a possible war of attrition that determines which firm monopolizes the market as analyzed in detail already, see Farrell (1996), Farrell and Shapiro (1988) and Simcoe (2005).

the potential entry of the other firm. After all, the other firm is prepared to offer the good at any price greater or equal to its marginal cost that we normalized to 0.

Lemma 2.2 *If $\widehat{t} < \left|\frac{\theta_A - \theta_B}{3}\right|$ only the firm with the superior quality serves the market. It will charge the limit price $p_i = |\theta_A - \theta_B| - \widehat{t}$, serve all customers, and make a profit of*

$$\pi_i = |\theta_A - \theta_B| - \widehat{t} - \frac{K}{2}\overline{\theta}_i^2.$$

Proof. See Appendix, Section 2.7.1. ■

Note that if only one firm serves the market price and profit are decreasing in $\widehat{t}$.

Proposition 2.2 *If only one firm serves the market the price and the profit of this firm are higher if firms did not agree on compatibility ($\widehat{t} = t - \alpha$) than if they did not agree on compatibility ($\widehat{t} = t$).*

Proof. See Appendix, Section 2.7.1. ■

The intuition for this result is that the firm with the superior product is constrained in its pricing decision by the threat of entry of the other firm. If there is a common standard and if products are compatible a consumer can switch to the inferior firm and still enjoy the network externality. Without the standard, this consumer enjoys the network benefits only in proportion to the customer base of the firm he buys from. Thus, if the entrant with the inferior product has no customers, it is much less attractive to buy his product. Therefore, the constraint on the pricing decision of the superior firm is relaxed.

To summarize, a common standard relaxes price competition if both firms have positive market share, but it facilitates entry and makes the market more contestable if only one firm serves the market.

2.3.2 Investments in Quality

At date 2 firms choose their quality levels simultaneously.

Proposition 2.3 *If $t \geq \frac{1}{9K}$ there exists a unique symmetric pure strategy equilibrium in which both firms invest in quality, each chooses $\overline{\theta}_A = \overline{\theta}_B = \frac{1}{3K}$, firms agree to make* *their products compatible and both firms serve the market with probability one. In this case expected profits are*

$$E(\pi_A) = E(\pi_B) = \frac{t}{2} + \frac{\Delta^2}{9t} - \frac{1}{18K}.$$

If $t < \frac{1}{9K}$ there is no symmetric pure strategy equilibrium. However, there are two asymmetric pure strategy equilibria in which only one firm invests in quality and chooses $\overline{\theta} = \frac{1}{K}$, while the other firm does not invest. There is no compatibility agreement in this case and the firm that invested monopolizes the market with probability one. If the firms play a correlated equilibrium such that firm A (B) invests and serves the market while firm B (A) abstains with probability 0.5, then expected profits are

$$E(\pi_A) = E(\pi_B) = \frac{1}{4K} - \frac{t-\alpha}{2}.$$

Proof. See Appendix, Section 2.7.1. ■

Proposition 2.3 allows for some simple comparative static results:

Corollary 2.1 *The higher the degree of product differentiation t and the larger the investment cost parameter K, the more likely it is that both firms serve the market and that a standard will be formed.*

The intuition for these results is straightforward. The more the two goods are horizontally differentiated, the larger are duopoly profits and the smaller is the profit of a monopolist. Thus, it is more likely that a duopoly can be sustained. Furthermore, a high marginal cost of quality improvement K deters firms in a duopoly from investing too much. Recall that in equilibrium both firms invest the same amount, so that prices are independent of quality and firms do not gain from their investments. The investment game is a prisoners' dilemma: anything that reduces investment levels makes the duopoly more profitable. This is not the case for a monopolist who can charge higher prices for higher quality. Thus, an increase of K makes the duopoly more attractive as compared to the monopoly and thus makes a standard more likely.

Corollary 2.2 *As long as the market structure is given, investments do neither depend on the degree of product differentiation nor on the degree of network effects. Thus, compatibility choices do not have a direct effect on investments. However, switching from a regime in which compatibility standards are possible to one in which they are* *illegal may have an indirect effect on investments because it may change the market structure.*

To see the last point of the Corollary 2.2 suppose that $\frac{1}{9K} < t < \frac{1}{9K} + \alpha$. If compatibility standards are possible, the first part of the inequality implies that there is room for two firms each of which will invest $\frac{1}{3K}$. However, if such standards are illegal, the relevant "transportation cost" is $t - \alpha$ and the second part of the inequality implies that only one firm will invest $\frac{1}{K}$ and serve the market. Thus, the feasibility of compatibility standards may affect the market structure and thereby investment incentives.

2.3.3 Welfare Evaluation

We now compare the decisions of the firms to the decisions of a social planner who wants to maximize social welfare, i.e. a weighted sum of consumer surplus and profits of the two firms, weighted with a factor γ, $0 \leq \gamma < 1$. The factor γ reflects that the social planner gives more weight to consumers than to producers, for example because of distributional concerns or because the companies are (partially) owned by foreigners. Note that if $\gamma = 1$, prices are a pure transfer that do not affect social welfare. The social planner wants to maximize this objective function by choosing quality investments and then prices subject to the constraint that firms do not make losses. The social planner can make lump-sum transfers τ_A and τ_B to the firms that have to be paid for by a tax $\tau = \tau_A + \tau_B$ on consumers. Note that transfers may be negative.

Consider first the case where both firms serve the market. In this case the social planner will always impose compatibility because consumers benefit from the positive network externality of the other good. Thus, the social planner's problem – once the realized technology shocks Δ_A, Δ_B are observed – is given by:

$$\begin{aligned}\max_{p_A, p_B, \overline{x}, \tau_A, \tau_B, \tau} \Bigg\{ & \int_0^{\overline{x}} (\nu + \overline{\theta}_A + \Delta_A - tx - p_A + \alpha - \tau) dx \\ & + \int_{\overline{x}}^1 (\nu + \overline{\theta}_B + \Delta_B - t(1-x) - p_B + \alpha - \tau) dx \\ & + \gamma \left(p_A \overline{x} - \tfrac{K}{2} \overline{\theta}_A^2 + \tau_A + p_B(1-\overline{x}) - \tfrac{K}{2} \overline{\theta}_B^2 + \tau_B \right) \Bigg\}\end{aligned}$$

subject to:

$$\begin{aligned} p_A\overline{x} - \frac{K}{2}\overline{\theta}_A^2 + \tau_A &\geq 0 \\ p_B(1-\overline{x}) - \frac{K}{2}\overline{\theta}_B^2 + \tau_B &\geq 0 \\ \tau_A + \tau_B &= \tau. \end{aligned}$$

The first two constraints reflect that firms cannot be forced to participate and have to make at least zero profits. The last condition requires a balanced budget. The social planer faces a trade-off between minimizing total transportation cost and allocating consumers to the firm with the better technology. Because $\gamma < 1$, the participation constraints must be binding. Note that consumers and firms care only about the sum of prices and transfers, so transfers and prices are not uniquely determined. Therefore, we look for the lowest transfers that can be used to implement the efficient allocation. The solution to the planner's problem is given by:

$$\begin{aligned} p_A &= p_B = p = \frac{K}{2}\overline{\theta}_A^2 + \frac{K}{2}\overline{\theta}_B^2 \\ \overline{x} &= \frac{1}{2} + \frac{\overline{\theta}_A + \Delta_A - \overline{\theta}_B - \Delta_B}{2t}, \end{aligned}$$

$$\tau_A = (1-\overline{x})\frac{K}{2}\overline{\theta}_A^2 - \overline{x}\frac{K}{2}\overline{\theta}_B^2 \text{ and } \tau_B = \overline{x}\frac{K}{2}\overline{\theta}_B^2 - (1-\overline{x})\frac{K}{2}\overline{\theta}_A^2, \text{ with } \tau = \tau_A + \tau_B = 0.$$

Note that it is optimal to charge the same price for both products that is independent of actual quality. Substituting the optimal allocation in the social welfare function and maximizing with respect to $\overline{\theta_i}$ implies:

$$\overline{\theta}_A = \overline{\theta}_B = \frac{1}{2K} \text{ and } p_A = p_B = \frac{1}{4K}.$$

Thus, in the first best expected total social welfare is given by:

$$EW = \frac{1}{4K} - \frac{1}{4}t + \alpha + \nu + \frac{\Delta^2}{2t}.$$

Consider now the possibility that only one firm, say firm A, serves the entire market. In this case the social planner is indifferent whether to impose compatibility, because all consumers buy from firm A anyway. Thus social welfare is given by:

$$W = \int_0^1 (\nu + \overline{\theta}_A + \Delta_A - tx - p_A + \alpha)dx + \gamma \left(p_A - \frac{K}{2}\overline{\theta}_A^2 \right).$$

Again, if $\gamma < 1$ the social planner will choose p_A as low as possible subject to the constraint that the firm breaks even. Substituting the break-even condition in the expected welfare function and maximizing with respect to $\overline{\theta}_A$ yields the first order condition

$$\frac{\partial EW}{\partial \overline{\theta}_A} = 1 - K\overline{\theta}_A = 0$$

which implies

$$\overline{\theta}_A = \frac{1}{K} \text{ and } p_A = \frac{1}{2K}.$$

Thus, expected social welfare is given by:

$$EW = \frac{1}{2K} - \frac{1}{2}t + \alpha + \nu.$$

Comparing the social welfare expressions with one firm and two firms, respectively, the social planner prefers to have both firms operating if and only if:

$$\begin{aligned} W^{FB}(2 \text{ firms}) = \quad & \tfrac{1}{4K} - \tfrac{1}{4}t + \alpha + \nu + \tfrac{\Delta^2}{2t} > \tfrac{1}{2K} - \tfrac{1}{2}t + \alpha + \nu \quad = W^{FB}(1 \text{ firm}). \\ \Leftrightarrow \quad & \underbrace{\frac{\Delta^2}{2t}}_{\substack{\text{sampling} \\ \text{effect}}} + \underbrace{\frac{1}{4}t}_{\substack{\text{transportation} \\ \text{cost effect}}} > \underbrace{\frac{1}{4K}}_{\substack{\text{investment} \\ \text{cost effect}}} \end{aligned}$$

There are two advantages of having two firms. First, with two firms there are two independent quality draws. Because more consumers buy the higher quality good, this gives rise to a sampling effect which becomes more valuable the smaller the transportation cost. Second, two firms increase variety and reduce the total transportation cost.

On the other hand, the advantage of having only one firm is that the investment cost has to be born only once, and so total investment is more efficient.

Proposition 2.4 *If $\Delta < \frac{1}{K\sqrt{8}}$ and $\frac{1-\sqrt{1-8K^2\Delta^2}}{2K} < t < \frac{1+\sqrt{1-8K^2\Delta^2}}{2K}$, it is more efficient that only one firm serves the market, invests $\overline{\theta}^{FB} = \frac{1}{K}$ and charges $p^{FB} = \frac{1}{2K}$, while the other firm is inactive. Otherwise, the first best efficient outcome is that two firms serve the market, each firm invests $\overline{\theta}_A^{FB} = \overline{\theta}_B^{FB} = \frac{1}{2K}$ and charges $p_A^{FB} = p_B^{FB} = \frac{1}{4K}$ and the two goods use a common standard.*

Proof. See Appendix, Section 2.7.1. ■
Comparing the first best solution to the actual market outcome, we get:

Corollary 2.3 *There are three potential inefficiencies that may arise in equilibrium:*
(a) *Market prices are inefficiently high and leave a rent to firms, in particular if only one firm is sustained by the market.*
(b) *Investments are chosen inefficiently low if there are two firms on the market (but efficiently if there is only one firm).*
(c) *The market structure may be inefficient:*
∘ *if $t < \frac{1}{9K}$ and $0 < t < \frac{1-\sqrt{1-8K^2\Delta^2}}{2K}$ the market sustains only one firm, but it would be socially optimal to have two firms using a common standard.*
∘ *if $\frac{1}{9K} < t < \frac{1+\sqrt{1-8K^2\Delta^2}}{2K}$ the market sustains two firms, but it would be more efficient to have only one firm.*

Suppose that the only policy instrument available to the government is to either impose a standard if firms don't choose one voluntarily or to forbid standards altogether. At first glance it may seem to be a good idea to make standards mandatory because in the first best the social planner would always impose a common standard. If only one firm serves the market, this is indeed the case. Imposing a standard is optimal as it shifts rents from the producer to consumers.

However, if two firms serve the market it may become optimal to make compatibility standards illegal. To see this suppose that $t > \frac{1}{9K} + \alpha$. Without government intervention the market would sustain a duopoly that opts for a compatibility standard. If compatibility standards are made illegal, competition would be more intense and prices would fall from $p_A = p_B = t$ to $p_A = p_B = t - \alpha$. Thus, in equilibrium each consumer gains α due to lower prices and loses $\frac{\alpha}{2}$ because of the reduced network externality (his good is now compatible with only half of the market). Thus, the net gain of each consumer from this policy is $\frac{\alpha}{2}$. On the other hand, the two firms jointly lose α because of the lower price. Therefore, if the weight of the firms in the social welfare is sufficiently small, making a standard illegal may actually improve social welfare.

Proposition 2.5 *In a second best world in which the government cannot directly control entry, investment and pricing decisions of firms,*
(a) *if $t < \frac{1}{9K}$ imposing a mandatory standard for ex post compatibility strictly increases social welfare*
(b) *for $t > \frac{1}{9K} + \alpha$ and $\gamma < \frac{9t(t-\alpha)}{2(9t(t-\alpha)-2\Delta^2)}$ forbidding a standard that the industry would like to adopt strictly increases social welfare.*

Proof. See Appendix, Section 2.7.1. ■

2.4 Ex Ante Compatibility, Technology Sharing and Royalties

So far we looked at standards that are set after investments have been sunk. We now consider the situation where parties can commit to a compatibility standard before they take their investment decisions. The parties may agree that the product with the superior quality will be the basis of the standard and that the firm with the inferior quality has to pay fixed and/or variable royalties. Furthermore, we allow for the possibility that the firms' investments not only improve the quality of their own good, but may also have positive spillover effects on the goods of their competitors. The parties may agree to different forms of technology sharing in order to control these spillovers in the initial contract.

2.4.1 Technology Sharing and Royalties

Suppose w.l.o.g. that $\theta_A > \theta_B$ and that good A sets the joint standard. A consumer located at $x \in [0,1]$ who buys good $i \in \{A, B\}$ enjoys utility:

$$U(x,i) = \begin{cases} \nu + \theta_A - tx + \alpha - p_A & \text{if } i = A \\ \nu + \theta_B + \lambda(\theta_A - \theta_B) - t(1-x) + \alpha - p_B & \text{if } i = B. \end{cases}$$

The parameter $\lambda \in [0,1]$ measures the positive spillover effects on the inferior good if it can use the superior standard. If $\lambda = 1$, inferior firm B completely adopts the superior technology of good A and both firms offer the same quality. If $\lambda = 0$ there are no spillovers, the standard merely allows for compatibility and does not affect the quality of the goods, and we are back to the model of the previous section. If $0 < \lambda < 1$ the adoption of the superior standard has some spillover effects, but some quality differences remain. The parameter λ may be affected by the standard setting agreement. The more comprehensive the standard and the more technology is shared by the parties, the higher is λ.

Suppose that both firms serve the market. The consumer who is just indifferent whether to buy product A or B is located at:

$$\overline{x} = \frac{1}{2} + \frac{(1-\lambda)(\theta_A - \theta_B) - p_A + p_B}{2t}.$$

The parties may agree on a fixed royalty R and/or linear royalties r that have to be paid by the firm with the inferior product to the firm that sets the standard. Thus, the profit function of firm A is given by:

$$\pi_A = \begin{cases} p_A \cdot \overline{x}(p_A, p_B) + r \cdot (1 - \overline{x}(p_A, p_B)) + R - \frac{K}{2}\overline{\theta}_A^2 & \text{if} \quad \theta_A \geq \theta_B \\ p_A \cdot \overline{x}(p_A, p_B) - r \cdot \overline{x}(p_A, p_B) - R - \frac{K}{2}\overline{\theta}_A^2 & \text{if} \quad \theta_A < \theta_B. \end{cases}$$

In both cases the first derivative of A's profit function with respect to p_A is the same and yields the reaction function:

$$p_A = \frac{t + r + (1-\lambda)(\theta_A - \theta_B) + p_B}{2}.$$

This is the same condition as in Section 2.3 with $\widehat{t}$ replaced by $t + r$ and $\theta_A - \theta_B$ replaced by $(1-\lambda)(\theta_A - \theta_B)$.

Lemma 2.3 *Suppose that* $t > \left|\frac{(1-\lambda)(\theta_A - \theta_B)}{3}\right|$. *Then there exists a unique symmetric Nash equilibrium of the pricing subgame with*

$$p_A = \frac{(1-\lambda)(\theta_A - \theta_B)}{3} + t + r \text{ and } p_B = \frac{(1-\lambda)(\theta_B - \theta_A)}{3} + t + r,$$

and the marginal consumer is given by $\overline{x} = \frac{1}{2} + \frac{(1-\lambda)(\theta_A - \theta_B)}{6t}$. *Suppose w.l.o.g. that firm A has the superior technology. Then firms' profits are given by*

$$\pi_A = \frac{[(1-\lambda)(\theta_A - \theta_B) + 3t]^2}{18t} + r + R - \frac{K}{2}\overline{\theta}_A^2, \; \pi_B = \frac{[(1-\lambda)(\theta_B - \theta_A) + 3t]^2}{18t} - R - \frac{K}{2}\overline{\theta}_B^2.$$

The proof is a simple extension of the proof of Lemma 2.1. Note that if we set $\lambda = r = R = 0$ Lemma 2.3 boils down to Lemma 2.1. In the following we will restrict attention to the case where both firms expect that they are both going to serve the market at date 4. Otherwise they would not be willing to agree to a common standard *ex ante*.

Consider now the investment decisions at date 2.

Proposition 2.6 *Suppose that the two firms agreed to a common standard and to royalties $r, R \geq 0$ at date 1. If $t \geq \frac{(1-\lambda)^2}{9K}$ there exists a unique symmetric pure strategy equilibrium in which firms choose investment levels*

$$\overline{\theta}_A = \overline{\theta}_B = \frac{1-\lambda}{3K} + \frac{2R+r}{2K\Delta}$$

and expected equilibrium payoffs are

$$E(\pi_A) = E(\pi_B) = \frac{t+r}{2} + \frac{(1-\lambda)^2\,\Delta^2}{9t} - \frac{(1-\lambda)^2}{18K} - \frac{(1-\lambda)(2R+r)}{6K\Delta} - \frac{(2R+r)^2}{8K\Delta^2}.$$

Proof. See Appendix, Section 2.7.1. ■

Note that if R and r increase, the incentives to invest go up because a higher prize is gained if a firm manages to come up with the superior standard. On the other hand, the incentives to invest decrease with K (because of higher investment cost), with Δ (because more of the vertical product differentiation is achieved by the uncertainty in the investment process) and with λ (because it is less profitable to invest if a larger share of the investment can be used by the competitor). Note also that expected equilibrium profits are increasing in t (because of stronger product differentiation), in K (because of lower investments) and in Δ (because of lower investment incentives and less ex post competition).

2.4.2 Optimal Royalties

Suppose that the parties can contract on linear and/or fixed royalties before they take their investment decisions. What royalties will they agree upon?

Proposition 2.7 *If the parties agreed to a common standard they will choose:*

$$R = 0 \text{ and } r = \max\left\{2K\Delta^2 - \frac{2\Delta\,(1-\lambda)}{3}, 0\right\}.$$

The optimal linear royalty r is increasing in the spillover parameter λ and the marginal cost of investment K. It is strictly positive and increasing in Δ if and only if $\Delta > \frac{1-\lambda}{3K}$. Given the optimal royalties, firms choose:

$$\overline{\theta}_A = \overline{\theta}_B = \begin{cases} \frac{1-\lambda}{3K} & \text{if } \Delta < \frac{1-\lambda}{3K} \\ \Delta & \text{if } \Delta \geq \frac{1-\lambda}{3K} \end{cases} .$$

Proof. See Appendix, Section 2.7.1. ■

To see why the fixed royalty R will be set to zero, note that it has no impact on equilibrium prices but only affects the investment incentives of the two parties. The higher R, the higher is the reward for developing the superior standard and the stronger are the incentives to invest. However, in equilibrium both parties make exactly the same investment. While the investment benefits consumers, it does not benefit the two firms. Both firms would be better off if they could commit not to invest. By setting $R = 0$, they eliminate any incentive to invest coming from the fixed part of royalties.

The linear royalty r, however, may be positive. It trades off two effects. On the one hand it is part of the marginal costs of both firms: It is a direct marginal cost for the inferior firm that has to pay the royalty for each of its customers. It is a marginal opportunity cost for the superior firm that loses the royalty income on each customer that it gains. Therefore, the equilibrium price at date 4 increases one to one with r which raises total profits by r. If this was the only effect, the parties would use r to implement the monopoly price. However, there is a second effect. The linear royalty induces the parties to invest more which is bad for total profits. Therefore r should not become too large. The optimal linear royalty increases with the spillover parameter λ and the marginal cost of investment K. The larger these parameters, the lower is the incentive to invest in quality which dampens the second effect and makes it optimal to raise r.

