The incentives of a monopolist to degrade interoperability: Theory and evidence from PCs

Christos Genakos[*], Kai-Uwe Kühn[†] and John Van Reenen[‡]

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Abstract

In this paper we present a model to analyse the incentives of a monopolist in one market has to monopolize a complementary market through interoperability degradation. In a framework incorporating heterogeneous demands based on the logit model we derive explicit conditions for the incentives to hold that are amenable to empirical testing. Essentially, in the absence of perfect price discimination, leveraging becomes a method to extract more rents from the monopoly market. We examine our test in the context of Microsoft's alleged strategic incentives to leverage market power from PC operating systems into the workgroup server market. We estimate a demand system for PCs extending Berry et al (1995) to the case of multiple customer segments. In the ontext of our model we find evidence that these incentives do exist and have grown stronger over time.

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[*] London Business School

[†] University of Michigan and CEPR

[‡] Corresponding author: j.vanreenen@lse.ac.uk; Centre for Economic Performance, London School of Economics, and CEPR

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1 Introduction

Many anti-trust cases in high tech industries now revolve around issues of interoperability and compatibility. The recent cases against Microsoft in the US and in Europe has focused around the allegation that Microsoft has deliberately limited interoperability between its monopoly products (e.g. PC operating systems) and those of complementary products (e.g. server operating systems sometimes called "middleware"). Limiting interoperability is a method of monopolizing the markets for those complementary products. Work group (or "low end") servers are one such complementary product but others could include web browsers, Personal Digital Assistants, data-enabled mobile phones and the growing market for web-based applications. As Bill Gates said in a 1997 internal memo:

"What we're trying to do is to use our server control to do new protocols and lock out Sun and Oracle specifically....the symmetry that we have between the client operating system and the server operating system is a huge advantage for us"

Naturally this could be cheap talk, and monopolists accused of "leveraging" into adjacent markets have, in the past, successfully defended themselves by arguing that they do not have a sufficient *economic incentive* to limit interoperability in the way suggested. The general defence has relied on the Chicago School's "One Monopoly Profit" theory. This claims that a monopolist can always extract monopoly rents at least as effectively from the market for the complementary product without attempting to monopolize it. In particular, the larger the size/more valuable is the market for the complementary product, the more valuable will be the monopolist's primary product. Consequently, the monopolist can extract all the rents simply by increasing the price of the monopoly product.

In this paper we examine in detail the argument that a monopolist can have an incentive to degrade interoperability and apply this to the market for PC operating systems (where Microsoft has a near monopoly and the European Commission has claimed that it has an incentive to degrade interoperability between Windows and rival server operating systems). We derive conditions under which a monopolist would have such an incentive and how this test can be empirically implemented.

There are short-run and long-run reasons for reducing interoperability. We focus more on the short run as it is easier to confront the short-run model with econometric evidence. The main reason the One Monopoly Profit theory breaks down in our model is that different consumers will have different willingness to pay for PCs and Microsoft cannot perfectly price discriminate between these consumers. As a result, controlling just the PC price will not be a sufficient weapon for Microsoft to extract all the rents in the server market. They will generally price their workgroup servers above marginal costs and use interoperability degradation to shift market share and profitability away form rival servers.

We detail a general model in which heterogeneous consumers choose to buy a workgroup (a bundle of a server and several PCs with their associated operating systems that can be from the same vendors or different vendors), PCs only or nothing. A monopolist of PC operating systems competes with rival sellers of server OSes. Demand is modelled in a general way, and in the empirical application we use an extension to the mixed logit model of Berry, Levinson and Pakes (1995) that explicitly allows price sensitivities to differ by type of consumers (e.g. small businesses and large businesses). The monopolist cannot price discriminate between different firm types due to arbitrage. We then derive the optimal pricing strategies of the players and investigate under what conditions a monopolist will have an incentive to reduce rival quality.

In our model the incentive to degrade interoperability depends on the balance of benefits (shifting market share to Microsoft servers) and the costs (losing some PC demand from lower interoperability). Whether this binds depends on the relative elasticity of demand of different types of customers. For example, customers who want PCs but do not intend to use intensively servers (e.g. small businesses) will also tend to be more price sensitive to PCs than large businesses. The PC monopolist would like to charge large businesses a higher PC price but cannot due to arbitrage. Leveraging into the server market is one way of extracting these unexploited rents. The size of the incentive to degrade quality will depend on the degree, if any, to which large firms are less sensitive to prices than small firms (which determines the relative mark-ups on servers vs. PCs). Heterogeneity among specific groups of consumers in the PC market and elsewhere, although explicitly recognized, for example, by the European Commission [1] in the Hewlett Packard-Compaq merger examination, has not been widely studied before.

In the empirical part of the paper we explicitly confront the theoretical model with econometric estimates of demand system, building on the findings of Genakos (2004). Using data from the US PC and server market since 1995 we estimate a structural model of demand both for the PC market as a whole and for three major segments (Home, Small Business and Large Business) separately. Using these parameter estimates we examine whether the incentive to degrade interoperability exists. We find that it does and that this incentive has grown stronger over time. Furthermore, a monopolist has further incentives to dominate future markets - we show how these reinforce the static incentives in a dynamic extension to the model (Appendix E)[2].