2.4.3 Incentives to Share Technology

So far we assumed that the parameter λ is exogenously given. However, the parties may be able to affect λ by agreeing to various forms of technology sharing in the *ex ante* contract. Consider the case where they can freely set $\lambda \in [0, 1]$. In this case, we get the following result:

Proposition 2.8 *If the parties can freely choose the spillover parameter λ, they will set $\lambda = 1$ and $r = 2K\Delta^2$. There is a unique symmetric equilibrium with $p_A = p_B = t + 2K\Delta^2$, $\overline{\theta}_A = \overline{\theta}_B = \Delta$ and*

$$E(\pi_A) = E(\pi_B) = \frac{t}{2} + \frac{K\Delta^2}{2}.$$

Proof. See Appendix, Section 2.7.1. ■

By setting $\lambda = 1$ the parties commit to fully share their technologies which minimizes their incentives to invest. However, they still have a positive incentive to invest because they will set $r > 0$ in order to increase product market prices.

2.5 Private and Social Incentives to Adopt a Common Standard

The question remains whether cooperative or competitive standard setting will prevail. Will the parties agree to a common standard or will each of them hope to be able to monopolize the market? If the firms do not agree to a common standard *ex ante* we are back to the analysis of Section 2.3. Clearly, if the parties expect that without an *ex ante* standard they will still both invest and both serve the market, the *ex ante* standard dominates by a simple revealed preference argument. After all, the parties could have agreed to an *ex ante* standard with $\lambda = r = 0$, but they chose not to do so.

If, however, without an *ex ante* standard only one firm would have invested and monopolized the market, i.e. if $t < \frac{1}{9K}$, the parties may be better off by not agreeing to an *ex ante* standard. Without a standard their expected profits are given by the second part of Proposition 2.3. Comparing them to the profits with an *ex ante* standard given by Proposition 2.8 we get:

Proposition 2.9 *Firms agree to form a standard with $\lambda = 1$ and $r = 2K\Delta^2$ if and only if:*

$$t > \min\left\{\frac{1}{9K}, \frac{1}{4K} + \frac{\alpha}{2} - \frac{K\Delta^2}{2}\right\}.$$

Proof. See Appendix, Section 2.7.1. ■

Thus, cooperative standard setting with technology sharing is more likely if the degree of horizontal product differentiation is large (which makes a monopoly of one firm less attractive), if investment costs are high and if there is a lot of uncertainty in the investment process (both of which induces firms to invest less). If firms cooperate on standardization *ex ante* and fully share their technologies, they will invest $\overline{\theta}_A = \overline{\theta}_B = \Delta$, while if they do not agree on a common standard, either both firms invest $\overline{\theta}_A = \overline{\theta}_B = \frac{1}{3K}$ or only one firm invests $\frac{1}{K}$ while the other firm stays out of the market. Thus, if royalties and technology sharing are feasible, standard setting may have a large impact on investment behavior.

Let us now compare the private incentives to form a standard with technology sharing and linear royalties to the social incentives. A social planner would always impose a common standard and he would always use both firms to produce. He will use both firms to invest if the sampling effect of having two quality realizations is sufficiently large as compared to the investment cost. Otherwise, only one firm invests but shares its technology with the other firm.

Proposition 2.10 *From a social welfare point of view it is always optimal to have a standard with full technology sharing. If $\Delta > \frac{3}{4K}$, it is optimal to make both firms invest $\overline{\theta}_A = \overline{\theta}_B = \frac{1}{2K}$, otherwise it is more efficient if only one firm invests $\overline{\theta}_i = \frac{1}{K}$.*

Proof. See Appendix, Section 2.7.1. ■

Thus, the market outcome generically fails to be efficient: Either the two firms agree on a common standard with $\lambda = 1$ (which is efficient), but in this case they will not invest efficiently (if $\Delta \neq \frac{1}{2K}$). Or they will not form a standard (which is always inefficient) and only one firm will enter the market which will then invest efficiently.

If both firms serve the market and if $\Delta < \frac{1}{2K}$, standard setting results in underinvestment. The reason is that the firms are unable to reap any of the benefits of their investments from consumers. Therefore, they have a joint incentive to restrict investments as much as possible, which is socially harmful[53]. If Δ is small, a cartel with little investments can be sustained by using the instruments of a common standard, technology sharing and optimal linear royalties. Furthermore, firms use the linear royalty to increase prices in the product market.

In order to restrict the collusive power of these standard setting agreements the government might consider to impose a royalty-free licensing rule, i.e. it might require firms to set $r = R = 0$. However, the next proposition shows that this reduces social welfare if the noise in the investment process is not too large.

[53] Firms would also underinvest even if there was competition from an outside competitor although this effect would not be as strong.

Proposition 2.11 *Suppose that both firms want to agree to an ex ante standard with full technology sharing and optimal royalties. If* $\Delta < \min\left\{\frac{1}{2K}, \sqrt{\frac{t}{2K}}\right\}$ *imposing a free licensing rule* ($r = R = 0$) *aggravates the underinvestment problem and reduces social welfare.*

Proof. See Appendix, Section 2.7.1. ■

The intuition for this result is straightforward. On the one hand, if $r = 0$ firms cannot use the royalty rate to inflate prices on the product market. On the other hand, with $r = 0$ there is no incentive to invest and firms will choose $\overline{\theta}_A = \overline{\theta}_B = 0$. The proposition shows that the welfare gain due to lower prices is lower than the welfare loss due to lower investments if Δ is small.

Note, however, that in our model the market size is fixed. If an increase in the quality of the goods induces new consumers to enter the market, firms would receive some benefits from their investments and therefore they would not want to eliminate all incentives to invest. However, it would still be the case that they would not be able to capture the entire increase in consumer surplus due to their investments and that their joint incentives to invest would be too low from a social point of view. Therefore, there is always an incentive to use a standard setting agreement *ex ante* to restrict investment incentives.

Another policy option is to forbid *ex ante* agreements on technology sharing, compatibility and royalties altogether, but to allow for *ex post* standardization. We have shown already that firms always prefer an *ex ante* agreement because they could have opted for an *ex ante* agreement with $\lambda = 0$ and a fixed royalty $R = r = 0$, giving the same investment incentives and the same expected profits as *ex post* standard setting, but they prefer $\lambda = 1$ and $r = 2K\Delta^2$.

However, from a social welfare point of view it is less clear whether *ex ante* agreements are desirable. On the one hand, an *ex ante* agreement will set $\lambda = 1$ which benefits consumers but reduces the incentives to invest. Furthermore, firms will choose r in order to increase prices on the product market which tends to increase investment incentives. If Δ is small and thus the investment levels given by an *ex ante* agreement are inefficiently low, it may be a welfare improvement if the government does not allow for *ex ante* standardization.

Proposition 2.12 *If Δ is small, ex post bargaining may be preferable from a social welfare point of view because it does not allow the parties to collectively reduce their investments.*

Proof. See Appendix, Section 2.7.1. ■

2.6 Conclusions

In this chapter we analyzed the implications of standards, technology sharing and royalties on product market competition and investment incentives. We have shown that if both firms expect to serve the market, they want to adopt a common standard because it relaxes product market competition. However, if they anticipate that only one firm will survive on the market, a common standard will not be chosen because it reduces the limit price that the successful company can charge. If there is no technology sharing and if there are no royalties, standards have no direct impact on investments. Even though in a first best world it is always optimal to have a common standard, forbidding a standard can strictly increase welfare by increasing competition and lowering prices.

If firms can, prior to their investment decisions, contractually agree to compatibility, technology sharing and fixed and/or linear royalties, this has a strong impact on investments. Firms will use these instruments to jointly reduce their incentives to invest and to increase the market price. Imposing a zero-royalty rate on standard setting agreements does not mitigate this problem but rather makes it worse.

The recent collaboration agreement between Microsoft and Novell serves as a good example to illustrate some of the points made in this chapter (See Appendix, Section 2.7.2). First, it seems that Microsoft has finally accepted that it will not succeed in excluding Linux from the market for operating systems. As a consequence, our model suggests that both firms should agree to a common standard. Consumers certainly gain from the increased compatibility and associated network effects. However, our model indicates that they may suffer from higher prices in the future.

Furthermore, our model predicts that under such an agreement firms will choose wide technology sharing and low but positive linear royalties. Unfortunately, the exact structure of royalty payments has not been publicized. However, the joint research facility, as proposed in the agreement, will allow for significant spillovers. This is facilitated by the agreement not to sue each other for IP rights violations. Because the fruits of future investments will be shared, investment incentives may be reduced. However, it has to be kept in mind that both firms are still competing against other companies (e.g. Red Hat) which may render this effect quantitatively less pronounced.

Our model restricts attention to the case where technologies are substitutes. If technologies are complements and if several complementary patents owned by different firms are required for the standard, different issues arise. In this case, the main purpose of licensing agreements is to mitigate the complements problem and to prevent parties from charging royalties that push the market price above the monopoly price (see Lerner and Tirole (2004), Schmidt (2006)). It would be an interesting and important topic for future research to extend the analysis of standard setting agreements and of the firms' investment incentives to this case.

2.7 Appendix

2.7.1 Proofs

Proof of Lemma 2.1 and Proposition 2.1: If both firms are active, the best-response functions of the pricing game are given by:

$$p_A = \frac{\theta_A - \theta_B + p_B + \widehat{t}}{2} \text{ and } p_B = \frac{\theta_B - \theta_A + p_A + \widehat{t}}{2}.$$

Thus, there is a unique symmetric Nash equilibrium with:

$$p_A = \frac{\theta_A - \theta_B}{3} + \widehat{t} \text{ and } p_B = \frac{\theta_B - \theta_A}{3} + \widehat{t}.$$

The marginal consumer and equilibrium profits are

$$\overline{x} = \frac{1}{2} + \frac{\theta_A - \theta_B}{6\widehat{t}} \text{ and } \pi_A = \frac{(\theta_A - \theta_B + 3\widehat{t})^2}{18\widehat{t}} - \frac{K}{2}\overline{\theta}_A^2 \text{ and } \pi_B = \frac{(\theta_B - \theta_A + 3\widehat{t})^2}{18\widehat{t}} - \frac{K}{2}\overline{\theta}_B^2.$$

Note that $\widehat{t} > \left|\frac{\theta_A - \theta_B}{3}\right|$ implies $\overline{x} \in (0,1)$ and $\pi(\widehat{t} = t) > \pi(\widehat{t} = t - \alpha)$. Thus, profits are strictly higher if firms agree to a common standard.

Proof of Lemma 2.2 and Proposition 2.2: If $\widehat{t} < \left|\frac{\theta_A - \theta_B}{3}\right|$ there is no pure strategy equilibrium with two firms on the market, because both firms would make losses. However, there is an asymmetric pure strategy equilibrium in which one firm serves the entire market. Suppose w.l.o.g. that this is firm A and that firm B stays out of the market but is ready to supply any customer at price $p_B = 0$. Firm A will optimally charge the limit price $p_A = \theta_A - \theta_B - \widehat{t}$ at which the consumer located at $x = 1$ is just indifferent between buying from A and B. Increasing the price even further reduces profits because with $\widehat{t} < \left|\frac{\theta_A - \theta_B}{3}\right|$ a marginal price increase lowers revenues. Hence, there is no incentive to deviate for firm A. It is straightforward to see that firm B has no incentive to deviate either. Thus, this is indeed an equilibrium. Of course, the mirror equilibrium in which firm B serves the market and A stays out also exists. In this equilibrium:

$$\pi_i = |\theta_i - \theta_j| - \widehat{t} - \frac{K}{2}\overline{\theta}_i^2 \text{ and } \pi_j = 0 \text{ where } i \in \{A, B\} \text{ and } j \neq i.$$

Thus, $\pi(\widehat{t}=t) < \pi(\widehat{t}=t-\alpha)$ and the firm prefers no standard $(\widehat{t}=t-\alpha)$ to a standard $(\widehat{t}=t)$.

Proof of Proposition 2.3: Suppose that both firms expect to serve the market at date 4 and therefore agree to compatibility at date 3. The expected profit of firm i is then:

$$E(\pi_i) = \int\limits_{\Delta_i}\int\limits_{\Delta_j} \frac{\left[\left(\overline{\theta}_i + \Delta_i - \overline{\theta}_j - \Delta_j\right) + 3t\right]^2}{18t} \frac{1}{2\Delta} d\Delta_j \frac{1}{2\Delta} d\Delta_i - \frac{K}{2}\overline{\theta}_i^2$$

where $i \in \{A, B\}$ and $j \neq i$. Differentiating with respect to $\overline{\theta}_i$ and rearranging the FOCs we get:

$$\overline{\theta}_A = \frac{3t - \overline{\theta}_B}{9tK - 1} \text{ and } \overline{\theta}_B = \frac{3t - \overline{\theta}_A}{9tK - 1}.$$

Note that the SOC $(t \geq \frac{1}{9K})$ implies that reaction functions are downward sloping. If this is satisfied there exists a unique[54] symmetric Nash equilibrium in quality levels and with expected equilibrium profits of:

$$\overline{\theta}_A = \overline{\theta}_B = \frac{1}{3K} \text{ and } E(\pi_A) = E(\pi_B) = \frac{t}{2} + \frac{\Delta^2}{9t} - \frac{1}{18K}.$$

If both firms invest the same, the maximum quality difference is 2Δ. By our assumption that $\Delta < \frac{3}{2}(t-\alpha)$ we have $\left|\frac{\theta_A - \theta_B}{3}\right| < \frac{2\Delta}{3} < (t-\alpha)$. Thus, if $t \geq \frac{1}{9K}$ both parties will indeed serve the market with probability one, no matter whether they agree to compatibility or not. But then it is a dominant strategy for each firm to agree on compatibility and the above investment strategies are indeed an equilibrium.

If $t < \frac{1}{9K}$ it is not an equilibrium that both firms invest the same (SOC not satisfied). In this case there are two asymmetric pure strategy equilibria in which only one firm invests and serves the entire market. Suppose w.l.o.g. that this is firm A. At date 4 it chooses the limit price $p_A = \overline{\theta}_A + \Delta_A - \Delta_B - t + \alpha$. Thus, at date 2 it chooses the quality level that maximizes:

[54] If $t - \alpha > \frac{2}{9K}$ this is the unique Nash equilibrium of the game. If $t - \alpha \leq \frac{2}{9K}$ there are two additional asymmetric equilibria in which one firm chooses a quality level of 0 and the other one a quality level of $\frac{3(t-\alpha)}{9K(t-\alpha)-1}$, and firms do not agree to form a standard. Because of the symmetry of the game, we focus on symmetric equilibria throughout.

$$E(\pi_A) = \int\limits_{\Delta_A}\int\limits_{\Delta_B} (\overline{\theta}_A + \Delta_A - \Delta_B - t + \alpha)\frac{1}{2\Delta}d\Delta_B\frac{1}{2\Delta}d\Delta_A - \frac{K}{2}\overline{\theta}_A^2.$$

The optimal investment is $\overline{\theta}_A = \frac{1}{K}$, while firm B invests $\overline{\theta}_B = 0$ and stays out of the market.
We still have to show that if $\overline{\theta}_A = \frac{1}{K}$ and $\overline{\theta}_B = 0$ firm A will indeed monopolize the market with probability one. This is the case if $\left|\frac{\overline{\theta}_A+\Delta_A-\overline{\theta}_B-\Delta_B}{3}\right| > t-\alpha$ for all realizations of θ_A, θ_B. Note that this is implied by $\frac{1}{K} - 2\Delta > 3(t-\alpha)$. Note further that $\frac{3}{2}t > \frac{3}{2}(t-\alpha) > \Delta$ implies $3(t-\alpha)+3t > 3(t-\alpha)+2\Delta$. Also, $\frac{1}{9K} > t$ implies $6\frac{1}{9K} - 3\alpha > 3(t-\alpha)+3t$. Finally, $\alpha \geq 0$ implies $\frac{1}{K} > \frac{2}{3K} - 3\alpha$. Thus, we have $\frac{1}{K} > \frac{2}{3K} - 3\alpha > 3(t-\alpha)+3t > 3(t-\alpha)+2\Delta$ so the firm that invests will indeed monopolize the market with probability one.

By symmetry, there is a mirror equilibrium in which firm B invests and firm A stays out. Thus, there also exists a correlated equilibrium in which each of the two pure strategy equilibria is played with probability 0.5. In this correlated equilibrium expected profits are:

$$E(\pi_A) = E(\pi_B) = \frac{1}{2}\left[\frac{1}{2K} - t + \alpha\right].$$

Proof of Proposition 2.4: Consider first the case where the planner uses both firms to invest and to produce. Note that he will always impose the common standard. For any given realizations of qualities the social planner's problem is:

$$\begin{aligned}\max_{p_A,p_B,\overline{x},\tau,\tau_A} &\left\{\int\limits_0^{\overline{x}} (\nu + \overline{\theta}_A + \Delta_A - tx - p_A + \alpha - \tau)dx\right. \\ &+ \int\limits_{\overline{x}}^1 (\nu + \overline{\theta}_B + \Delta_B - t(1-x) - p_B + \alpha - \tau)dx \\ &\left. +\gamma\left(p_A\overline{x} - \frac{K}{2}\overline{\theta}_A^2 + \tau_A + p_B(1-\overline{x}) - \frac{K}{2}\overline{\theta}_B^2 + \tau - \tau_A\right)\right\}\end{aligned}$$

s.t.: $p_A\overline{x} - \frac{K}{2}\overline{\theta}_A^2 + \tau_A \geq 0$, $p_B(1-\overline{x}) - \frac{K}{2}\overline{\theta}_B^2 + \tau_B \geq 0$, $\overline{x} = \frac{1}{2} + \frac{\overline{\theta}_A+\Delta_A-\overline{\theta}_B-\Delta_B}{2t}$ and $\tau_A + \tau_B = \tau$.

The FOCs imply:

$$\pi_A = p_A\overline{x} - \frac{K}{2}\overline{\theta}_A^2 + \tau_A = 0 \text{ and } \pi_B = p_B(1-\overline{x}) - \frac{K}{2}\overline{\theta}_B^2 + \tau - \tau_A = 0$$

with $p_A^{FB} = p_B^{FB} = p^{FB} = \frac{K}{2}\overline{\theta}_A^2 + \frac{K}{2}\overline{\theta}_B^2$ and $\overline{x} = \frac{1}{2} + \frac{\overline{\theta}_A + \Delta_A - \overline{\theta}_B - \Delta_B}{2t}$.
The subsidies τ_i guarantee zero profits even with unfavorable investment quality realizations:

$$\tau_A = (1-\overline{x})\frac{K}{2}\overline{\theta}_A^2 - \overline{x}\frac{K}{2}\overline{\theta}_B^2 \text{ and } \tau_B = \overline{x}\frac{K}{2}\overline{\theta}_B^2 - (1-\overline{x})\frac{K}{2}\overline{\theta}_A^2.$$

Given this solution the social planner maximizes expected welfare by choosing the optimal investment levels:

$$\begin{aligned}\max_{\overline{\theta}_A,\overline{\theta}_B} \int_{\Delta_B}\int_{\Delta_B} \Bigg\{ & \int_0^{\overline{x}} (\nu + \overline{\theta}_A + \Delta_A - tx - p_A + \alpha - \tau)dx \\ & + \int_{\overline{x}}^1 (\nu + \overline{\theta}_B + \Delta_B - t(1-x) - p_B + \alpha - \tau)dx \\ & + \gamma\left(p_A\overline{x} - \frac{K}{2}\overline{\theta}_A^2 + \tau_A + p_B(1-\overline{x}) - \frac{K}{2}\overline{\theta}_B^2 + \tau_B\right)\Bigg\} \frac{1}{2\Delta}d\Delta_B\frac{1}{2\Delta}d\Delta_A.\end{aligned}$$

The FOCs of this problem imply:

$$\overline{\theta}_A^* = \overline{\theta}_B^* = \frac{1}{2K}.$$

Substituting this result in the above expressions for optimal prices, market shares and subsidies, we get $p^{FB} = \frac{1}{4K}$ and

$$EW^{FB}(2 \text{ firms}) = \frac{1}{4K} - \frac{1}{4}t + \alpha + \nu + \frac{\Delta^2}{2t}.$$

Consider now the case where the planner uses only one firm to invest and to supply the market, so

$$W = \int_0^1 (\nu + \overline{\theta} + \Delta - tx - p + \alpha)dx + \gamma \left(p - \frac{K}{2}\overline{\theta}^2 \right)$$

Again, because $\gamma < 1$, the firm must break-even ($\pi = p - \frac{K}{2}\overline{\theta}^2 = 0 \Rightarrow p = \frac{K\overline{\theta}^2}{2}$). From the maximization of expected social welfare we get the optimal investment level $\overline{\theta}^* = \frac{1}{K}$. Thus, expected welfare with one active firm is given by

$$EW^{FB}(1 \text{ firm}) = \frac{1}{2K} + \alpha + \nu - \frac{1}{2}t.$$

Comparing social welfare with one and two active firms we get

$$EW^{FB}(2 \text{ firms}) > EW^{FB}(1 \text{ firm}) \text{ if and only if } t^2 - \frac{t}{K} + 2\Delta^2 > 0$$

Note that $t^2 - \frac{t}{K} + 2\Delta^2 = 0$ if $t = \frac{1 \pm \sqrt{1-8K^2\Delta^2}}{2K}$. Thus, if $\frac{1-\sqrt{1-8K^2\Delta^2}}{2K} < t < \frac{1+\sqrt{1-8K^2\Delta^2}}{2K}$ and $\Delta < \frac{1}{K\sqrt{8}}$ it is optimal to have one firm, otherwise two firms are more efficient.

Proof of Proposition 2.5: If $t < \frac{1}{9K}$ only one firm serves the market and no standard will be chosen. Expected welfare is given by: $EW = \nu + \frac{t}{2} + \gamma \left(\frac{1}{2K} - t + \alpha \right)$. If the government imposes a standard there is still only one firm, but price falls to the new limit price, $p_A = \theta_A - t = \frac{1}{K} - t$ and expected welfare is $EW = \frac{t}{2} + \nu + \alpha + \gamma \left(\frac{1}{2K} - t \right)$. Thus, welfare improves because $\alpha > \gamma\alpha$. This proves part (a).

Suppose now that $t > \frac{1}{9K} + \alpha$. In this case two firms serve the market and a standard will be chosen. Welfare is given by: $EW = \frac{1}{3K} - \frac{5-4\gamma}{4}t + \alpha + \nu + \gamma\frac{2\Delta^2}{9t} - \frac{\gamma}{9K}$. Suppose, the government makes the standard illegal. Then we still have 2 firms, but prices fall to $p_A = p_B = t - \alpha$ and expected social welfare is $EW = \frac{1}{3K} - \frac{5-4\gamma}{4}t + \left(\frac{3}{2} - \gamma \right) \alpha + \nu + \gamma\frac{2\Delta^2}{9(t-\alpha)} - \frac{\gamma}{9K}$. Thus, welfare improves if γ is small enough: $\gamma < \frac{9t(t-\alpha)}{2(9t(t-\alpha)-2\Delta^2)}$, e.g. as $\Delta^2 \to 0$ we need $\gamma < \frac{1}{2}$. This proves part (b) of the proposition.

Proof of Proposition 2.6: Expected profits are given by:

$$\begin{aligned} E(\pi_A) &= \int\limits_{\Delta_A}\int\limits_{\Delta_B} \frac{\left[(1-\lambda) \left(\overline{\theta}_A + \Delta_A - \overline{\theta}_B - \Delta_B \right) + 3t \right]^2}{18t} \frac{1}{2\Delta} d\Delta_B \frac{1}{2\Delta} d\Delta_A - \frac{K}{2}\overline{\theta}_A^2 \\ &\quad + \Pr(\theta_A > \theta_B)(R + r) \end{aligned}$$

Note that $\Pr\left(\theta_A > \theta_B\right) = \frac{1}{2} + \frac{\left(\overline{\theta}_A - \overline{\theta}_B\right)}{2\Delta}$. Thus, we get (similarly for firm B):

$$\begin{aligned} E\left(\pi_A\right) &= \frac{\left[(1-\lambda)\left(\overline{\theta}_A - \overline{\theta}_B\right) + 3t\right]^2}{18t} + \left(\frac{1}{2} + \frac{\overline{\theta}_A - \overline{\theta}_B}{2\Delta}\right) r \\ &\quad + \left(\frac{\overline{\theta}_A - \overline{\theta}_B}{\Delta}\right) R + \frac{2\left(1-\lambda\right)^2 \Delta^2}{18t} - \frac{K}{2}\overline{\theta}_A^2. \end{aligned}$$

At date 2 the first order conditions for profit maximization give the reaction functions:

$$\overline{\theta}_A = \frac{-(1-\lambda)^2\overline{\theta}_B + 3\left(1-\lambda\right)t + 9t\frac{2R+r}{2\Delta}}{9tK - (1-\lambda)^2} \text{ and } \overline{\theta}_B = \frac{-(1-\lambda)^2\overline{\theta}_A + 3\left(1-\lambda\right)t + 9t\frac{2R+r}{2\Delta}}{9tK - (1-\lambda)^2}.$$

Note that the second order condition requires: $9tK - (1-\lambda)^2 > 0$. Investments in the symmetric equilibrium are thus $\overline{\theta}_A = \frac{(1-\lambda)}{3K} + \frac{2R+r}{2K\Delta} = \overline{\theta}_B$. Hence, expected profits are:

$$E\left(\pi_A\right) = E\left(\pi_B\right) = \frac{t+r}{2} + \frac{(1-\lambda)^2\Delta^2}{9t} - \frac{\left(1-\lambda\right)^2}{18K} - \frac{\left(1-\lambda\right)\left(2R+r\right)}{6K\Delta} - \frac{\left(2R+r\right)^2}{8K\Delta^2}.$$

Proof of Proposition 2.7: Using the profit expression from Proposition 2.6 we have:

$$\frac{\partial E\left(\pi_A\right)}{\partial R} = -\frac{2\left(1-\lambda\right)}{6K\Delta} - \frac{4\left(2R+r\right)}{6K\Delta^2} < 0 \Rightarrow R = 0$$

$$\frac{\partial E\left(\pi_A\right)}{\partial r} = \frac{1}{2} - \frac{\left(1-\lambda\right)}{6K\Delta} - \frac{\left(2R+r\right)}{4K\Delta^2} = 0 \Rightarrow r = 2K\Delta^2 - \frac{2\Delta\left(1-\lambda\right)}{3}.$$

To exclude negative royalties, we have: $r = \max\left\{2K\Delta^2 - \frac{2\Delta(1-\lambda)}{3}, 0\right\}$. Note that $\frac{\partial r}{\partial \lambda} \geq 0$, $\frac{\partial r}{\partial K} \geq 0$ and $\lim_{\Delta^2 \to 0} r = 0$. Note further that $\frac{\partial r}{\partial \Delta} = 4K\Delta - \frac{2(1-\lambda)}{3} \geq 0$ only if $\Delta \geq \frac{(1-\lambda)}{6K}$ and positive if $\Delta \geq \frac{(1-\lambda)}{3K}$. Substituting optimal royalties in the investment levels of Proposition 2.6 gives the result in the proposition.

Proof of Proposition 2.8: Substituting the optimal royalties of Proposition 2.7 into the expected profits (assuming $\Delta \geq \frac{(1-\lambda)}{3K}$, s.t. $r^* > 0$) and simplifying gives:

$$E\left(\pi_A\right) = E\left(\pi_B\right) = \frac{t}{2} + \frac{K\Delta^2}{2} - \frac{\left(1-\lambda\right)\Delta}{3} + \frac{\left(1-\lambda\right)^2\Delta^2}{9t}.$$

Note that expected profits are a convex function of λ $\left(\frac{\partial^2 E(\pi_A)}{\partial \lambda^2} = \frac{2\Delta^2}{9t} > 0\right)$. Firms will either go for $\lambda = 0$ or $\lambda = 1$, and choose $\lambda = 1$ iff $E(\pi_A \mid \lambda = 1) > E(\pi_A \mid \lambda = 0)$, i.e. $\Delta < 3t$. Note that because of our assumption that $\Delta < \frac{3}{2}t$, this condition always holds. Thus, if $\Delta \geq \frac{(1-\lambda)}{3K}$, $r^* > 0$ and $\lambda = 1$. Substitution for the royalty, prices, investments and profits gives $r = 2K\Delta^2$, $p_A = p_B = t + 2K\Delta^2$, $\overline{\theta}_A = \overline{\theta}_B = \Delta$ and

$$E(\pi_A) = E(\pi_B) = \frac{t}{2} + \frac{K\Delta^2}{2}.$$

Comparative statics are: $\frac{\partial E(\pi_A)}{\partial t} = \frac{1}{2} > 0$ and $\frac{\partial E(\pi_A)}{\partial \Delta^2} = \frac{K}{2} > 0$.
However, if $\Delta < \frac{(1-\lambda)}{3K}$, firms could also set $\lambda = 0$ which implies that $\Delta < \frac{1}{3K}$ and $r^* = 0$. In this case, expected profits are $E(\pi_A) = E(\pi_B) = \frac{t}{2} + \frac{\Delta^2}{9t} - \frac{1}{18K}$. Comparing profit expressions shows that firms always prefer $\lambda = 1$ and $r = 2K\Delta^2 - \frac{2\Delta(1-\lambda)}{3} > 0$ which yields the profits above.

Proof of Proposition 2.9: Recall from Proposition 2.8 that profits with an *ex ante* standard setting agreement are: $E(\pi_A) = E(\pi_B) = \frac{t}{2} + \frac{K\Delta^2}{2}$.

- Assume first that $t < \frac{1}{9K}$. If firms do not agree to an *ex ante* standard, a monopoly without standard would obtain. Expected profits are given by Proposition 2.3: $E(\pi_i) = \frac{1}{4K} - t + \alpha$. Comparing this to expected profits with an *ex ante* standard shows that the *ex ante* standard is preferred iff:

$$\frac{t}{2} + \frac{K\Delta^2}{2} > \frac{1}{4K} - \frac{t-\alpha}{2}, \text{ i.e. if } t > \frac{1}{4K} + \frac{\alpha}{2} - \frac{K\Delta^2}{2} \text{ and } t < \frac{1}{9K} \text{ holds.}$$

- Assume now that $t > \frac{1}{9K}$. In this case firms will choose to make their products compatible anyway. If they do not agree to a standard *ex ante* this is equivalent to an ex ante standard with $\lambda = r = 0$. However, by Proposition 2.8 we know that an ex ante standard with $\lambda = 1$ and $r = 2K\Delta^2$ is strictly better.

Proof of Proposition 2.10: Note that a social planner will always impose the common standard and moreover use full technology sharing ($\lambda = 1$). Thus, consumers always get the quality of $\max\{\theta_A, \theta_B\}$, independent of whether they buy from firm A or B. To minimize transportation costs, both firms will always sell and prices will be equalized: $p = p_A = p_B$, $\overline{x} = \frac{1}{2}$.

The expected social welfare maximization problem for the planner is:

$$\max_{\overline{\theta}_A,\overline{\theta}_B} EW^{FB} = \nu + \alpha - \frac{t}{4} + \iint\limits_{\Delta_A \Delta_B} \left\{ \max\left\{\theta_A, \theta_B\right\} - \frac{K}{2}\overline{\theta}_A^2 - \frac{K}{2}\overline{\theta}_B^2 \right\} \frac{1}{2\Delta} d\Delta_B \frac{1}{2\Delta} d\Delta_A.$$

Assume that $\overline{\theta}_A - \overline{\theta}_B < 2\Delta$. Evaluating the inner integral over Δ_B and then differentiating this expression first with respect to $\overline{\theta}_A$ gives the FOC of the problem as:

$$\int\limits_{\Delta_A} \left[\frac{1}{2\Delta} \left[\overline{\theta}_A - \overline{\theta}_B + \Delta_A + \Delta\right] \right] \frac{1}{2\Delta} d\Delta_A - K\overline{\theta}_A = 0.$$

Evaluating this integral over Δ_A gives:

$$\frac{1}{2\Delta} \left[\overline{\theta}_A - \overline{\theta}_B + \Delta\right] - K\overline{\theta}_A = 0$$

Similarly, we derive the condition with respect to $\overline{\theta}_B$. Together these imply that both firms invest: $\overline{\theta}_A = \overline{\theta}_B = \frac{1}{2K}$ and EW^{FB}(2 firms)$= \nu + \frac{1}{4K} + \frac{\Delta}{3} - \frac{t}{4} + \alpha$. Note that $\overline{\theta}_A - \overline{\theta}_B < 2\Delta$ is satisfied. To satisfy the zero profit condition (as $\gamma < 1$), $p = \frac{K}{2}\overline{\theta}_A^2 + \frac{K}{2}\overline{\theta}_B^2$ and $\tau = \tau_A = \tau_B = 0$.
Suppose now that $\overline{\theta}_A - \overline{\theta}_B > 2\Delta$. Then the social planner's problem simplifies to:

$$EW^{FB} = \nu + \alpha - \frac{t}{4} + \int\limits_{-\Delta}^{\Delta} \left[\max\left\{\overline{\theta}_A + \Delta_A, \overline{\theta}_B + \Delta_B\right\}\right] \frac{1}{2\Delta} d\Delta_B - \frac{K}{2}\overline{\theta}_A^2 - \frac{K}{2}\overline{\theta}_B^2.$$

Clearly, taking the derivative with respect to $\overline{\theta}_B$ directly yields $\overline{\theta}_B = 0$. The FOC with respect to $\overline{\theta}_A$ yields $\overline{\theta}_A = \frac{1}{K}$. To satisfy this, firm A's zero profit condition requires, $p = \frac{K}{2}\overline{\theta}_A^2$ and $\tau_A = -\tau_B$ with $\tau_A = \frac{K}{2}\overline{\theta}_A^2$. Thus, expected social welfare is given by: EW^{FB}(1 firm)$= \nu + \frac{1}{2K} - \frac{t}{4} + \alpha$. Comparing the expressions yields EW^{FB}(2 firms)$> EW^{FB}$(1 firm) if and only if $\Delta > \frac{3}{4K}$.

Proof of Proposition 2.11: If firms set a common standard with $\lambda = 1$ and $r = 2K\Delta^2$, social welfare is given by:

$$\begin{aligned} EW &= 2 \cdot \int\limits_0^{\frac{1}{2}} \left(\Delta + \frac{\Delta}{3} - t - 2K\Delta^2 + \alpha + \nu - tx\right) dx + 2 \cdot \gamma \left[\frac{t}{2} + \frac{K\Delta^2}{2}\right] \\ &= \frac{4}{3}\Delta - \frac{5 - 4\gamma}{4} t - (2 - \gamma) K\Delta^2 + \alpha + \nu. \end{aligned}$$

Suppose that the government imposes $r = R = 0$. If it does so, the expected profits of firms that have a common standard reduce to:

$$E(\pi_A) = E(\pi_B) = \frac{t}{2} + \frac{2(1-\lambda)^2 \Delta^2}{18t} - \frac{(1-\lambda)^2}{18K} = \frac{t}{2} + (1-\lambda)^2 \left[\frac{2K\Delta^2 - t}{18Kt}\right].$$

Note that $\frac{\partial E(\pi)}{\partial \lambda} > 0 \Leftrightarrow \Delta^2 < \frac{t}{2K}$. Thus, if $\Delta < \sqrt{\frac{t}{2K}}$, firms will set $\lambda = 1$ which is efficient, but then choose $\overline{\theta}_A = \overline{\theta}_B = 0$, because with $r = 0$ and $\lambda = 1$ there is no private incentive to invest. In this case expected social welfare is given by:

$$EW = 2 \cdot \int_0^{\frac{1}{2}} \left(E\left(\max\{\theta_A, \theta_B\}\right) - t + \alpha + \nu - tx\right) dx + \gamma \cdot 2\left[\frac{1}{2}t\right] = \frac{\Delta}{3} + \alpha + \nu - \frac{t}{4} - (1-\gamma)\, t.$$

Thus, the government reduces social welfare with this policy if $\Delta < \frac{1}{(2-\gamma)K}$. This is implied by $\Delta < \frac{1}{2K}$. Thus, if firms underinvested if left alone, social welfare is reduced by the policy.

Proof of Proposition 2.12: From the proof of Proposition 2.11 we have for the welfare of the optimal *ex ante* standard setting agreement that:

$$EW = \frac{4}{3}\Delta - \frac{5-4\gamma}{4}t - (2-\gamma)K\Delta^2 + \alpha + \nu \Rightarrow \lim_{\Delta^2 \to 0} EW = -\frac{5-4\gamma}{4}t + \alpha + \nu.$$

The welfare from an *ex post* standard agreement is:

$$\begin{aligned} EW &= \frac{1}{3K} - t + \alpha + \nu + \frac{\Delta^2}{18t} - \frac{t}{4} + 2\gamma\left[\frac{t}{2} - \frac{1}{18K} + \frac{\Delta^2}{9t}\right] \\ &\Rightarrow \lim_{\Delta^2 \to 0} EW = \frac{1}{3K} - \frac{5-4\gamma}{4} + \alpha + \nu - \frac{\gamma}{9K}. \end{aligned}$$

Thus, as $\Delta^2 \to 0$, welfare from an *ex post* standard agreement is greater as long as $\frac{1}{3K} - \frac{\gamma}{9K} > 0$, i.e. $3 - \gamma > 0$ which is always true.

2.7.2 Novell-Microsoft Agreement

The Novell-Microsoft Agreement of November 2, 2006.
The agreement covers distribution, development and legal indemnification. In summary, the following three parts to the agreement can be distinguished:

1. Business Collaboration Agreement (BCA): Microsoft has entered into a reseller arrangement with Novell and committed to purchase and distribute 70000 SUSE Linux Enterprise Server license coupons per year for five years. The license coupons entitle the customer to one year of maintenance and support and will involve dedicated sales resources from Microsoft. The companies will also provide joint marketing behind the resale arrangement.

2. Technical Collaboration Agreement (TCA): The two companies will form a joint development effort aligned around virtualization, management and document format compatibility.

3. Patent Agreement (PA): The cooperative patent resolution provides customers with assurance for patent infringement claims. Essentially, Microsoft will not assert patent rights over IP that may be incorporated in the SUSE distribution. The concern of patent infringement suits by Microsoft has acted as a barrier to enterprise adoption of Linux. The PA applies only to the SUSE distribution of Linux. It specifies that both companies will make upfront payments covering IP protection with a net balancing payment to Novell, due to the volume of Windows versus SUSE shipments. In return, Microsoft will receive royalty payments from Novell tied to the company's Open Platform segment.

Source: JPMorgan Analyst Report on Novell on November 8, 2006 by Aaron M. Schwartz, downloaded via Thomson Financial on December 12, 2006.
See http://www.novell.com/linux/microsoft/ for further details on the agreement.

Chapter 3

Vertical Structure, Investment and Financing of Network Utilities

3.1 Introduction

Network utilities such as electricity, gas, water, telecoms and rail provide services essential for the functioning of today's economy and society. An effective and reliable, yet cost-efficient network infrastructure is at the heart of these services and thus indispensable for a powerful, modern economy.[55] To retain and further improve the capabilities of infrastructure requires investments into its quality and cost-effectiveness. In this chapter we explore which vertical industry structure provides the best possible investment incentives into infrastructure.

A network utility's vertical structure consists of an upstream infrastructure component and downstream services offered on this infrastructure. The upstream network is capital-intensive, durable and immovable and involves large fixed costs. These properties render it a natural monopoly. The downstream segment is potentially competitive as it involves comparably low fixed and higher marginal costs.

We compare two conceivable vertical structures. Under *vertical integration* the infrastructure provider is also active in the downstream services segment through an "affiliate" whereas under *vertical separation* he only operates the infrastructure. A regulator handles the familiar conflict between allowing firms to recover their large sunk

[55]Besides accounting for ~15% of GDP in developed economies (Newbery (2000)), utilities are indispensable intermediate inputs to most production processes. Hence, growth and stability are inextricably linked to a reliable, sustainable infrastructure of utilities – an uncertain supply would paralyze the entire economy.

investments and protecting consumers' interests of low prices. Here, we are particularly interested in the consequences that access regulation and vertical structure have for infrastructure investment incentives.

Over the past decades privatization and restructuring of network utilities have launched a dispute on what the optimal structure for these industries may be. By-and-by policy makers have come to realize the importance of infrastructure investment incentives for economic efficiency. The unsatisfactory experience with the rail privatization in the UK is frequently cited as the prime example for insufficient infrastructure quality investments. The worry about underinvestment leading to power outages is anxiously debated in the course of the EU Commission's proposal to separate ownership of infrastructure and services in the electricity industry.

The formal model analyzes competition within a vertical industry structure where the upstream infrastructure good is provided monopolistically. Downstream firms require access to the infrastructure to supply their services to consumers. These services are offered by an oligopoly that competes in quantities à la Cournot. The infrastructure owner – whether vertically integrated with an affiliate on the downstream market or fully independent (vertical separation) – invests into both, the quality and cost-effectiveness of the infrastructure. This investment decision is undertaken after a regulator has set the optimal linear access price to infrastructure but before firms supply products competitively to consumers.

Both types of infrastructure investments increase efficiency but have distinct economic implications. Quality-increasing investments boost efficiency through an increase in the consumers' willingness to pay and enhance demand for the final product provided upon the infrastructure. In the railroad example, demand-enhancing features of infrastructure correspond to improved infrastructure facilities (e.g. tracks and stations) affecting variables such as maximum train speed, punctuality, safety, station quality and track condition. In contrast, cost-reducing infrastructure investments lower the marginal costs of infrastructure provision. For example, cost-reducing investments improve the processing of traffic through stations and on tracks. Thus, these investments are critical to keep the infrastructure and the services of utilities affordable. If investments result in lower access prices to infrastructure the customers and finally also the consumers benefit.

Our main results are the following. First, we show that with linear access prices infrastructure investment incentives into cost-reduction decrease in the regulatory access price under both vertical integration and vertical separation. This is mainly due to an *access margin effect*. Because we assume that access prices cannot be conditioned on investments, cost-reducing investments increase the access margin for every unit of infrastructure sold. However, with a larger access price, the demand for infrastructure falls and thus also the *access margin effect* decreases which lowers investment incentives into cost-reduction. In contrast, infrastructure investments into quality rise with the access price under both vertical integration and vertical separation. This result is mainly driven by an *access quantity effect*. An increase in the quality of infrastructure increases the demand of consumers and thereby also the demand for infrastructure. This increase in access quantity is the sole driver of investment incentives under vertical separation and requires a positive access margin. The larger the access margin, the more the infrastructure owner benefits from investments and consequently, the more the owner invests.

Second, we find that – for linear demand – infrastructure investments under vertical integration, whether in cost-reduction or quality-increases, exceed those under vertical separation for any given access price. The presence of a downstream affiliate amplifies incentives for both investment types. With quality-increasing infrastructure investments, the affiliate benefits directly from a demand expansion. Under cost-reducing investments, the downstream affiliate's competitive position is strengthened. He profits directly from reduced infrastructure costs which represent his effective marginal costs. In contrast, its competitors still pay the unadjusted access price. Under both, quality-increasing and cost-reducing investments, the infrastructure owner can thus capture some gains through the downstream activity of its affiliate directly. In consequence, investment incentives under vertical integration are larger. We also derive first-best investments. Neither investments under vertical separation nor those under integration achieve the first-best – there is underinvestment in quality and cost-effectiveness of infrastructure.

Third, we demonstrate that while investments into cost-reduction always increase in the number of competitors because of an *access quantity effect*, this is not generally true for quality-increasing investments. Under vertical integration, quality investments into infrastructure *decrease* in the number of downstream competitors as the market share and profits of the downstream subsidiary are eroded. However, quality-increasing infrastructure investments under vertical separation *rise* in the number of competitors if the access margin is positive. Again this is driven by increased downstream competition generating more demand for access.

The above results have significant implications for policy. They justify an industry-specific institutional structure depending on the particularities of the network utility. Whereas some industries, such as telecommunications, stand out for their innovative and fast-moving business environments and demand infrastructure investments in quality, other network utilities have long-winded cycles of innovation.[56] In industries where infrastructure investments come frequently and at low cost, a vertically integrated structure should perform better to indeed stimulate economic efficiency through investments.

There is a large literature on the economics of vertical structures.[57] Network utilities, however, distinguish themselves from many other vertical structures as their upstream component is a natural monopoly. This requires access regulation or some form of monitoring by policy makers.[58] The special features of different network utilities have resulted in a tendency towards an industry perspective.[59] The problem discussed in this chapter is, however, of general nature. Let us thus illustrate some results of the literature which are generally applicable and related to this work.

In any vertical structure, as long as there is market power and some separation of ownership in the upstream and the downstream markets, the problem of double marginalization arises (first identified by Spengler (1950)). In our model the regulator cannot solve this problem with linear access prices if he must set an access price above marginal cost to allow the infrastructure firm to recover the fixed costs of infrastructure provision. For this reason, the vertically integrated structure has an efficiency advantage for any positive access margin.

Surprisingly, as Valletti (2003) points out, there has not been a lot of work on the linkage between access prices and investment incentives that we focus on. Biglaiser and Ma (1999) study investment incentives of a regulated, incumbent firm in a deregulation process. In contrast to this study, they explore the impact of an unregulated firm's entry during the deregulation process. The work by Buehler (2005), Buehler et al. (2004, 2006) addresses the issue of potential underinvestment in network infrastructures explicitly. Their papers show that, for reasonable assumptions on demand, investment incentives into infrastructure quality are smaller under vertical separation as compared

[56]Although some innovation is specific to downstream services, these often necessitate prior infrastructure investments for downstream innovation to take place.

[57]For an overview see Motta (2004), chapter 6.

[58]A detailed survey on regulation is Armstrong and Sappington (2007). For work more related to this chapter see Biglaiser and DeGraba (2001) who analyze downstream integration of a bottleneck input supplier and Gans (2001) who discusses informational issues of regulating private infrastructure investments.

[59]Newbery (2000) describes several network utilities in detail.

to vertical integration. In addition, we point out the diverging effects that access price changes have on the different types of infrastructure investments. Moreover, we also show that the result can be extended to cost-reducing infrastructure investments. Vareda (2007) analyzes investment incentives into both infrastructure quality and cost-reduction of a vertically integrated firm under price competition. However, his paper does not compare these against the performance of a vertically separated industry structure and he can therefore not draw any conclusions on the optimal market structure for different network utilities depending on their characteristics. A new strand of literature is the work on legal unbundling as an intermediate structure between vertical integration and vertical separation. The papers by Cremer et al. (2006) and Höffler and Kranz (2007) investigate in which situations legal unbundling can deliver a superior performance through combining the benefits of both vertical structures but they do not consider investments.

Recent papers have stressed the importance of non-price discrimination of the upstream input provider.[60] Although, these actions harm economic efficiency whereas investments improve it, the underlying incentives resemble those considered in this chapter.[61] Methodologically akin is the work on the incentives of an integrated firm to raise the costs of rivals on the downstream market or to sabotage the input good, for example by degrading its quality when supplied to rivals. Sibley and Weisman (1998) show that a regulated upstream monopolist may have incentives to raise rivals' costs as this improves the competitiveness of the downstream affiliate of the integrated firm. However, they also emphasize that there is a countervailing effect: a higher downstream market price will reduce demand for the intermediate product and thus reduces the integrated firm's profit. Whereas discriminatory actions are specific to vertical integration, infrastructure investment generically remains desirable under vertical separation as well.

This chapter proceeds with the model setup in Section 3.2. Section 3.3 examines competition under vertical integration and the implications for infrastructure in-

[60] Economides (1998) analyzes a monopolist's incentives to discriminate against downstream rivals through degradation of quality. Similarly, the literature on sabotage investigates the incentives of a vertically integrated supplier to "sabotage" the activities of downstream rivals through cost-increases or demand-reduction. Beard et al. (2001) and Mandy and Sappington (2007) show that cost-increasing sabotage is typically profitable for a vertically integrated firm. In contrast, demand-reducing sabotage is often profitable under Cournot competition, but less so under Bertrand competition.

[61] Those effects are usually countervailing and orthogonal to those examined in this chapter. The idea that a vertically integrated firm may use its market power in supplying the input in an anticompetitive way is not new and has been analyzed in the literature on vertical foreclosure. For a survey see Rey and Tirole (2003).

vestment incentives into both, cost-reduction and quality-increases. Section 3.4 then explores a vertically separated infrastructure provider and compares the investment incentives to those under vertical integration. Section 3.5 relates the above incentives to a welfare benchmark. Here, we also discuss implications for policy. Section 3.6 investigates possible consequences of public infrastructure financing and the impossibility to commit to access prices. This section is largely orthogonal and can be read independently of the rest of the chapter. Section 3.7 concludes.

3.2 The Model Setup

We consider an industry that consists of an upstream infrastructure component and a downstream services segment. The infrastructure good is provided by a monopolist, firm I, and is an essential facility that is needed to produce the final product downstream. Downstream firms require one unit of the infrastructure good to produce one unit of the downstream good.[62] The provision of the upstream infrastructure good involves a fixed cost F, which is incurred whenever there is a positive amount of infrastructure provided. In addition, each unit of infrastructure comes at a constant marginal cost of c_I. The upstream industry thus exhibits economies of scale which also justifies why it is provided monopolistically.

The infrastructure provider is bound to supply all units that are demanded at the *regulated*, *linear* access price $p_I \geq c_I$.[63] Regulation is necessary to avoid strong anticompetitive effects due to the monopolistic provision of the infrastructure good. The assumption of linear access prices is crucial for the results of our study but also realistic: the literature on regulation emphasizes that non-linear pricing schemes (e.g. a two-part tariff) have inferior properties with respect to demand risks. Two-part tariffs usually shift the risk on the downstream firms by imposing a fixed charge. This disadvantages smaller and thus financially weaker downstream competitors. The problem is aggravated in network industries where fixed costs represent a particularly large fraction of total infrastructure costs. Also, two-part tariffs lend themselves better to discrimination as traffic-independent and firm-specific payments are more difficult to monitor for regulators. Discrimination favoring the incumbent operator could therefore

[62] For simplicity we normalize the factor of proportionality to one – results generalize to other fixed proportions relationships.

[63] The access price is also non-discriminatory as the same price is charged to any downstream firm, including the affiliate of a potentially integrated firm.

be maintained.[64] Besides considering only linear access prices, we assume that these cannot be conditioned on investments, presuming that infrastructure quality and cost characteristics cannot be contracted upon for reasons of verifiability.[65]

There are n downstream firms, indexed $j \in \{1, ..., n\}$ that offer their services directly to consumers but require the infrastructure as an input. The final product is homogeneous and firms compete in quantities, q_j, à la Cournot. The downstream industry thus captures oligopolistic competition where firms are endowed with some market power.[66] The marginal cost of providing the downstream service is symmetric and normalized to zero so that the only cost that downstream producers incur, stems from buying the infrastructure good at the per unit price p_I. Downstream firms face an inverse demand function $p(Q)$, with $Q = \sum_{j=1}^{n} q_j$. Throughout this chapter, we assume conditions that ensure existence of a quantity $\overline{Q} > 0$ such that $P(Q) > 0$ for all $Q < \overline{Q}$ and $P(Q) = 0$ for all $Q \geqslant \overline{Q}$. To guarantee existence and uniqueness in the Cournot game we make use of the Hahn-Novshek assumptions which are equivalent to assuming that outputs are strategic substitutes.[67] Here, we restrict attention to a linear demand specification for reasons of tractability. Although some results generalize to other types of demand functions, the linear case is needed to derive closed form solutions. This allows us to better illustrate effects at work and to investigate implications for welfare. The linear inverse demand function takes the following simple form:

$$p(Q) = a - bQ \tag{3.1}$$

with $a > p_I$ being the maximum willingness to pay and b being the slope of the inverse demand function which we normalize to $b = 1$.

In our model, investment into infrastructure is undertaken by the owner and can take two distinct forms. First, the infrastructure owner can invest into *cost-reduction*, h, to lower the marginal cost of providing the infrastructure from c_I to $c_I - h$. Second, the infrastructure owner can invest k to *enhance the quality* of infrastructure. This increases consumers' willingness to pay for every unit of the service from a to $a + k$.

[64] In fact, many countries have abolished two-part tariffs as the access pricing scheme for this reason. An example is the German rail sector. By contrast, regulators in the US and Canada have allowed rail infrastructure operators to apply two-part tariffs when charging for access. Compare Pittman (2003) for a discussion.

[65] This is a standard assumption as, for example, in Laffont and Tirole (1993), chapter 4.

[66] This could be modeled similarly within a framework of differentiated goods price or quantity competition. Compare Martin (2002) for a discussion.

[67] Although the assumptions mentioned are not restrictive in basic models, existence cannot be taken for granted (compare e.g. Novshek (1985)).

This type of investment implies a parallel shift out of the demand function. Note that both types of investments are fully equivalent for quantity decisions in a Cournot model without vertical structure.[68] However, the vertical structure causes distinct incentive effects for each investment type: cost-reducing investments accrue directly at the upstream level, affecting the infrastructure provider's cost function. They benefit downstream firms and consumers only indirectly if access prices are adjusted downwards. In contrast, benefits from quality-increasing investments accrue at the downstream level by affecting the demand of the final product.[69] We assume quadratic cost functions for both types of investments where η and κ are the respective marginal cost parameters[70].

Investment Type	Variable	Effect	Cost
Cost-reducing (CR)	h	$h \rightarrow c_I - h$	$\eta/2\, h^2$
Quality-increasing (QI)	k	$k \rightarrow a + k$	$\kappa/2\, k^2$

The time structure of the game is as follows. At stage 1 the regulator chooses and commits to a linear access price p_I that every downstream firm pays for the units of infrastructure demanded. At stage 2, the (upstream) infrastructure owner, firm I, chooses the investment levels into infrastructure, k and h. In the third stage, each downstream firm simultaneously chooses the quantity q_j which determines the total quantity produced, Q. Also, the final goods price, $p(Q)$, and the associated infrastructure demand and profits result in stage 3.

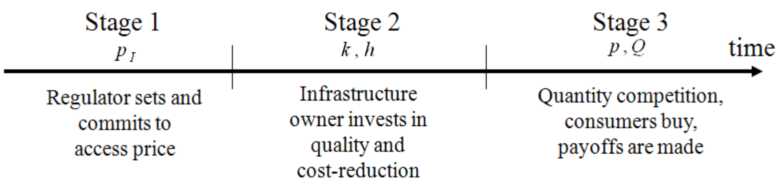

Figure 3.1: Time Structure of the Model

[68] For a simplified graphical illustration see Appendix, Section 3.8.1.

[69] Note further that investments considered here are also different to those considered in the well-known free-riding problem with respect to downstream services, as described in Motta (2004). There, the *downstream* firms invest in quality and since the resulting increase in utility can be appropriated by both, the investor as well as its competitors, underinvestment will obtain. Similarly, investments in our model are also distinct to cost-reducing investments as in d'Aspremont and Jacquemin (1988). Also, we do not model synergies and/or complementarities between up- and downstream investments.

[70] The quadratic cost functions $(C(k), C(h))$ fulfill the desired and realistic properties that $C(h = 0) = 0$, $C(k = 0) = 0$, $C'(h = 0) = 0$, $C'(k = 0) = 0$ and $C''(k) > 0$, $C''(h) > 0$ for $k > 0$, $h > 0$.

In a further step, one could also endogenize the choice of vertical structure by introducing a stage 0 where the government institution decides on implementing either of the vertical structures. In fact, this is the aim of our discussion using comparative statics in Section 3.5. We now proceed by first analyzing the equilibrium under vertical integration (VI). Here, the infrastructure owner, firm I, is also active in the downstream services sector through its downstream *affiliate*, firm i.

3.3 Vertical Integration

3.3.1 Cost-Reducing Investments

At stage 3, there are $n-1$ symmetric competitors and the affiliate of the vertically integrated firm that compete in quantities on the downstream market. The profit maximization problem of the vertically integrated firm is:

$$\pi_I = (p_I - (c_I - h))(Q_{-I} + q_I) + (P(Q) - p_I)q_I - \frac{\eta}{2}h^2 - F \tag{3.2}$$

where Q_{-I} is the total quantity provided but excluding the affiliate's output, $q_i \equiv q_I$. The first term characterizes the access profits when paid in a non-discriminatory way by all downstream firms. The second term constitutes the profits of the downstream affiliate. Note that the access charges for the downstream affiliate of the integrated firm cancel out in the profit function because they are a pure transfer. One can therefore re-write the above profit function as:

$$\pi_I = (p_I - (c_I - h))(Q_{-I}) + (P(Q) - (c_I - h))q_I - \frac{\eta}{2}h^2 - F. \tag{3.3}$$

This formalization shows that the vertically integrated firm faces an effectively lower marginal cost, $(c_I - h)$, of providing the service to consumers. It also reveals that the double marginalization problem is solved for those units that are sold through the downstream affiliate of the vertically integrated firm which improves efficiency. It facilitates recouping the infrastructure costs through access revenues and downstream affiliate's profits. The optimality condition with respect to quantity thus requires[71]:

[71] The FOC reveals that access revenues do not directly affect the best response of the integrated firm. This is intuitively surprising. After all, access revenues obtained through competitors seeking infrastructure access represent a kind of opportunity cost. Combining the FOCs for equilibrium quantities introduces this trade-off indirectly.

$$\frac{\partial \pi_I}{\partial q_I} = (P(Q) - (c_I - h)) + \frac{\partial P(Q)}{\partial q_I} q_I = 0.$$

For the case of linear demand, the best response calculates as:

$$q_I = \frac{a - Q_{-I} - (c_I - h)}{2}. \tag{3.4}$$

A representative firm j of the $n-1$ downstream competitors makes profits:

$$\pi_j = (a - Q - p_I) q_j \ \forall j \neq i.$$

The corresponding FOC after imposing symmetry on rivals is:

$$q_j = \frac{a - q_I - p_I}{n} \ \forall j \neq i. \tag{3.5}$$

Combining equations (3.4) and (3.5) yields the unique Nash equilibrium quantities:

$$\begin{aligned} q_I &= \frac{a + (n-1)p_I - n(c_I - h)}{n+1} \\ q_j &= \frac{a + (c_I - h) - 2p_I}{n+1} \ \forall j \neq i. \end{aligned}$$

The total quantity provided is:

$$Q^{CR,VI} = \frac{an - (n-1)p_I - (c_I - h)}{n+1} \tag{3.6}$$

and is therefore decreasing in the access price p_I.[72] As the access price and the mark-up increase, the affiliate's competitive advantage and its output increase ($\frac{\partial q_I}{\partial p_I} > 0$). However, the competitors downscale ($\frac{\partial q_j}{\partial p_I} < 0$) by more and thus total output decreases. Stronger downstream competition, n, in contrast, increases total quantity.[73] The

[72] This also implies that an inefficient (lax) regulator that allows a "too high" access price causes to "too low" quantities. If there were differences in efficiency of regulation under vertical integration and vertical separation, this would impact our comparison. We assume those effects are absent.

[73] Quantity also decreases in marginal costs. It is a feature of the Cournot model that total quantity depends only on the sum of marginal costs.

associated equilibrium market price is:

$$p^{CR,VI} = \frac{a + (c_I - h) + (n-1)p_I}{n+1} \tag{3.7}$$

and is increasing in marginal costs but decreasing in the amount of investment in cost-reduction, h, and the intensity of competition downstream, n.[74]

At stage 2, the vertically integrated infrastructure provider decides on investment into cost-reduction. The firm anticipates downstream demand and takes the access price as given. The presence of the affiliate in the downstream market has important implications for competition but also for investment incentives. The profit of the infrastructure provider can be decomposed into an upstream profit contribution, a downstream profit contribution and a cost component which jointly drive the incentives to invest into cost-reduction:

$$\pi_I = \underbrace{(p_I - (c_I - h))(Q_{-I} + q_I)}_{\text{upstream profit contribution}} + \underbrace{(p^{CR,VI} - p_I)q_I}_{\text{downstream profit contribution}} \underbrace{- \frac{\eta}{2}h^2 - F}_{\text{cost term}}.$$

Re-writing illustrates that the effective marginal cost of the affiliate is given by $c_I - h$:

$$\pi_I = (p_I - (c_I - h))(Q_{-I}) + (p^{CR,VI} - (c_I - h))q_I - \frac{\eta}{2}h^2 - F.$$

The first order condition shows that investment incentives into cost-reduction under vertical integration are made up of the following four effects:

$$\begin{aligned}\frac{\partial \pi_I}{\partial h} \quad = \quad & \underbrace{(Q_{-I}^{CR,VI})}_{\text{rivals' access margin effect}} + \underbrace{(p_I - (c_I - h))(\frac{\partial Q_{-I}}{\partial h})}_{\text{rivals' access quantity effect}} \\ & + \underbrace{(\frac{\partial p^{CR,VI}}{\partial Q}\frac{\partial Q}{\partial h} + 1)q_I}_{\text{affiliate margin effect}} + \underbrace{(p^{CR,VI} - (c_I - h))\frac{\partial q_I}{\partial h}}_{\text{affiliate quantity effect}} - \eta h.\end{aligned} \tag{3.8}$$

- *rivals' access margin effect:* An increase in cost-reducing investments, increases the effective access margin per unit of output that the infrastructure owner re-

[74] As we assume away any downstream fixed costs of production or other scale economies, there are no economic costs of increasing the number of competitors downstream.

ceives from its rivals. Revenues from investment into cost-reduction are larger, the larger is this downstream demand, $Q_{-I}^{CR,VI}$.

- *rivals' access quantity effect:* Cost-reducing investments do not directly affect the cost function of downstream rivals and their supplied quantity. The rivals' marginal cost p_I is exogenous to changes in costs of infrastructure provision as long as the access price cannot be conditioned on investments. However, there is an indirect, strategic effect through competition. An increase in cost-reducing investments lowers the affiliate's effective marginal cost and therefore alters not only the optimal quantity of the affiliate but also – through strategic interaction – the quantity offered by rivals. This effect is negative as upstream revenues from access fall through the shift in production.

- *affiliate margin effect:* The third effect examines the overall impact on the mark-up of the affiliate. There are two effects: The price effect which is always negative – the lower marginal cost reduces the market price through an increase in total quantity provided. However, there is a second effect. Investments also reduce the marginal cost of the downstream affiliate which then tends to increase the downstream mark-up of the affiliate. Hence, the overall effect depends on the relative size of the two effects. The first effect is generically larger. For linear demand, for example, the affiliate margin effect is: $-\frac{1}{n+1} + 1 > 0$.

- *affiliate quantity effect:* An increase in cost-reducing investments also increases the quantity supplied by the downstream affiliate as its effective marginal cost is lowered. The increased output implies higher profits as not only the quantity supplied increases but also the margin the affiliate receives on every unit (compare *affiliate margin effect*). This fourth effect is hence unambiguously positive.

When considering how much to invest, the vertically integrated firm trades off the effects stemming from both, access and downstream profit contributions. A cost-reducing investment increases the affiliate's downstream revenues as the competitive advantage over the rivals increases (the *affiliate quantity* and *affiliate margin effects*). Not only the affiliate's output increases but also the total quantity provided to consumers. On the upstream component, investments also cause a negative effect, the rivals' *access quantity effect.* Due to the weakened position of the competitors they supply less of the final product and also demand less of the infrastructure good. This effect is countervailed as the rivals' *access margin* increases with investments for all units of infrastructure sold to competitors. If the regulated access price cannot be made contingent on these investments, the benefits of investments in cost-reduction are specific to the integrated firm and do, in fact, harm competitors through more competitive pressure from the affiliate.[75] In sum, cost-reducing investments increase total supply, result in lower prices for consumers and thus boost efficiency.

For the reference case of linear demand, we obtain the following profit-maximizing level of cost-reducing investments:

$$h^{CR,VI} = \frac{(n+1)^2(a-p_I) - 2(a+c_I-2p_I)}{(n+1)^2\eta - 2}$$

Note that the SOC is fulfilled if $\eta > \frac{2}{(n+1)^2}$ which also guarantees that the denominator of the above expression is positive.[76] The comparative statics of interest are with respect to the access price p_I and the intensity of downstream competition, n. We derive the following expression:

$$\frac{\partial h^{CR,VI}}{\partial p_I} = -\frac{(n+1)^2 - 4}{(n+1)^2\eta - 2} < 0.$$

Corollary 3.1 *Under vertical integration and with linear demand, optimal cost-reducing investments are decreasing in the access price.*

Proof. See Appendix, Section 3.8.3. ■

The intuition for this result is two-fold. On the one hand, the increase in the access price makes competitors less efficient. Consequently, the downstream affiliate gains market share. This implies, however, that cost-reducing investments are less effective at winning additional downstream sales through investments. Moreover, the demand for access to infrastructure decreases as the downstream competitors produce less. Thus, incentive effects through access revenues are also dampened, decreasing the incentives to invest into cost-reduction.

We now examine the comparative statics with respect to the intensity of downstream competition:

[75] In this respect, cost-reducing investments cause similar relative competitive changes as cost-increasing sabotage. However, whereas the investments into cost-reduction increase efficiency through an effectively lower marginal cost on the sales through the affiliate, cost-increasing sabotage increases the costs of all rivals, harming efficiency. With respect to upstream revenues, both forms of intervention by the upstream firm cause a decrease in access demand of rivals.

[76] We further require that cost-reducing investments are not larger than *ex ante* marginal costs $(c_I - h) \geq 0$ for effective marginal costs to remain non-negative: $\eta > \frac{(a-p_I)(n+1)^2 - 2(a-2p_I)}{c_I(n+1)^2}$.

$$\frac{\partial h^{CR,VI}}{\partial n} = 4\frac{(n+1)\left(p_I - a + \eta(a + c_I - 2p_I)\right)}{\left(\eta(n+1)^2 - 2\right)^2} > 0.$$

Corollary 3.2 *Under vertical integration and with linear demand, cost-reducing investments are increasing in the intensity of downstream competition, n.*

Proof. See Appendix, Section 3.8.3. ■

A higher number of downstream competitors reduces the margin of these firms, increases total output and thus results in higher demand for infrastructure. As cost-reducing investments increase the margin on these, investment becomes more desirable. Also, as downstream competition becomes fiercer and tends to erode the affiliate's market share, cost-reducing investments can re-establish a cost-difference between the affiliate and the symmetric competition downstream. Moreover, they increase access revenues as the access price remains unchanged.[77]

We now turn to stage 1 in which the regulator sets the welfare-optimal access price. The sustainability of the industry structure requires a positive access margin to cover any upstream fixed and investment costs and therefore inevitably introduces competitive distortions. Only if the regulator were to set an access price p_I that reflects the true marginal cost of infrastructure provision, $p_I = (c_I - h)$, competitive distortions could be avoided.[78] However, as the access price cannot be contracted upon investment this is not feasible.[79] Neither would this access price be able to recoup the fixed costs. Although the distortion is socially undesirable, it cannot be avoided here if there are no other sources of financing the costs associated with infrastructure provision.

With investment incentives into cost-reduction decreasing in the access price and competitive distortions increasing, intuition suggests that the regulator should seek to keep the access price at the lowest level feasible. When the objective function is social welfare, this lowest value is mainly pinned down by the size of upstream fixed costs that need to be recouped to allow the integrated infrastructure provider to earn his reservation profit.[80] The social welfare measure for an access price p_I is given by the sum of producer and consumer surplus:

[77] The proof of the above corollary relies on the condition that $\eta > \frac{a-p_I}{a+c_I-2p_I}$. This condition must hold in equilibrium as it ensures that competitors' profits are non-negative. It establishes a bound on the effectiveness of investments. If investments were cheaper, the vertically integrated firm could use them to drive competitors off the market. Note that this condition is not fully exogenous. The regulator can influence the range of parameters for competitors being profitable.

[78] Downstream firms would then be fully symmetric.

[79] We assume that the lowest access price that can be set is marginal cost c_I.

[80] For the reservation profit there are two conceivable benchmarks. The first is given by a zero-profit condition. This would be the relevant benchmark if the infrastructure provider was (for historical

$$
\begin{aligned}
W^{CR,VI} &= CS + \pi_I + (n-1)\pi_j \\
W^{CR,VI} &= \frac{\left((n-1)(a-p_I) + \eta (n+1)(n(a-p_I) + p_I - c_I)\right)^2}{2\left(\eta (n+1)^2 - 2\right)^2} \\
&+ \frac{(a-p_I)^2 (n^2+2n-3) + 2\eta((a+c_I-2p_I)^2 + (n+1)^2 (p_I - c_I)(a-p_I))}{2\left(\eta (n+1)^2 - 2\right)} \\
&- F + (n-1)(n+1)^2 \frac{(-a+p_I+\eta(a+c_I-2p_I))^2}{\left(\eta (n+1)^2 - 2\right)^2}.
\end{aligned}
$$

Proposition 3.1 *Under vertical integration with cost-reducing investments and linear demand, welfare is falling in the access price (if $p_I \geqslant c_I$). Thus, a welfare maximizing regulator chooses the smallest mark-up and access price that guarantees the vertically integrated firm its reservation profits.*

Proof. See Appendix, Section 3.8.3. ■

The proof also reveals that the individual welfare components depict intuitive comparative statics. The integrated firm's profit is generically increasing in the access price and competitors' profits and consumer surplus falling in the access price.[81] The above proposition urges the regulator to choose a low access price as this is not only important for the competitive efficiency of the vertical structure but also for investment incentives into cost-reduction. The proposition thus reveals that there is no trade-off between allocative and productive efficiency for cost-reducing investments. This is particularly important when costs of the associated investments are rather low, i.e. when η is small. In such an industry where cost-reducing investments into infrastructure are cheap, i.e. an industry that is affine to cost-reduction, and where these are important for its efficiency, the regulator should be especially cautious not to increase the access price excessively.

reasons) an incumbent provider and if there was no competition about who would be in charge of running the infrastructure. The second feasible benchmark is the profit of the downstream competitors. This would be relevant if there was a prior stage where firms could bid for being charged with the infrastructure provision; we go with the second idea.

[81] The condition that guarantees that the profits of the vertically integrated firm are not increasing in the access price, p_I, is again given by the non-negativity condition for rivals' profits. Thus, it can never be the case that investments in cost-reduction are so cheap that they overrule the effect of an increase in access price on the profit of the vertically integrated firm.

3.3.2 Quality-Increasing Investments

We now examine the incentives of a vertically integrated firm to invest into quality-enhancing technology for its infrastructure. We proceed along the lines of Section 3.3.1.

The profit function of the vertically integrated firm now takes the following form for the general inverse demand function $P(k, Q)$:

$$\pi_I = (p_I - c_I)(Q_{-I} + q_I) + (P(k, Q) - p_I)q_I - \frac{\kappa}{2}k^2 - F.$$

In contrast to cost-reducing investments which affect the cost function of the infrastructure provider, quality-enhancing investments into infrastructure affect the demand by increasing the willingness to pay of consumers for a unit of the good or service. As the access charges cannot be made contingent upon the amount invested into quality, the impact of investment emerges mainly at the downstream level. However, there are add-on effects for infrastructure demand. We re-write the above profit function as:

$$\pi_I = (p_I - c_I)(Q_{-I}) + (P(k, Q) - c_I)q_I - \frac{\kappa}{2}k^2 - F.$$

The effective marginal cost of the downstream affiliate now remains equal to the cost of infrastructure provision, c_I. Thus, quality-increasing investments do not translate into a competitive advantage at the downstream level. The first order condition is then given by:

$$\frac{\partial \pi_I}{\partial q_I} = (P(k, Q) - c_I) + \frac{\partial P(k, Q)}{\partial q_I} = 0.$$

Solving the FOC for the case of linear demand yields the following best response function:

$$q_I = \frac{a + k - c_I - (n-1)q_j}{2}. \tag{3.9}$$

A representative firm j out of the $n - 1$ downstream competitors makes profits of:

$$\pi_j = (a + k - Q - p_I)q_j \ \forall j \neq i.$$

Maximizing and imposing symmetry gives the corresponding best response:

$$q_j = \frac{a + k - p_I - q_I}{n} \ \forall j \neq i. \tag{3.10}$$

Combining equations (3.9) and (3.10) yields the unique Nash equilibrium output levels in terms of quality-increasing investments k:

$$\begin{aligned} q_I &= \frac{a + k + (n-1)p_I - nc_I}{n+1} \\ q_j &= \frac{a + k + c_I - 2p_I}{n+1} \ \forall j \neq i. \end{aligned}$$

Under quality-increasing investments all firms increase the quantity supplied to consumers in response to the quality-increase by the same amount, $\frac{k}{n+1}$. The investor is not able to exclude its rivals from benefiting from the quality-increasing investments. As all firms expand their output with higher investment into quality-increases, also the total quantity supplied unambiguously increases – as under cost-reducing investments. The total quantity supplied is given by:

$$Q^{QI,VI} = \frac{(a+k)n - (n-1)p_I - c_I}{n+1}.$$

The total quantity offered also increases in the intensity of downstream competition, n, and decreases in the sum of marginal costs for downstream firms – like under cost-reducing investments. In contrast to the market price under cost-reducing investments, which was decreasing in the amount of infrastructure investment, the market price under quality-increasing investments is – *ceteris paribus* – increasing in investments:

$$p^{QI,VI} = \frac{a + k + c_I + (n-1)p_I}{n+1}.$$

It is important to record that consumers do not only face higher prices but also get a higher quality of what they buy. This is in line with the results of a simple, non-vertical, competition model with cost-reducing and quality-increasing investments as illustrated in Section 3.8.1 of the Appendix. In fact, the quality increase causes more consumers to buy the good or service even though the price is higher compared to the case without investments: $Q^{QI,VI}(k > 0) > Q^{QI,VI}(k = 0)$. Consumer surplus increases for the same reason when positive quality investments are undertaken.

At stage 2, the vertically integrated infrastructure provider determines how much to invest into the quality of the infrastructure. In contrast to cost-reducing investments, the benefits of quality-increasing investments into infrastructure are not firm-specific to the investor but trigger a shift out of the demand function faced by all firms.[82] As the gains arise in the downstream sector, the benefits from investment can only be reaped indirectly by the investor or through the downstream subsidiary. Competitors free-ride on the investment of the vertically integrated firm.

As before, the profit of the infrastructure provider can be decomposed into the upstream profit contribution, the downstream profit contribution and a cost component:

$$\begin{aligned}
\pi_I &= \underbrace{(p_I - c_I)(Q_{-I} + q_I)}_{\text{upstream profit contribution}} + \underbrace{(p^{QI,VI} - p_I)q_I}_{\text{downstream profit contribution}} \underbrace{- \frac{\kappa}{2}k^2 - F}_{\text{cost term}} \\
\pi_I &= (p_I - c_I)(Q_{-I}(k)) + (p^{QI,VI}(k) - c_I)q_I(k) - \frac{\kappa}{2}k^2 - F.
\end{aligned}$$

The general first order condition shows that investment incentives under vertical integration consist of three distinct components:

$$\frac{\partial \pi_I}{\partial k} = \underbrace{(p_I - c_I)\frac{\partial Q_{-I}(k)}{\partial k}}_{\text{rivals' access quantity effect}} \tag{3.11}$$

$$+\underbrace{\frac{\partial p^{QI,VI}(k)}{\partial k}q_I(k)}_{\text{affiliate margin effect}} + \underbrace{(p^{QI,VI}(k) - c_I)\frac{\partial q_I(k)}{\partial k}}_{\text{affiliate quantity effect}} - \kappa k. \tag{3.12}$$

The following can be said about the direction and intuition of these effects:

- *rivals' access quantity effect:* The higher quality induces higher output of competitors which in turn increases the total demand for access to infrastructure. This effect considers only the impact on profits through higher output supplied by competitors downstream. Increased revenues are made up of increased access

[82] Thus, effects of quality-enhancing investment are distinct to those from quality-decreasing sabotage. There, the literature assumes that the worsened quality is specific to rivals. It thus gives the acting firm a relative quality advantage. Under quality-enhancing investments a similar relative advantage may also be introduced by a regulator if he distorts downstream competition by increasing the access price over marginal cost. In so far as this is necessary to make the infrastructure quality provision sustainable, it is again the vertically integrated firm that benefits more.

units ($\frac{\partial Q_{-I}(k)}{\partial k}$) that each contribute the access margin. However, this effect vanishes if the regulator sets an access charge equal to marginal cost. For a positive access margin, the effect is positive.

- *affiliate margin effect:* The market price also increases in response to investments in quality along with the consumers' willingness to pay. This effect increases revenues for every unit sold through the downstream affiliate of the vertically integrated firm. The infrastructure investor only considers the effect on own profits and not on the rivals. Nevertheless, this effect is positive and remains so even for a zero access margin.

- *affiliate quantity effect:* This last term examines the effect of an increased quality on the affiliate's output. It is thus similar to the first term, however, it carries a higher "weight". While every other firm contributes the margin of $(p_I - c_I)$ for every unit produced downstream (through access revenues), the affiliate sells at the higher margin of $(p^{QI,VI}(k) - c_I)$. Note also that the market price the affiliate receives on every unit rises with increased quality investments as well. Thus, the third effect is positive as well.

Let us illustrate the combined effects using the linear demand function. The profit-maximizing level of quality-increasing investments is given by:

$$k^{QI,VI} = \frac{(p_I - c_I)(n+1)^2 + 2(a + c_I - 2p_I)}{\kappa (n+1)^2 - 2}.$$

Note that the SOC is fulfilled if $\kappa > \frac{2}{(n+1)^2}$.[83] The SOC thus also guarantees non-negativity of investments. In fact, there will always be positive investments into quality, even if the access price equals marginal cost, i.e. $p_I = c_I$. The reason is the presence of the affiliate in the downstream market. The *affiliate quantity* and *affiliate margin effect* remain positive even when there are no access revenues to be made. However, the effects can become rather small when the intensity of downstream competition increases. With a positive access margin and a higher access price, the rivals' *access quantity effect* increases investments further.

Examining the comparative statics properties of quality-increasing investments with respect to access price and intensity of downstream competition, we find that both,

[83] If $\kappa < \frac{2}{(n+1)^2}$ a quality-escalation strategy of the vertically integrated firm is profitable and profits are maximized for infinite investments. We therefore restrict attention to $\kappa > \frac{2}{(n+1)^2}$.

the marginal profitability of quality-increasing investments and also the optimal level of investments, increase in the regulated access price p_I.[84] The above hypothesis is confirmed analytically:

$$\frac{\partial k^{QI,VI}}{\partial p_I} = \frac{(n+1)^2 - 4}{\kappa(n+1)^2 - 2} > 0.$$

Corollary 3.3 *Under vertical integration and with linear demand, quality-enhancing investments are increasing in the regulatory access price p_I.*

Proof. See Appendix, Section 3.8.3. ■

The infrastructure investor trades off the above mentioned positive effects against the costs of investment. An increased access margin implies a stronger rivals' *access quantity effect*. Although the quantity of competitors decreases in the access price, this is more than outweighed by the increase in the access margin (at least for small access margins $p_I - c_I$). At the same time, the market share of the downstream affiliate increases which implies that more of the benefits from investment go directly to the vertically integrated firm and consequently the firm will invest more (the *affiliate quantity effect*). With a high number of competitors, the rivals' *access quantity effect* is the main driver for investments. For a given intensity of competition, n, a higher access price improves the competitive position of the affiliate on the downstream market which dampens free-riding effects and boosts investments further.

Corollary 3.4 *Under vertical integration and with linear demand, quality-increasing investments are decreasing in the intensity of downstream competition, n.*

Proof. See Appendix, Section 3.8.3. ■

$$\frac{\partial k^{QI,VI}}{\partial n} = -4\frac{(n+1)\left(p_I - c_I + \kappa(a + c_I - 2p_I)\right)}{\left(\kappa(n+1)^2 - 2\right)^2} < 0$$

With more intense competition downstream, the affiliate profits less from any investment into quality-increases. The contribution of both, the *affiliate margin* and the *affiliate quantity effect* are marginalized with fierce downstream competition, i.e. with large n. The effect of increased upstream infrastructure demand due to stronger

[84] This result holds for all values of the access prices up to the independent (upstream) monopoly price $p_I = \frac{a+c_I}{2}$ at which competitors would no longer produce positive output levels ($Q_{-I} = 0$).

competition cannot overrule the weakened incentives due to fiercer competition that reduce investment incentives as the downstream margins shrink.[85]

The effect of changes in the access price on welfare is not readily determined. On the one hand, investments into quality-increases are enhanced with a higher access price which improves welfare. On the other hand, a higher access price causes double marginalization and the resulting competitive distortions lower welfare.[86] We can understand the overall effect by exploring the social welfare function:

$$
\begin{aligned}
W^{QI,VI} &= CS + \pi_I + (n-1)\pi_j \\
W^{QI,VI} &= \frac{\left((n+2)(n-1)(p_I - c_I) + \kappa(n+1)(n(a-p_I) + p_I - c_I)\right)^2}{2\left(\kappa(n+1)^2 - 2\right)^2} \\
&\quad + \frac{(p_I - c_I)^2 (n+3)(n-1) + 2\kappa((a + c_I - 2p_I)^2 + (n+1)^2 (p_I - c_I)(a - p_I))}{2(\kappa(n+1)^2 - 2)} \\
&\quad - F + (n-1)(n+1)^2 \frac{(p_I - c_I + \kappa(a + c_I - 2p_I))^2}{\left(\kappa(n+1)^2 - 2\right)^2}.
\end{aligned}
$$

Proposition 3.2 *Under vertical integration with quality-increasing investments and linear demand, welfare may be increasing in the access price (if $p_I > c_I$). Thus, a welfare maximizing regulator may choose a mark-up over marginal cost even if this is not required to meet reservation profits of the integrated firm.*

Proof. See Appendix, Section 3.8.3. ■

Corollary 3.5 *Under vertical integration with quality-increasing investments, consumer surplus may be increasing in the access price (if $p_I > c_I$). Thus, a regulator that maximizes consumer surplus may choose a positive mark-up over marginal cost even if this is not required to meet reservation profits of the integrated firm.*

Proof. See Appendix, Section 3.8.3. ■

[85] Note that the comparative statics with respect to access price and number of competitors have important joint implications for policy. A decrease in the regulated access price reduces quality investments *per se* (as shown). In addition, lower access prices would cause more entry if entry was endogenous (because profits to be gained are higher). More intense competition would then reinforce the above effect, weakening investment incentives further.

[86] In fact, by setting the access price to $p_I = c_I$, the regulator can ensure competition on equal grounds and mitigate the double marginalization problem fully. However, as fixed costs need to be recouped this will generically not be sustainable.

The intuition for the above results is straightforward. Increases in the access prices may be undesirable under quite general conditions and without investments into quality as they distort downstream competition and raise downstream prices that consumers pay. However, with quality-increasing investments, higher access prices also stimulate quality investments. Thus, although consumers suffer from increased downstream prices, this is countervailed by an increase in the quality of the infrastructure and the service that consumers get. In fact, even though the price of the intermediate input is increased (the access price), which in turn increases downstream prices, consumers are better off due to investments. Therefore, positive access margins may be socially desirable in an environment where quality-increasing investments are important for efficiency (e.g. if they are relatively cheap, i.e. if κ is small enough). Of course, this is important for policy and we will discuss consequences in Section 3.5.

3.4 Vertical Separation

We now investigate the performance of a vertically separated industry structure (VS) and compare it against the vertically integrated structure examined in Section 3.3. Here, the infrastructure provider invests but is independent and therefore not active on the downstream market. Under vertical separation, we assume that the infrastructure owner finances investment and infrastructure costs through access revenues only.

3.4.1 Cost-Reducing Investments

At stage 3, n symmetric firms compete downstream in quantities taking the investment decision, h, and the access price, p_I, as given. All downstream firms face symmetric profit maximization problems of the form:

$$\pi_j = (P(Q) - p_I)q_j.$$

The first order condition for a profit maximum requires

$$\frac{\partial \pi_j}{\partial q_j} = (p(Q) - p_I) + \frac{\partial p}{\partial Q} q_j = 0.$$

There exists a unique Nash equilibrium in which each downstream firm produces a quantity of $q_j^{CR,VS}$ and total output is given by $Q = n \cdot q_j^{CR,VS}$. In the case of linear demand (see equation (3.1)), we find the symmetric Cournot quantities of:

$$q_j^{CR,VS} = \frac{a - p_I}{n+1}.$$

The total quantity provided is thus $Q^{CR,VS} = n \cdot \frac{a-p_I}{n+1}$ and the market price is given by:

$$p^{CR,VS} = \frac{a + np_I}{n+1}.$$

Cost-reducing investments do not impact downstream competition as long as the access price cannot be conditioned on h. Clearly, an increase in the access price is equivalent to an increase in marginal costs and hence decreases total output and increases the market price. In contrast, an increase in the number of downstream competitors, n, increases total output and lowers downstream mark-ups and the market price. Note that compared to total quantity and market price under vertical integration (equations (3.6) and (3.7)) the market price is weakly higher under vertical separation and the quantity weakly lower for any given access price p_I. This is simply because of the better efficiency properties of vertical integration which avoids some of the double marginalization. For this reason also the access price needed to recover fixed costs upstream is higher under vertical separation.

At stage 2 of the game, the upstream infrastructure provider chooses how much to invest into cost-reduction. It takes the access price p_I as given and anticipates the above demand for stage 3. The upstream infrastructure provider maximizes:

$$\pi_I = (p_I - (c_I - h))Q^{CR,VS} - \frac{\eta}{2}h^2 - F.$$

where under linear demand $Q^{CR,VS} = n \cdot \frac{a-p_I}{n+1}$. The FOC yields the following optimality condition:

$$\frac{\partial \pi_I}{\partial h} = Q^{CR,VS} - \eta h = 0. \tag{3.13}$$

- *access margin effect:* Cost-reducing investments increase the margin on every unit sold. The infrastructure provider raises revenues per unit of output by h on $Q^{CR,VS}$ units. The more units are sold downstream, i.e. the larger $Q^{CR,VS}$, the more investments into cost-reduction pay off. Note that there is one difference to the effect under vertical integration. Whereas here, the infrastructure investor considers the output of all downstream firms and weights them equally, the effect is weighted differently under vertical integration due to the presence of the affiliate in the downstream market. Under vertical integration the corresponding counterpart is the first term in equation (3.8).

Thus, under vertical separation, the infrastructure provider's incentives to invest in cost-reduction stem solely from an increased margin. Note that there is no additional effect of h influencing the actual total quantity produced ($\frac{\partial Q^{CR,VS}}{\partial h} = 0$) as the access price is set by a regulator and it is set independently of the effective marginal cost resulting from cost-reducing investment.

For linear demand, the profit-maximizing level of cost-reducing investments is:

$$h^{CR,VS} = \frac{n}{n+1} \cdot \frac{a - p_I}{\eta}.$$

The SOC is thus fulfilled for any $\eta > 0$.[87] The comparative statics properties of cost-reducing investments are similar to those under vertical integration:

$$\frac{\partial h^{CR,VS}}{\partial p_I} = -\frac{n}{\eta\,(n+1)} < 0.$$

Corollary 3.6 *Under vertical separation and with linear demand investments into cost-reduction also decrease in the regulatory access price, p_I.*

Proof. See Appendix, Section 3.8.3. ■

The intuition works through the *access margin effect.*[88] The strength of this effect depends only on the quantity demanded downstream. Thus, a decrease in the access price spurs demand downstream and also the demand for infrastructure. Cost-reducing investments thus exhibit a greater benefit when downstream demand is strong. This is also the intuition behind the comparative statics of cost-reducing investments with respect to intensity of competition downstream:

$$\frac{\partial h^{CR,VS}}{\partial n} = \frac{a - p_I}{\eta\,(n+1)^2} > 0.$$

[87] To ensure that cost-reducing investments do not surpass marginal costs c_I, we further need $\eta > \frac{n}{n+1}\frac{a-p_I}{c_I}$.

[88] Because the *access margin effect* stems solely from the positive downstream demand, the above proposition holds for general demand functions that are not a function of h itself.

Corollary 3.7 *Under vertical separation and with linear demand investments into cost-reduction also increase in the intensity of downstream competition, n.*

Proof. See Appendix, Section 3.8.3. ∎

Although comparative statics are qualitatively the same as under vertical integration, they differ quantitatively. Some of the effects under vertical integration (equation (3.8)) are absent under vertical separation.[89] Comparing the investment incentives into cost-reduction under vertical separation with those under vertical integration, we find:

Proposition 3.3 *Infrastructure investment incentives for cost-reduction are stronger under vertical integration than under vertical separation for any access price, p_I, when demand is linear.*

Proof. See Appendix, Section 3.8.3. ∎

Whereas the investment incentives under vertical separation are solely due to the *access margin effect* there are additional effects boosting the investment into cost-reduction under vertical integration. Specifically, cost-reducing investments improve the competitive position of the downstream affiliate under vertical integration. Furthermore, an additional effect under vertical integration arises through avoiding double marginalization which increases total output. Overall, investments into cost-reduction are hence lower under vertical separation.

The regulator chooses the access price to maximize the following total welfare expression:

$$W^{CR,VS} = \frac{n\,(a-p_I)}{2} \cdot \frac{2\eta(a-c_I) + n(a-p_I) + n\eta(a+p_I-2c_I)}{\eta\,(n+1)^2} - F.$$

Proposition 3.4 *Under vertical separation with cost-reducing investments and linear demand, welfare is falling in the access price (if $p_I \geqslant c_I$). Thus, a welfare maximizing regulator which can commit to access prices chooses the smallest mark-up and access price that guarantees the infrastructure provider its reservation profits.*

Proof. See Appendix, Section 3.8.3. ∎

[89] In particular, investments in cost-reduction decrease less with an increase in the access price under vertical separation as compared to vertical integration.

An increase in the access price is again socially undesirable for two reasons: it increases the competitive distortion as the associated mark-up over marginal cost causes double marginalization. In addition, it also lowers investment incentives into cost-reduction. The regulator thus faces no trade-off in the case of cost-reducing investments as both, the investment incentives and efficient production are stimulated through an access price that is the lowest feasible. The regulator must only guarantee the sustainability of infrastructure provision.[90]

3.4.2 Quality-Increasing Investments

We proceed analogously to the previous subsection to investigate the incentives for quality-increasing investments under vertical separation. At stage 3, the symmetric downstream firms compete in quantities, taking investments, k, and the access price, p_I, as given.

$$\pi_j = (p(Q,k) - p_I)q_j$$

The first order condition for a profit maximum requires:

$$\frac{\partial \pi_j}{\partial q_j} = (p(k,Q) - p_I) + \frac{\partial p}{\partial Q} q_j = 0.$$

In the unique Nash equilibrium each downstream firm produces a quantity of $q_j^{QI,VS}$ and total output is given by $Q^{QI,VS} = n \cdot q_j^{QI,VS}$. An increase in the access price decreases total output and increases the market price. However, an increase in the number of downstream competitors, n, increases total output and lowers downstream mark-ups and the market price. In the case of linear demand we find:

$$q_j^{QI,VS} = \frac{a + k - p_I}{n+1}.$$

Downstream demand thus depends directly on the investments of the infrastructure provider. The total quantity is given by $Q^{QI,VS} = n\frac{a+k-p_I}{n+1}$ and the market price is $p^{QI,VS} = \frac{a+k+np_I}{n+1}$.

[90] For the infrastructure provider's profit to be non-decreasing in the access price we again require investments to be sufficiently costly, i.e. $\eta > \frac{n(a-p_I)}{(n+1)(a+c_I-2p_I)}$.

At stage 2 of the game, the upstream infrastructure provider chooses how much to invest in quality-enhancing technology taking the access price p_I as given.

$$\pi_I = (p_I - c_I)Q^{QI,VS} - \frac{\kappa}{2}k^2 - F$$

where $Q^{QI,VS} = n \cdot \frac{a+k-p_I}{n+1}$ in case of linear demand. For optimality the FOC requires:

$$\frac{\partial \pi_I}{\partial k} = (p_I - c_I)\frac{\partial Q^{QI,VS}}{\partial k} - \kappa k = 0. \tag{3.14}$$

Thus, under vertical separation, the infrastructure provider only invests if there is a positive access margin that allows the investments to be recouped. The investment incentives in quality-increases arise solely due to the following effect:

- *access quantity effect:* the infrastructure provider invests because – for a given positive access margin – quality-enhancing investments lead to an expansion of downstream quantity which, in turn, increases access demand. This effect corresponds to the joint quantity effects on affiliate and downstream firms under vertical integration (compare equation (3.11)). However, under vertical integration the effect working through competitors and affiliate had different weights, i.e. margins, attached.

Again, quality-enhancing investments benefit all downstream competitors through higher prices. However, the investor cannot participate in these benefits as the access price does not respond to investments. Thus, effects that stimulated additional investments through an increase in the margin downstream under vertical integration are no longer present here.

For linear demand, the profit-maximizing level of quality-enhancing investments is:

$$k^{QI,VS} = \frac{n(p_I - c_I)}{\kappa(n+1)}.$$

Note that the SOC is fulfilled for any $\kappa > 0$ which also guarantees that investments are not negative. The comparative statics with respect to the access price correspond – in direction – to those under vertical integration:

$$\frac{\partial k^{QI,VS}}{\partial p_I} = \frac{n}{\kappa\,(n+1)} > 0.$$

Corollary 3.8 *Under vertical separation and with linear demand, quality-increasing investments also increase in the regulatory access price, p_I.*

Proof. See Appendix, Section 3.8.3. ■

The above effect is, however, stronger under vertical integration. Thus, for every marginal increase in the access price, investments in quality-enhancing technology increase more under vertical integration than under vertical separation. In contrast to quality investments under vertical integration, investments increase in the intensity of downstream competition under vertical separation:

$$\frac{\partial k^{QI,VS}}{\partial n} = \frac{p_I - c_I}{\kappa (n+1)^2} > 0.$$

Corollary 3.9 *Under vertical separation and with linear demand, quality-increasing investments increase in the intensity of downstream competition, n.*

Proof. See Appendix, Section 3.8.3. ■

Under vertical separation, incentives to invest in quality of infrastructure are stimulated solely because of the *access quantity effect* which is enhanced by stronger downstream competition. In contrast, the incentives to invest in quality under vertical integration arise primarily from the impact on the affiliate's profit. This causes comparative statics to be diametrically opposed.

Overall, infrastructure investment incentives, also into quality, are weaker under vertical separation than under vertical separation:

$$k^{QI,VI} = \frac{(p_I - c_I)(n+1)^2 + 2(a + c_I - 2p_I)}{\kappa (n+1)^2 - 2} > \frac{n(p_I - c_I)}{\kappa(n+1)} = k^{QI,VS}.$$

Proposition 3.5 *Infrastructure investment incentives for quality-increases are stronger under vertical integration than under vertical separation for any given access price p_I, when demand is linear.*

Proof. See Appendix, Section 3.8.3. ■

Thus, as long as the downstream market under vertical integration is not perfectly competitive, investment incentives are stronger under vertical integration.

In stage 1, the regulator commits to an access price that maximizes the sum of producer and consumer surplus. The welfare measure is:

$$\begin{aligned} W^{QI,VS} &= \frac{n\,(p_I - c_I)}{2} \frac{n(p_I - c_I) + 2\kappa(n+1)(a - p_I)}{\kappa\,(n+1)^2} \\ &+ \frac{n^2 + 2n}{2} \left(\frac{n(p_I - c_I) + \kappa(n+1)(a - p_I)}{\kappa\,(n+1)^2}\right)^2 - F. \end{aligned}$$

Proposition 3.6 *Under vertical separation with quality-increasing investments, welfare may be increasing in the access price (if $p_I > c_I$). Thus, a welfare maximizing regulator may choose a mark-up over marginal cost even if this is not required to meet reservation profits of the infrastructure provider.*

Proof. See Appendix, Section 3.8.3. ■

The intuition for the result is similar to that under vertical integration. Whereas the regulator wants to keep competitive distortions to a minimum by setting a low access price, a higher access price stimulates investments into infrastructure quality. Therefore, it may be socially desirable – if investments are cheap enough – to actually increase the access price. An equivalent result holds for consumer surplus.

3.5 Welfare and Policy Implications

The above considerations illustrate that the regulator is left with a difficult task. To stimulate optimal competition and investment he can only deploy one policy instrument, the (linear) access price p_I. Clearly, it will therefore not be feasible to achieve the first-best outcome along all dimensions.

When considering competitive and investment efficiency, the vertically integrated structure performs better than the vertically separated one, especially if a positive mark-up is necessary to recoup the fixed costs of infrastructure provision.[91] However, even the vertically integrated structure does not achieve socially optimal infrastructure investment levels:

[91] This result relies on the assumed absence of discriminatory action of the vertically integrated firm and further assumes "efficient" regulation.

Proposition 3.7 *Under vertical integration there is more infrastructure investment into cost-reduction than under vertical separation. However, both fall short of the first-best investment levels (underinvestment).*

Proof. See Appendix, Section 3.8.3. ■

At first, this result may seem surprising. After all, the vertically integrated infrastructure provider does not only achieve the increased access margin through investing in cost-reduction but it also secures a competitive advantage of its affiliate over downstream rivals. However, these incentives are surpassed by the social planner's incentives because he considers the impact on all downstream firms' profits and on the consumers, in addition. In particular, a large social benefit of investments is derived from increased quantities being exchanged under the socially optimal price, $p^* = c_I - h$, that is clearly lower than the competitive market price.[92] In contrast, the vertically integrated firm will not factor these benefits in when investing but only considers the impact on own profits. This result continues to hold for lower access prices despite the fact that those stimulate investment incentives further (as shown in corollaries 3.1 and 3.6).

For quality-enhancing investments we derive an equivalent result:

Proposition 3.8 *Under vertical integration there is more investment into infrastructure quality-increases than under vertical separation. However, both fall short of the first-best investment levels (underinvestment).*

Proof. See Appendix, Section 3.8.3. ■

The social planner again considers the full benefits from increased quality investments on all market participants, including the integrated firm's competitors and consumers. Unlike the social planner, a vertically integrated infrastructure provider can only recoup a fraction of these benefits because competitors free-ride on infrastructure quality investments. Therefore, it will underinvest. This result would collapse if the vertically integrated firm was a monopolist and was allowed to perfectly price discriminate at the downstream level. Only then, the investor could accrue all the social benefits of quality investments and would, in fact, invest optimally. Here, because we assume linear access prices and competition downstream, the proposition continues to

[92] In fact, absent fixed costs and investments, a social planner would set access prices below marginal costs to counter the imperfect downstream competition in the Cournot model. Here, we assume that the lowest feasible price is $p_I = c_I - h$, so that firm I still makes zero profits on each marginal unit.

hold – even for high access prices. Although a higher access price stimulates quality-increasing investments under both vertical structures (recall corollaries 3.3 and 3.8), a higher access price also implies that less consumers buy and hence gain from the investments. This, in turn, means that incentives must fall short of the social incentives for infrastructure quality investments – for all feasible access prices.

The above propositions show that it will, in general, be impossible to achieve first-best investment levels. This observation is aggravated if we consider markets where both, cost-reducing investments and quality-increasing investments co-exist (compare Section 3.8.2 of the Appendix). The regulator will then have to set an access price which additionally reflects the relative importance of each type of infrastructure investment. When quality-increasing investments are "cheap" and desirable, there should be a significant positive access margin reflecting this. When cost-reducing infrastructure investments should be stimulated, this should be reflected by rather low access prices.[93] Thus, in equilibrium, industries where quality-increasing infrastructure investments are important are likely to depict higher access margins relative to industries where cost-reducing infrastructure investments are desirable.

If quality-increasing and cost-reducing investments matter in an industry, a vertically integrated structure is likely to perform better. This finding is strengthened further in Appendix, Section 3.8.2, where we show that the two types of infrastructure investments are strategic complements. In addition, vertical integration exhibits stronger complementarities. Hence, co-existence of both investment types wind each other up more and more, especially under integration. This further substantiates the relevance of investigating which vertical structure achieves the best infrastructure investment incentives.

3.6 Excursion: Public Financing

The preceding analysis has shown that the vertically integrated structure performs better in providing infrastructure investment incentives into quality and cost-reduction. With fixed costs of infrastructure investment vertical integration is also more efficient at recovering these through access revenues. The results are reinforced if one considers

[93] In our model these affinities would show up in the cost function parameters η and κ. As, for example, $\eta \rightarrow \infty$ it becomes unattractive to invest in cost-reduction because increasing h by one unit becomes very costly. In this industry, cost-reducing investments are unimportant. If κ is rather small, quality-increasing investments are important drivers for efficiency of the industry.

both types of investments jointly because they are strategic complements and the complementarities are stronger under vertical integration than under vertical separation.

In reality, there are at least two important benefits of vertical separation that the model did not capture so far. Firstly, vertical separation has better properties to avoid discriminatory behavior.[94] Secondly, there is the abiding argument that vertical separation lends itself better to continuous government financing. The idea that financing may alter the optimal vertical structure is mentioned but not formalized in both, Newbery (2004) and Hellwig (2006). Hellwig (2006) and Röller et al. (2005) as well as practitioners have argued that government financing in conjunction with vertical integration may suffer from a soft budget constraint problem that seriously worsens its performance. The work by Röller et al. (2005) delivers an explanation for why it may not be desirable to publicly finance a vertically integrated structure. It analyzes the incentives for efficient production when a firm is obliged to provide a social good (in our context the infrastructure) in addition to a private good (downstream services). In this situation a soft budget constraint problem arises because providing the social good is socially desirable but privately unprofitable. Röller et al. (2005) show that it is then better to separate the provision of the private and the social good. In the following, we therefore investigate public financing in conjunction with vertical separation and compare its performance against a privately-financed, vertically integrated structure (as in Section 3.3) – and we do so in a very simple and stylized way.[95]

We assume two implications of government financing:

1. **loss of commitment to access prices:** Government financing is prominent in network utilities, partly because of the natural monopoly properties of infrastructure, partly because of their strategic importance for the functioning of the economy as a whole.[96] Regulatory institutions usually have to enforce access price cuts against a strong lobby when the infrastructure provider is private.

[94] Price-, quality or other soft discrimination may stem from different sources. It could be a result of sabotage or raising rivals costs' (as discussed in Section 3.1 and footnotes on pages 101 and 106). It could also be due to inefficient regulation where socially too high access prices are granted, for example, as a result of problems in coping with imperfect information on actual costs of providing the infrastructure. These arguments are not considered in our model.

[95] Caillaud et al. (2004) also consider essential facilities financing but focus on effects of private information. Else (1996) illustrates the importance of government financing for the example of British rail. Shleifer (1998) gives a good overview of potential pitfalls and benefits of public ownership.

[96] Network utilities, such as water, electricity, telecoms and transportation build the basis for almost all economic activities. The universal service proposition stresses the idea that it is in society's interest that every individual has access to these services. In some countries this is written down in constitutional law ("Daseinsfürsorge"$\approxeq$ realization of precautions).

Private owners require specified, long-run returns and thus guaranteed access conditions for planning reliability. Arguably, this is less so for a public infrastructure provider where funds are negotiable, especially in times of sudden but potentially inevitable access price increases. We therefore believe that private financing and commitment to a positive access margin go hand in hand, whereas public financing implies a loss of commitment power. We model the extreme case where there is no commitment by the regulator.

2. **government subsidies are costly:** With growing budgets and the efforts of governments to strive to reduce the size of public spending, government financing comes at a social cost, $\mu > 0$.[97] We assume that this cost is constant given the probably rather small fraction that government funds for network utilities contribute to the entire budget. However, depending on the economic environment, this cost parameter may be prohibitively high or rather low. Government payments are capped to a maximum of $\overline{s} = F$.

We now explore the consequences of public financing for a vertically separated structure to later compare it against a privately-financed, vertically integrated infrastructure. Note that the first assumption has direct implications for the time structure of the game. In contrast to our assumption in the previous sections, the investment decision is now undertaken before the access price is finally being determined.[98] Therefore, the timing is as follows.

In stage 1, the upstream infrastructure provider, firm I, chooses the investment levels into infrastructure, k and h. We assume that the infrastructure provider continues to maximize profits as its objective function when deciding on investments.[99] In stage 2 the regulator chooses a linear access price p_I to maximize social welfare. When doing so, he anticipates the welfare consequences of trading-off social losses due to higher access prices against those associated with supply of additional government funds (in stage 3). Moreover, we assume that – being the owner – the government and the regulator may now set the access price to effective marginal costs, $c_I - h$. In stage

[97] The social cost of public funds could be due to costs in obtaining the funds in the first place (e.g. through distortionary taxes) or they could be thought of as an opportunity cost for not being able to fund other potentially socially desirable projects. Here, collection of \$1 of funds (e.g. through tax revenues) is associated with deadweight costs of $\$(1 + \mu)$ – following Segal (1998).

[98] Any access price announcement made prior to investment is no longer credible. The investor anticipates this.

[99] In general, public financing may also imply that the government secures some power in deciding on the structure, capacity and investment of infrastructure. We abstract from modeling this here.

3 each downstream firm chooses the quantity q_j which determines the total quantity produced, Q, the final goods price, $p(Q)$, and the associated infrastructure demand and profits. The government pays "subsidies" s to ensure the infrastructure provider receives his reservation profits. Subsidies are modeled in the simplest form – they are a fixed transfer and socially costly to raise.

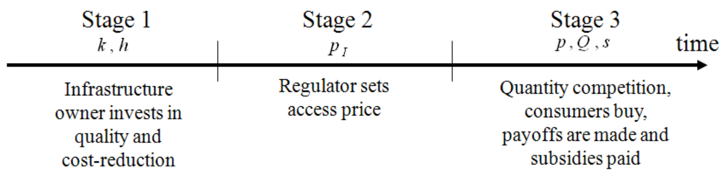

Figure 3.2: Time Structure of the Model (No Commitment)

We now examine the implications of the change in timing for optimal investments and social efficiency. In the last stage of the game, the optimal quantity decisions of downstream firms remain as in Section 3.4. The government pays a subsidy which depends in size on how the regulator set the access charge in the previous stage:

$$s = \begin{cases} F & \text{if } \Pi_{\setminus F} = 0 \\ F - \Pi_{\setminus F} & \text{if } \Pi_{\setminus F} > 0 \end{cases}$$

where $\Pi_{\setminus F} = (p_I - (c_I - h))Q(k,h) - C(k,h)$ with $C(k,h)$ being the costs from infrastructure investment and Q being the total quantity produced downstream which also depends upon infrastructure investments.

For the regulator's decision in stage 2 let us first assume costless government financing, $\mu = 0$. We then find the following:

Remark 2 *Under vertical separation, costless government financing and no commitment to access prices, the regulator sets the access price equal to marginal cost, $p_I = (c_I - h)$. This deters the infrastructure provider from undertaking any investments into infrastructure in the first stage of the game.*

Proof. See Appendix, Section 3.8.3. ■

The intuition for the result is simple. When government financing does not involve additional social costs, it is superior to private financing through access charges which involve a socially undesirable mark-up over marginal cost. In fact, given that investments have already taken place in stage 1, the regulator will always choose the lowest access price feasible. The fact that investments cannot be recouped through access revenues will deter the infrastructure provider from undertaking investments in the first stage.[100] This is to the detriment of social welfare, especially if investments are important for welfare, but cannot be avoided if there is no commitment.

With a positive cost of social funds, $\mu > 0$, there will generally be a mixture of financing infrastructure through access revenues and government subsidies. The reason is that the regulator will weigh the relative social losses from increasing the access price and mark-up against the social loss associated with government funding – taking investments as given. For low fixed costs to be covered, private funding will usually perform better as distortions introduced are small. Therefore, when public funding is very costly (i.e. μ large), the access margin chosen is positive despite the commitment problem. However, as shown in Appendix, Section 3.8.1, each *additional* unit of access revenues introduces larger *marginal* distortions.[101] In contrast to these distortions under private funding which increase on the margin, marginal distortions under public financing are constant (μ). At the point where the distortion through an additional increase in the access margin is greater than μ, the government will then use subsidies in addition. This must be the case for very high fixed costs.[102]

Remark 3 *For high costs of infrastructure provision F, a publicly financed infrastructure provider outperforms a privately-financed infrastructure provider if social costs of government funds, μ, are not too large.*

To grasp the intuition of the remark, it is easiest to consider the most extreme example. Whereas private funding can only support a structure that has fixed costs F that are below or equal to monopoly profits ($F \leq \Pi^M$), public funding is able to sustain infrastructures that are privately unprofitable but socially desirable. This case exists because a monopoly is unable to raise the entire social surplus with linear access charges. Nevertheless, an (at least partially) publicly financed infrastructure is feasible if associated costs, μ, are not too large.

[100] Thus, once the investment has taken place, the bargaining power switches to the regulator – the costs of investment are sunk and need to be recovered (hold-up problem). Thus, the investor, if there is no guarantee for him to recover his sunk costs, may be reluctant to invest in infrastructure. We assume that the infrastructure provider does not invest in case of indifference.

[101] The argument is that for an additional, marginal unit of financing F, the access price has to be increased. As the quantity base decreases with access price increases, the needed price increases become larger on the margin – distortions increase more than proportionately.

[102] Whether investments are stimulated through the positive access margin depends on whether the resulting benefits can be recouped by the investor. If subsidies are reduced as a result, investments may still not occur in the first place; this is assumed here.

Section 3.5 demonstrated that under the assumptions of our model, the vertically integrated market structure was superior under private financing.[103] However, when we introduce the possibility of government financing under vertical separation, this result may reverse. In particular, we have shown that public financing may sustain a market structure which cannot be privately financed through access revenues. Even if there is a commitment problem associated with public financing of the infrastructure, the system may outperform a privately-financed, vertically integrated structure if the social cost of public financing μ is rather low and investment incentives are not too important for the industry.

Within the framework of our model we are thus able to give recommendations on the best-suited form of vertical structure, the desired way of financing infrastructure costs and the imperative features of sector-specific access regulation. These need to be tailored to the economic environment characterized by the investment-affinity of infrastructure – with respect to both quality and cost-effectiveness, the size of fixed costs of its provision and the social costs of government financing. If quality-increasing and cost-reducing investments are important, a privately-financed, vertically integrated structure is likely to perform best. This is especially true for industries where a positive mark-up over marginal cost leads to significant quality-increasing investments. In contrast, if investments are expensive and thus not important drivers for efficiency of the industry, the vertically integrated structure is only preferable as long as fixed costs and associated distortions are not too large and public financing is socially costly. However, as fixed costs increase and the private financing of the infrastructure becomes more inefficient, choosing a vertically separated, publicly-financed structure may well be preferable.

Arguably the railroad industry could be considered a good example for depicting the just described industry characteristics. Whereas infrastructure investments into quality and cost-reduction are potentially important, the associated costs of infrastructure provision, F, are very large and it has been argued that private financing will not be able to fully recoup these.[104] If this is so, a publicly financed but vertically separated infrastructure should be advocated according to our model. However, our model also warns that it is crucial to find alternative incentive mechanisms that ensure sufficient infrastructure investments as these may suffer strongly under a vertically separated,

[103] This presumes that the regulator will set and commit to an access price p_I that is high enough to guarantee that the infrastructure costs can be recouped.

[104] Compare Nash et al. (2002) and Newbery (2004) who show that European railways have a cost-recovery ratio that lies significantly below 100%.

publicly-financed structure. Similar arguments are often made for the water industry.[105]

3.7 Conclusions

In this chapter we developed a framework to explore the performance of different vertical structures for network industries. We paid special attention to questions related to infrastructure investment into cost-effectiveness and quality.

In our analysis we showed that infrastructure investments play an important role in determining the optimal regulatory policy and in deciding on the optimal industry structure. In particular, we highlighted that a vertically integrated structure – if efficiently regulated – provides better incentives for infrastructure investment into both, cost-reduction and quality-increases. Depending on the relative importance of cost-reducing and quality-increasing investments, a positive access margin may be socially desirable to stimulate quality-increasing investments even if this causes competitive distortions. Moreover, we were able to show that downstream competition typically stimulates infrastructure investments through increased demand for access to the infrastructure (for quality-increasing investments) or an increased access margin (for cost-reducing investments). However, the opposite may be the case for quality-increasing infrastructure investments under vertical integration as the increased intensity of competition erodes downstream profits and thus investment incentives through free-riding of competitors.

Although very stylized, our model does deliver important implications for policy. Industries, in which infrastructure investments play a dominant role in determining the efficiency of the industry, demand a vertically integrated structure. Whereas quality-increasing investments are enhanced through increased access prices, the opposite holds for cost-reducing investments. Thus, considering cost-reducing and quality-increasing investments jointly may leave the regulator indifferent between promoting a low quality, low price environment through low access prices (cost-effectiveness) or one of high quality at high prices resulting from quality investments stimulated through high access prices. The underlying heterogeneity in consumers' preferences and wealth would then take the role of determining what the preferred scenario would be.

[105] However, experts note that technological complementarities and synergies between the upstream and the downstream market are considerable for the water industry. These are not considered in our model but would work in favor of vertical integration. For the German railroads case see Booz Allen Hamilton (2006) for a discussion.

Our model leaves out other important but largely orthogonal aspects that should be taken into account when determining the vertical structure of a network industry. On the one hand, vertical integration is prone to discrimination of various forms, whether price, non-price (e.g. quality or cost) or soft discrimination. Especially in those industries where regulation has a difficult task to detect those anticompetitive actions or where regulation is less efficient in determining the optimal access price, vertical separation may ease the problems considerably. On the other hand, technological complementarities, also with respect to upstream and downstream investments, or other types of synergies may favor vertical integration as the better vertical industry structure. We deduce that vertically integrated industry structures may be optimal despite the problems they cause related to discrimination.

Infrastructure investment incentives may be considerably altered through alternative forms of financing. In particular, we argued that public financing may be associated with a commitment problem that seriously harms investment incentives. However, if fixed costs are extremely large, a publicly-financed infrastructure could be the only viable alternative.

An interesting topic for further research arises out of the interdependencies of upstream (infrastructure) and downstream (services) investments. At first glance, one would suspect that there are also strategic complementarities between these types of investments, similar to those considered in Appendix 3.8.2. If that is confirmed, this would further reinforce the relevance that infrastructure investments have for economic efficiency. More effort should be devoted into highlighting these interrelations on the one hand and the differences of cost-reducing and quality-increasing investments on the other.

3.8 Appendix

3.8.1 Graphical Analysis of Investments in a Cournot Model

Cost-Reducing and Quality-Increasing Investments in a Cournot Model

In a standard, non-vertical Cournot model the effects of cost-reducing and quality-increasing investments are equivalent for quantities. In a symmetric Cournot model, the equilibrium quantities are given by $Q = \frac{n(a-c_I)}{n+1}$. Thus, whether quality-increasing investments (which increase output to $Q(k) = \frac{n(a-c_I+k)}{n+1}$) or cost-reducing investments (which increase output to $Q(h) = \frac{n(a-c_I+h)}{n+1}$), the effect is exactly the same. Note, however, that quality-increasing investments cause equilibrium price to increase whereas cost-reducing investments cause a decrease in equilibrium price with imperfect downstream competition.

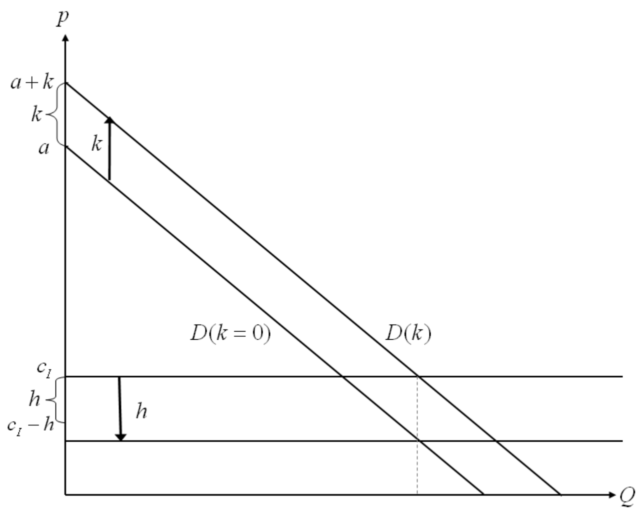

Figure 3.3: Cost-Reducing and Quality-Increasing Investments

Illustration of Private and Public Financing of Infrastructure

The welfare loss under private financing resembles the well-known deadweight-loss under monopoly. The dotted triangle describes the welfare loss in the figure below. Note that the maximum financing the private infrastructure can raise is monopoly profit. However, even if fixed costs are larger than the monopoly profit, production may be worthwhile. Therefore, private financing may sometimes not be feasible and production breaks down although it would be socially desirable.

Under public financing the associated welfare loss can be illustrated with the rectangle in the figure below. The shaded rectangle describes the fixed cost of production. Social losses (under a constant social cost of public funds) are proportional to this rectangle.

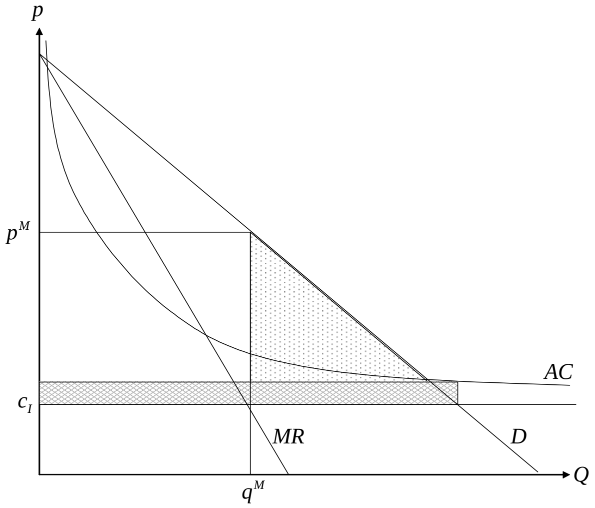

Figure 3.4: Public vs. Private Financing

Note that the deadweight loss under private financing increases with every incremental increase in the fixed cost that needs to be recouped. For illustration, consider a monopoly's profit maximization problem with the following parameters:

Linear demand function: $p = 10 - q$; no marginal costs. The monopolist therefore maximizes profits by selling at ($p = 5$, $q = 5$) and earns a profit of $\pi = 25$. To achieve the first unit of these profits, the monopolist only has to raise the price slightly above marginal cost to the level, ϵ, that fulfills:
First Unit: $\epsilon(10 - \epsilon) = 1$ where the solution is given by $\epsilon = 5 - \sqrt{24}$ and the associated deadweight loss is $\frac{\epsilon^2}{2} = \frac{(5-\sqrt{24})^2}{2}$
Second Unit: $\delta(10 - \delta) = 2$ where the solution is given by $\delta = 5 - \sqrt{23}$ and the associated deadweight loss is $\frac{\delta^2}{2} = \frac{(5-\sqrt{23})^2}{2}$
The total deadweight loss, of course, increases in the number of units to be raised but so does the *marginal* deadweight loss. The marginal deadweight loss of the first unit is $\frac{(5-\sqrt{24})^2}{2}$, the one for the second is $\frac{(5-\sqrt{23})^2}{2} - \frac{(5-\sqrt{24})^2}{2} > \frac{(5-\sqrt{24})^2}{2}$. The argument holds for all units up until the last unit to be raised – the 25th unit. Thus, raising each additional unit, for example to cover a fixed cost F, becomes increasingly costly. This

result holds for linear inverse demand functions but generalizes to other (e.g. convex) functional forms.

3.8.2 Co-Existence of Both Investments

Clearly, both types of investments into infrastructure may co-exist. Implications will be examined in the following two subsections.

Vertical Integration

The integrated firm's and a representative rival's profit function are given by:

$$\begin{aligned}\pi_I &= (p_I - (c_I - h))(Q\ (h,k)) + (a + k - Q(h,k) - p_I)q_I - \frac{\eta}{2}h^2 - \frac{\kappa}{2}k^2 - F \\ \pi_j &= (a + k - Q(k) - p_I)q_j.\end{aligned}$$

In the unique Nash equilibrium of the Cournot game at stage 3 firms choose the following quantities under linear demand:

$$\begin{aligned}q_I &= \frac{a + k + (n-1)p_I - n(c_I - h)}{n+1} \\ q_j &= \frac{a + k + (c_I - h) - 2p_I}{n+1}.\end{aligned}$$

Thus, the total quantity is given by $Q^{VI} = \frac{n(a+k-p_I)+p_I-(c_I-h)}{n+1}$ and the market price is $p^{QI,VI} = \frac{a+k+(c_I-h)+(n-1)p_I}{n+1}$. In stage 2, the vertically integrated infrastructure provider determines investments into cost-reduction and quality. The FOCs show that investment incentives under vertical integration are made up of the following components:

$$\begin{aligned}\frac{\partial \pi_I}{\partial h} &= (Q_{-I}^{VI}) + (p_I - (c_I - h))(\frac{\partial Q_{-I}}{\partial h}) + (\frac{\partial p^{VI}}{\partial Q}\frac{\partial Q}{\partial h} + 1)q_I + (p^{VI} - (c_I - h))\frac{\partial q_I}{\partial h} - \eta h \\ \frac{\partial \pi_I}{\partial k} &= (p_I - (c_I - h))\frac{\partial Q_{-I}}{\partial k} + \frac{\partial p^{VI}}{\partial Q}\frac{\partial Q}{\partial k}q_I(k) + (p^{VI} - (c_I - h))\frac{\partial q_I}{\partial k} - \kappa k.\end{aligned}$$

Note that these effects are, intuitively, the same as in Section 3.3. However, their size may differ due to the interdependencies between investments. Testing for strategic interdependencies, we find for general demand:

$$\begin{aligned}\frac{\partial^2 \pi_I}{\partial h \partial k} &= \frac{\partial Q_{-I}^{VI}}{\partial k} + (p_I - (c_I - h))(\frac{\partial^2 Q_{-I}}{\partial h \partial k}) + (\frac{\partial^2 p^{VI}}{\partial h \partial k}) q_I \qquad (3.15)\\ &+(\frac{\partial p^{VI}}{\partial h} + 1)\frac{\partial q_I}{\partial k} + \frac{\partial p^{VI}}{\partial k}\frac{\partial q_I}{\partial h} + (p^{VI} - (c_I - h))\frac{\partial^2 q_I}{\partial h \partial k}\\ \frac{\partial^2 \pi_I}{\partial k \partial h} &= \frac{\partial Q_{-I}^{VI}}{\partial k} + (p_I - (c_I - h))\frac{\partial^2 Q_{-I}}{\partial k \partial h} + \frac{\partial^2 p^{VI}}{\partial k \partial h} q_I \qquad (3.16)\\ &+\frac{\partial p^{VI}}{\partial k}\frac{\partial q_I}{\partial h} + (\frac{\partial p^{VI}}{\partial h} + 1)\frac{\partial q_I}{\partial k} + (p^{VI} - (c_I - h))\frac{\partial^2 q_I}{\partial k \partial h}.\end{aligned}$$

For the linear demand model, investments are strategic complements:

$$\frac{\partial^2 \pi_I}{\partial h \partial k} = \frac{\partial^2 \pi_I}{\partial k \partial h} = 1 - \frac{2}{(n+1)^2} > 0. \qquad (3.17)$$

Remark 4 *Under vertical integration and linear demand, cost-reducing and quality-increasing investments are strategic complements. If the infrastructure provider invests more in one type of investment, this enhances the marginal profitability of investing in the other type of investment.*

The optimal investment levels for linear demand are then given by:

$$\begin{aligned} k &= \frac{(n+1)^2 (p_I - c_I) + 2(a + c_I - 2p_I)}{\kappa (n+1)^2 - 2} + \frac{(n+1)^2 - 2}{\kappa (n+1)^2 - 2} h\\ h &= \frac{(n+1)^2 (a - p_I) - 2(a + c_I - 2p_I)}{\eta (n+1)^2 - 2} + \frac{(n+1)^2 - 2}{\eta (n+1)^2 - 2} k\end{aligned}$$

and these are larger compared to investment levels without co-existence due to the strategic complementarity.

Vertical Separation

At stage 3 downstream firms compete in quantities and face a symmetric profit maximization problem of the form:

$$\pi_j = (p(Q) - p_I)q_j.$$

The first order condition for a profit maximum requires:

$$\frac{\partial \pi_j}{\partial q_j} = (p(Q,k) - p_I) + \frac{\partial p}{\partial Q} q_j = 0.$$

At stage 2 of the game, the upstream infrastructure provider chooses how much to invest in both cost-reduction and quality by maximizing:

$$\pi_I = (p_I - (c_I - h))Q^{VS}(k) - \frac{\eta}{2}h^2 - \frac{\kappa}{2}k^2 - F$$

where $Q^{VS}(k) = n \cdot \frac{a+k-p_I}{n+1}$. The FOCs give the following conditions for optimality:

$$\frac{\partial \pi_I}{\partial h} = Q^{VS}(k) - \eta h = 0 \tag{3.18}$$

$$\frac{\partial \pi_I}{\partial k} = (p_I - (c_I - h))\frac{\partial Q^{VS}}{\partial k} - \kappa k = 0. \tag{3.19}$$

Thus, the FOCs remind us of equations of first order (3.13) and (3.14). Note, however, that here investment incentives are stronger. $Q^{VS}(k)$ in equation (3.18) is larger than $Q^{VS}(k=0)$ and $(p_I - (c_I - h))$ in equation (3.19) is larger than $p_I - c_I$. Thus, the co-existence of investments leads to higher incentives to invest. This is confirmed by the following finding:

$$\frac{\partial^2 \pi_I}{\partial h \partial k} = \frac{\partial^2 \pi_I}{\partial k \partial h} = \frac{\partial Q^{VS}(k)}{\partial k} > 0. \tag{3.20}$$

For linear demand we find:

$$\frac{\partial^2 \pi_I}{\partial h \partial k} = \frac{\partial^2 \pi_I}{\partial k \partial h} = \frac{n}{n+1} > 0. \tag{3.21}$$

Remark 5 *Under vertical separation cost-reducing and quality-increasing investments are strategic complements. If the infrastructure provider invests more in one type of investment, this enhances the marginal profitability of investing in the other type of investment.*

Thus, investments are also strategic complements under vertical separation but the complementarity is smaller. This implies the following optimal investment levels for the case of linear demand which are again greater than in Section 3.4:

$$\begin{aligned} k &= \frac{n(p_I - c_I)}{\kappa(n+1)} + \frac{n}{\kappa(n+1)}h \\ h &= \frac{n(a - p_I)}{\eta(n+1)} + \frac{n}{\eta(n+1)}k. \end{aligned}$$

3.8.3 Proofs

Proof of Corollary 3.1:

To show that $\frac{\partial h^{CR,VI}}{\partial p_I} = -\frac{(n+1)^2-4}{\eta(n+1)^2-2}$ is indeed negative, recall that the denominator is greater zero by assumption ($\eta > \frac{2}{(n+1)^2}$). This was required by the SOC for a maximum when deriving $h^{CR,VI}$. The numerator is also greater zero for all $n > 1$.

Proof of Corollary 3.2:

For $\frac{\partial h^{CR,VI}}{\partial n} = 4\frac{(n+1)(p_I - a + \eta(a + c_I - 2p_I))}{(\eta(n+1)^2-2)^2}$ to be positive, consider again numerator and denominator in turn. The denominator is always positive (as in proof of Corollary 3.1). The numerator is also positive because for rivals' profits to be non-negative, we require that $(p_I - a + \eta(a + c_I - 2p_I)) > 0$, i.e. $\eta > \frac{a-p_I}{a+c_I-2p_I}$ which implies $\eta > 1$. Note that all assumptions undertaken on η are such that we require to be greater than a certain value. Therefore, the assumptions can hold jointly.

Proof of Proposition 3.1:

The welfare function is given by:

$W^{CR,VI} = CS^{CR,VI} + \pi_I + (n-1)\pi_j$

where by substitution of $h^{CR,VI}$:

$CS^{CR,VI} = \frac{((n-1)(a-p_I)+\eta(n+1)(n(a-p_I)+p_I-c_I))^2}{2\left(\eta(n+1)^2-2\right)^2}$

$\pi_I = \frac{(a-p_I)^2(n+3)(n-1)+2\eta((a+c_I-2p_I)^2+(n+1)^2(p_I-c_I)(a-p_I))}{2\left(\eta(n+1)^2-2\right)} - F$

$(n-1)\pi_j = (n-1)(n+1)^2 \frac{(-a+p_I+\eta(a+c_I-2p_I))^2}{\left(\eta(n+1)^2-2\right)^2}$

Comparative statics with respect to p_I take the expected signs:

$\frac{\partial}{\partial p_I}(CS) = \frac{(n-1)(\eta+n\eta+1)(-(n-1)(a-p_I)-\eta(n+1)(n(a-p_I)+p_I-c_I))}{\left(\eta(n+1)^2-2\right)^2} < 0$

$\frac{\partial}{\partial p_I}(\pi_I) = \frac{((n+1)^2-4)(\eta(n+1)^2-2)(-a+p_I+\eta(a+c_I-2p_I))}{(\eta(n+1)^2-2)^2} > 0$

$\frac{\partial}{\partial p_I}((n-1)\pi_j) = -\frac{2(2\eta-1)(n-1)(n+1)^2(-a+p_I+\eta(a+c_I-2p_I))}{\left(\eta(n+1)^2-2\right)^2} < 0$ as $2\eta - 1 > 0$ by $\eta > \frac{2}{(n+1)^2}$.

Summing the terms, we get the following expression:

$-\frac{(n-1)(\eta+n\eta+1)((n-1)(a-p_I)+\eta(n+1)(n(a-p_I)+p_I-c_I))}{\left(\eta(n+1)^2-2\right)^2} + \frac{(n-1)^2\left(\eta(n+1)^2+2n+4\right)(-a+p_I+\eta(a+c_I-2p_I))}{(\eta(n+1)^2-2)^2}$

Our aim is to show that the above expression is indeed negative. Denominators are positive, thus we require the sum of numerators to be negative. Gathering terms, we get:

$(n-1)\left\{(5-n(3+2n))(a-p_I) - \eta \cdot X\right\} < 0$

Note that this expression is negative if $X > 0$ where X is given by:

$X = \frac{2(a-p_I)(1-n)+3c_I(1-n)+(n^2-3)p_I(1-n)+n^2(a-c_I)+n^2(an-c_I)+\eta \cdot Y}{1}$.

As $Y = a - p_I + n(2a - c_I - p_I) + n^2(a - c_I) + n^3(p_I - c_I) + n^2(p_I - c_I) > 0$, we require:

$2(a-p_I)(1-n) + 3c_I(1-n) + (n^2-3)p_I(1-n) + n^2(a-c_I) + n^2(an-c_I) > 0$

$\Leftrightarrow (2(a-p_I) + 3c_I + (n^2-3)p_I)(1-n) + n^2(a(1+n) - 2c_I) > 0$

which is true if $n^2(a(1+n) - 2c_I) > (n-1)(2(a-p_I) + n^2 p_I - 3(p_I - c_I))$

or $n^2(a(1+n) - 2c_I) > (n-1)(2(a-p_I) + n^2 p_I)$,

i.e. if $n^2(an - 2c_I) > (n-1)(2(a-p_I))$ which is indeed the case.

The regulator will therefore set the lowest possible access price that makes the industry viable. This requires the following reservation profits for the integrated firm:

(a) under assumption that reservation profit is given by the zero profit condition:

$\frac{(a-p_I)^2(n+3)(n-1)+2\eta((a+c_I-2p_I)^2+(n+1)^2(p_I-c_I)(a-p_I))}{2\left(\eta(n+1)^2-2\right)} - F = 0$

(b) under assumption that reservation profit is the rivals' profit:

$\frac{(a-p_I)^2(n+3)(n-1)+2\eta((a+c_I-2p_I)^2+(n+1)^2(p_I-c_I)(a-p_I))}{2\left(\eta(n+1)^2-2\right)} - F = (n+1)^2 \frac{(-a+p_I+\eta(a+c_I-2p_I))^2}{\left(\eta(n+1)^2-2\right)^2}$.

Proof of Corollary 3.3:

The expression $\frac{\partial k^{QI,VI}}{\partial p_I} = \frac{(n+1)^2-4}{\kappa(n+1)^2-2}$ is positive as $\kappa > \frac{2}{(n+1)^2}$ by assumption to guarantee the SOC for a maximum on $k^{QI,VI}$ and $(n+1)^2 > 4$ holds for all $n > 1$.

Proof of Corollary 3.4:

$\frac{\partial k^{QI,VI}}{\partial n} = -4\frac{(n+1)(p_I-c_I+\kappa(a+c_I-2p_I))}{(\kappa(n+1)^2-2)^2} < 0$ holds if $p_I - c_I + \kappa(a + c_I - 2p_I) > 0$ which is always the case.

Proof of Proposition 3.2:

The welfare function is given by:

$W^{QI,VI} = CS + \pi_I + (n-1)\pi_j$

where by substitution of $k^{QI,VI}$:

$CS^{QI,VI} = \frac{((n+2)(n-1)(p_I-c_I)+\kappa(n+1)(n(a-p_I)+p_I-c_I))^2}{2\left(\kappa(n+1)^2-2\right)^2}$

$\pi_I = \frac{(p_I-c_I)^2(n+3)(n-1)+2\kappa((a+c_I-2p_I)^2+(n+1)^2(p_I-c_I)(a-p_I))}{2(\kappa(n+1)^2-2)} - F$

$(n-1)\pi_j = (n-1)\,(n+1)^2\,\frac{(p_I-c_I+\kappa(a+c_I-2p_I))^2}{\left(\kappa(n+1)^2-2\right)^2}$

When investments are costly, i.e. κ is large, standard theory tells us that the lowest feasible mark-up is welfare maximizing. This is confirmed by:

$\underset{\kappa\to\infty}{lim} W^{QI,VI} = \frac{n(n+2)(a-c_I)^2-2(p_I-c_I)(n-1)(a-c_I)-(n-1)^2(p_I-c_I)^2}{2(n+1)^2} - F$

for which $\frac{\partial}{\partial p_I}(\underset{\kappa\to\infty}{lim} W_{QI}) = -\frac{n-1}{(n+1)^2}\,(a-p_I+n(p_I-c_I)) < 0$ holds.

To examine the comparative statics with investments around $p_I = c_I$, we define the mark-up as $\epsilon = p_I - c_I$ and substitute:

$W^{QI,VI}(p_I = c_I+\epsilon) = \frac{((n+2)(n-1)(\epsilon)+\kappa(n+1)(n(a-c_I-\epsilon)+\epsilon))^2}{2\left(\kappa(n+1)^2-2\right)^2}$

$+ \frac{(\epsilon)^2(n+3)(n-1)+2\kappa((a-c_I-2\epsilon)^2+(n+1)^2(\epsilon)(a-c_I-\epsilon))}{2(\kappa(n+1)^2-2)} - F + (n-1)\,(n+1)^2\,\frac{(\epsilon+\kappa(a-c_I-2\epsilon))^2}{\left(\kappa(n+1)^2-2\right)^2}$

If raising the access price above marginal cost is indeed welfare maximizing, we must find a positive value for ϵ maximizing the above expression. The FOC requires:

$\frac{\partial}{\partial\epsilon}(W^{QI,VI}) =$

$-\frac{(n-1)\left(\epsilon(8-2n-11\kappa-5n^2-n^3-\kappa^2)+4a\kappa-4\kappa c_I+a\kappa^2-\kappa^2c_I+an^2\kappa^2-4an\kappa\right)}{\left(\kappa(n+1)^2-2\right)^2}$

$-\frac{(n-1)(\epsilon(\kappa^2n(n^2+n-1)+\kappa n(3+7n+n^2))-n^2\kappa^2c_I+4n\kappa c_I+n\kappa(a-c_I)(2\kappa-n^2-5n))}{\left(\kappa(n+1)^2-2\right)^2}$

$= 0$

with the second order condition for a maximum given by:

$-\frac{(n-1)^2\left((n+1)^2\kappa^2+n^2(\kappa-1)+\kappa(8n+11)-6n-8\right)}{\left(\kappa(n+1)^2-2\right)^2} < 0$

This condition is fulfilled if κ is large enough, i.e. investments sufficiently costly. Otherwise welfare is maximized with infinite investments. The optimal mark-up is only positive and welfare maximizing for values where:

$\kappa \in (\frac{(n+3)\sqrt{18n+5n^2+17}-(n^2+11+8n)}{2(n+1)^2}, \frac{4n+5n^2+n^3-4}{2n+n^2+1})$.

While the SOC dictates the lower bound (to arrive at a stable solution $\kappa > \frac{(n+3)\sqrt{18n+5n^2+17}-(n^2+11+8n)}{2(n+1)^2}$), the FOC gives a condition for the upper bound as otherwise investments are not important enough and the access margin should be non-positive ($\kappa < \frac{4n+5n^2+n^3-4}{2n+n^2+1}$).

Illustration with $\kappa = 1$ – solving the FOC for ϵ and taking $\kappa \to 1$:

$\epsilon = \lim_{\kappa\to 1}\left(-\frac{\left(4a\kappa-4\kappa c_I+a\kappa^2-\kappa^2c_I+an^2\kappa^2-4an\kappa-n^2\kappa^2c_I+4n\kappa c_I+2an\kappa^2-5an^2\kappa-an^3\kappa-2n\kappa^2c_I+5n^2\kappa c_I+n^3\kappa c_I\right)}{-2n-11\kappa+n^2\kappa^2+n^3\kappa^2+3n\kappa-\kappa^2-n\kappa^2+7n^2\kappa+n^3\kappa-5n^2-n^3+8}\right)$

$= \frac{(a-c_I)\left(2n+4n^2+n^3-5\right)}{(n-1)(n+2)^2} > 0$

SOC: $\lim_{\kappa\to 1}\left(-\frac{(n-1)^2\left(n^2\kappa^2+n^2\kappa-n^2+2n\kappa^2+8n\kappa-6n+\kappa^2+11\kappa-8\right)}{\left(\kappa(n+1)^2-2\right)^2}\right)$

$= -(n-1)^2\,\frac{(n+2)^2}{(2n+n^2-1)^2} < 0$

The optimal mark-up ϵ is then given by: $\frac{(a-c_I)\left(2n+4n^2+n^3-5\right)}{(n-1)(n+2)^2} > 0$ for the illustrative example of $\kappa = 1$.

Proof of Corollary 3.5:

The consumer surplus expression is given by:

$CS^{QI,VI} = \frac{((n+2)(n-1)(p_I-c_I)+\kappa(n+1)(n(a-p_I)+p_I-c_I))^2}{2\left(\kappa(n+1)^2-2\right)^2}$

$\frac{\partial}{\partial p_I}(CS^{QI,VI}) = (n-1)\frac{(n+2-\kappa(1+n))((n+2)(n-1)(p_I-c_I)+\kappa(n+1)(n(a-p_I)+p_I-c_I))}{\left(\kappa(n+1)^2-2\right)^2} > 0$ if $\kappa < \frac{n+2}{n+1}$

From the SOC of the Cournot game, we have that $\kappa > \frac{2}{(n+1)^2}$. Thus, if $0 < \frac{2}{(n+1)^2} < \kappa < \frac{n+2}{n+1}$, CS indeed increases with p_I due to the positive investment effect, i.e. if investments are not too costly to be unimportant and not too cheap so that quality-escalation is excluded.

Proof of Corollary 3.6:

$\frac{\partial h^{CR,VS}}{\partial p_I} = -\frac{n}{\eta(n+1)} < 0$ as clearly both numerator and denominator are positive.

Proof of Corollary 3.7:

$\frac{\partial h^{CR,VS}}{\partial n} = \frac{a-p_I}{\eta(n+1)^2} > 0$. Again, both numerator and denominator are positive.

Proof of Proposition 3.3:

$h^{CR,VI} = \frac{(n+1)^2(a-p_I)-2(a+c_I-2p_I)}{(n+1)^2\eta-2} > \frac{n}{n+1} \cdot \frac{a-p_I}{\eta} = h^{CR,VS}$

Multiplying and dividing the term under $h^{CR,VS}$ with $(n+1)$, we have:

$\frac{n(n+1)(a-p_I)}{\eta(n+1)^2} = h^{CR,VS}$

It then becomes clear that the denominator is larger than the one under VI but the numerator is smaller (as $2(p_I - c_I) + (n-1)(a-p_I) > 0$). Hence the entire term is smaller.

Proof of Proposition 3.4:

Substitution of $h^{CR,VS}$ yields:

$W^{CR,VS} = \frac{n(a-p_I)}{2} \cdot \frac{2\eta(a-c_I)+n(a-p_I)+n\eta(a+p_I-2c_I)}{\eta(n+1)^2} - F$

$\frac{\partial}{\partial p_I}(W^{CR,VS}) = -\frac{n(n(a-p_I)+\eta(a-c_I)+n\eta(p_I-c_I))}{\eta(n+1)^2} < 0$ as the negative sign is multiplied with a positive expression.

Proof of Corollary 3.8:

$\frac{\partial k^{QI,VS}}{\partial p_I} = \frac{n}{\kappa(n+1)} > 0$ as both, numerator and denominator are positive.

Proof of Corollary 3.9:

$\frac{\partial k^{QI,VS}}{\partial n} = \frac{p_I-c_I}{\kappa(n+1)^2} > 0$ as both, numerator and denominator are positive.

Proof of Proposition 3.5:

$k^{QI,VI} = \frac{(p_I-c_I)(n+1)^2+2(a+c_I-2p_I)}{\kappa(n+1)^2-2} > \frac{n(p_I-c_I)}{\kappa(n+1)} = k^{QI,VS}$

Multiplying and dividing $k^{QI,VS}$ by $(n+1)$ it is easy to see that the denominator is smaller under VI. The numerator is larger under VI as $(n+1)^2 > n(n+1)$ and $2(a+c_I-2p_I)>0$. Hence the term under VI is larger.

Proof of Proposition 3.6:

By substituting $k^{QI,VS}$ we have:

$W^{QI,VS} = \frac{n(p_I-c_I)}{2}\frac{n(p_I-c_I)+2\kappa(n+1)(a-p_I)}{\kappa(n+1)^2} + \frac{n^2+2n}{2}(\frac{n(p_I-c_I)+\kappa(n+1)(a-p_I)}{\kappa(n+1)^2})^2$

$\frac{\partial}{\partial p_I}(\frac{n(p_I-c_I)}{2}\frac{n(p_I-c_I)+2\kappa(n+1)(a-p_I)}{\kappa(n+1)^2}) =$

$= \frac{n}{\kappa(n+1)^2}(n(p_I-c_I)+\kappa(n+1)(a+c_I-2p_I)) > 0$

$\frac{\partial CS^{QI,VS}}{\partial p_I} = \frac{\partial}{\partial p_I}(\frac{n^2+2n}{2}(\frac{n(p_I-c_I)+\kappa(n+1)(a-p_I)}{\kappa(n+1)^2})^2) =$

$= -\frac{n(n+2)(\kappa-n+n\kappa)(\kappa(n+1)(a-p_I)+n(p_I-c_I))}{\kappa^2(n+1)^4} > 0$ if $\kappa < \frac{n}{n+1}$.

Thus, the result holds for both, welfare and CS if $\kappa < \frac{n}{n+1}$. In fact, welfare may also increase for values slightly below this threshold.

Proof of Proposition 3.7:

We derive the socially optimal investment incentives for the access price $p_I = c_I - h$. Although the socially optimal price lies below this (to counter Cournot mark-ups at the downstream level), $p_I = c_I - h$ is by assumption the lowest feasible access price:

$W^{CR,VI} = \frac{(a+(c_I-h)-2(c_I-h))^2+(n+1)^2((c_I-h)-(c_I-h))(a-(c_I-h))}{(n+1)^2}$

$+ (n-1)(\frac{a+(c_I-h)-2(c_I-h)}{n+1})^2 + \frac{(n(a-(c_I-h))+(c_I-h)-(c_I-h))^2}{2(n+1)^2} - \frac{\eta}{2}h^2 - F$

$\frac{\partial}{\partial h}(W^{CR,VI}(p_I = c_I - h)) =$

$= -\frac{\left(h\eta+2nc_I-an^2-hn^2+n^2c_I-2an-2hn+2hn\eta+hn^2\eta\right)}{(n+1)^2} = 0$

$h^* = \frac{n(n+2)(a-c_I)}{\eta(n+1)^2-n(n+2)} > h^{CR,VI} = \frac{(n+1)^2(a-p_I)-2(a+c_I-2p_I)}{(n+1)^2\eta-2}$

as the numerator is larger and the denominator smaller under h^*. Note that as incentives for investment decrease in the access price, this result holds for all access prices.

Proof of Proposition 3.8:

Here, we derive socially optimal investment incentives under the presumption of the lowest feasible access price $p_I = c_I$:

$W^{QI,VI} = \frac{(n(a+k-c_I)+c_I-c_I)^2}{2(n+1)^2} +$

$+ \frac{(a+k+c_I-2c_I)^2+(n+1)^2(c_I-c_I)(a+k-c_I)}{(n+1)^2} + (n-1)(\frac{a+k+c_I-2c_I}{n+1})^2 - \frac{\kappa}{2}k^2 - F$

$\frac{\partial}{\partial k}(W^{QI,VI}(p_I = c_I)) =$

$= -\frac{k\kappa+2nc_I-an^2-kn^2+n^2c_I-2an-2kn+2kn\kappa+kn^2\kappa}{(n+1)^2} = 0$ where we require $\kappa > \frac{n(n+2)}{(n+1)^2}$ for the SOC to be fulfilled.

$k^* = \frac{n(n+2)(a-c_I)}{\kappa(n+1)^2-n(n+2)} > 0$ as $\kappa > \frac{n(n+2)}{(n+1)^2}$ by assumption.

$k^* = \frac{n(n+2)(a-c_I)}{\kappa(n+1)^2-n(n+2)} > k^{QI,VI} = \frac{(p_I-c_I)(n+1)^2+2(a+c_I-2p_I)}{\kappa(n+1)^2-2}$

As $\frac{\partial k^{QI,VI}}{\partial p_I} > 0$, we compare directly at highest possible access price under VI, i.e. the monopoly price:
$k^* - k^{QI,VI}(p_I = \frac{a+c_I}{2}) = \frac{n(n+2)(a-c_I)}{\kappa(n+1)^2 - n(n+2)} - \frac{(\frac{a+c_I}{2} - c_I)(n+1)^2 + 2(a+c_I-2\frac{a+c_I}{2})}{\kappa(n+1)^2-2} =$
$= \frac{1}{2}(a-c_I)\frac{4n^2\kappa+4n^3\kappa+n^4\kappa+n^2+4n^3+n^4-6n-\kappa}{(\kappa(n+1)^2-n(n+2))(\kappa(n+1)^2-2)} > 0$ as the denominator is greater zero from $\kappa > \frac{n(n+2)}{(n+1)^2}$ and the numerator as well by $n > 1$.

Proof of Remark 2:

Without commitment and $\mu = 0$, welfare maximization takes the following form – taking k, h as given:
$W^{QI,VI} = \frac{(n(a+k-p_I)+p_I-c_I)^2}{2(n+1)^2} + \frac{(a+k+c_I-2p_I)^2+(n+1)^2(p_I-c_I)(a+k-p_I)}{(n+1)^2} + (n-1)(\frac{a+k+c_I-2p_I}{n+1})^2 - \frac{\kappa}{2}k^2 - F$
$\frac{\partial W^{QI,VI}}{\partial p_I} = -\frac{n-1}{(n+1)^2}(a+k-p_I+n(p_I-c_I)) < 0$
$W^{QI,VS} = (p_I-c_I)n\frac{a+k-p_I}{n+1} + n(\frac{a+k-p_I}{n+1})^2 + \frac{n^2(a+k-p_I)^2}{2(n+1)^2} - \frac{\kappa}{2}k^2 - F$
$\frac{\partial W^{QI,VS}}{\partial p_I} = -\frac{n}{(n+1)^2}(a+k-c_I+n(p_I-c_I)) < 0$
$W^{CR,VI} = \frac{(a+(c_I-h)-2p_I)^2+(n+1)^2(p_I-(c_I-h))(a-p_I)}{(n+1)^2} + (n-1)(\frac{a+(c_I-h)-2p_I}{n+1})^2 + \frac{(n(a-p_I)+p_I-(c_I-h))^2}{2(n+1)^2} - \frac{\eta}{2}h^2 - F$
$\frac{\partial W^{CR,VI}}{\partial p_I} = -\frac{n-1}{(n+1)^2}(a-p_I+n(p_I-(c_I-h))) < 0$
$W^{CR,VS} = (p_I-(c_I-h))n\frac{a-p_I}{n+1} + n(\frac{a-p_I}{n+1})^2 + \frac{n^2(a-p_I)^2}{2(n+1)^2} - \frac{\eta}{2}h^2 - F$
$\frac{\partial W^{CR,VS}}{\partial p_I} = -\frac{n}{(n+1)^2}(a-(c_I-h)+n(p_I-(c_I-h))) < 0$
Because all derivatives are negative throughout, the regulator chooses the lowest access price feasible which is an access price equal to the true marginal cost.

In contrast, private financing introduces a deadweight loss. Consider, for illustration, a perfectly competitive downstream industry with total output Q at marginal cost c_I. Then, to finance a fixed cost of F, the access provider requires a mark-up that satisfies: $(p_I - c_I)Q = F$. Note that following standard theory, the mark-up (and hence the associated deadweight loss) increases more than proportionately with an increase in F! Compare Section 3.8.1 of the Appendix.

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Jan Philipp Bender

Curriculum Vitae

10/2004 – 09/2008	Research and Teaching Assistant Chair of Prof. Dr. Klaus M. Schmidt Ph.D. Program in Economics Munich Graduate School of Economics Ludwig-Maximilians-Universität, Munich
10/2006 – 03/2007	Visiting Ph.D. Student in Economics Nuffield College, University of Oxford
09/2003 – 07/2004	Master of Philosophy in Economics Queens' College, Cambridge University
10/2000 – 07/2003	Bachelor of Science in Economics London School of Economics (LSE)
05/2000 – 08/2000	Studies in Business Economics University of Mannheim
07/1999	Abitur Städtisches Görres-Gymnasium, Düsseldorf
August 27, 1979	Born in Düsseldorf, Germany