The paper is structured in the following way. Section 2 presents the general theoretical model and section 3 presents a slightly simplified version incorporating the main features of our empirical application. Section 4 de-

[1] "*Because, among other elements, individual consumers show different purchasing patterns,..., the market for PCs could be broken down between consumers and commercial customers.*" Case No COMP/M. 2609-HP/COMPAQ, Office for Official Publications of the European Communities.

[2] First, reduced interoperability lowers the relative incentives for rivals to innovate. This ensures that the workgroup server becomes progressively more monopolized by Microsoft. Secondly, by excluding other firms, Microsoft reduces the threat of the workgroup servers becoming an alternative platform for applications. The existence of such a substitute for PCs would endanger its primary PC OS monopoly. Finally, by controlling the workgroup server bottleneck, Microsoft can leverage into emerging software markets such as the market for delivery of applications on the Internet, for market for Personal Digital Assistants and for wireless devices.

tails the econometrics and section 5 the data. Section 6 discusses the results and section 7 offers some concluding remarks. In the appendices we describe in more detail the econometric techniques (A and B), the data (C), the mapping between the results and theoretical incentive effects (D) and a dynamic extension to the theory (E).

2 Degradation of Interoperability: The General Model

We model the demand for work group purchases. A buyer i of type w has demand for a PC work group which consists of w PCs and 1 server. We assume that each buyer can connect his work group to one server or not connect it. There are J producers of PCs and K producers of servers indexed by j and k respectively. A buyer i with workgroup size w who buys the PCs from producer j and the server from producer k in market t has utility:

$$u_{ijkt}(w) = wx_{jt}\beta_i^* + f(w)A_k y_{kt}\gamma_{ij}^* - \alpha_i^*[wp_{jt} + p_{kt}] + \xi_{jt} + \xi_{kt} + \xi_{jkt} + \varepsilon_{ijkt} \quad (1)$$

The term $x_{jt}\beta_i^*$ captures the quality assessment of buyer i about the PC from producer j. The characteristics of the PC are captures by the vector x_j while the number of PCs that the buyer may purchases are captured by w. The quality of the server purchased is reflected by the expression $f(w)A_k y_k \gamma_i^*$. The vector y_k represents the attributes of the server and the server software, while A_k is diagonal matrix that captures the degree to which each dimension of the server interoperates with the PC operating system (Windows). We normalize things by assuming that $A_k = I$ whenever server producer k has the windows operating system[3]. The expression $f(w)$ indicates how many users are connected to the server[4].

The total price for the work group is given by $wp_{jt}+p_{kt}$. We will allow p_{kt} to take the form $p_{kt}(w) = p_{kt1} + wp_{kt2}$ to allow for server pricing structures in which there is a base price and some w licenses have to be purchased. We can accommodate such pricing without any problems in our approach. The term ξ_{jt} and ξ_{kt} represent PC and server specific unobserved factors in utility and ξ_{jkt} is a cross-effect between PC and server type[5]. The term ε_{ijkt} represents a buyer specific shock to utility for the particular work group solution selected. Not buying any server is included in this setup by allowing y_k to be the null vector. The buyer can decide not to purchase at all, which is represented by x_j and y_j both being null. We do not allow pure server purchases, i.e. x being null and y not, which is justified by complementarity.

This set up includes some brutal simplification from reality. We are assuming that purchases are independent of server or PC stock and that purchase decisions are only about the setup of a whole "work group". If server systems are used for serving one work group we effectively assume that the whole system is scalable by the factor$1/w$. This therefore allows no direct

[3]If there are multiple versions of Windows operating system we normalize the most recent version to generate the matrix $A_k = I$

[4]We will typically make this linear, but the more general form indicates that there can be congestion effects.

[5]The latter may be important to control for differences in server value between laptop and desktop models.

modelling of the impact on firm size. Instead we will allow the heterogeneity across buyers in the parameter vector $(\beta_i^*, \gamma_i^*, \alpha_i^*)$ to depend on firm size. The idea is to make the relationship between size and purchases less dependent on functional form and instead rely on different distributional patterns across subgroups for which we are segmenting the market.

The probability that a type w buyer will purchase jk in period t is given by:

$$s_{jkt}(w) = \int_{A_{jk}(x,y,p,a,w)} dP(\text{relevant random variables} \mid w) \tag{2}$$

and the total demand for PCs of type j from users of system jk is then given by $q_{jk} = M \int w s_{jk}(w) d\Gamma(w)$, where $M \int w d\Gamma(w)$ is the maximal number of PCs that could possibly be sold to all buyers of all types. This means that M is the maximal number of potential work groups. Let $s_{jt}(w) = \sum_{k=0}^{K} s_{jkt}(w)$, then the demand for PC j in period t is given by:

$$q_{jt} = M \int w s_{jt}(w) d\Gamma(w) \tag{3}$$

The demand for server k from users of system jk is analogously given by $M \int s_{jkt}(w) d\Gamma(w)$ and total demand for server k is given by:

$$q_{kt} = M \int s_{kt}(w) d\Gamma(w) \tag{4}$$

where $s_{kt} = \sum_{j=1}^{J} s_{jkt}$. Note that we are summing up from 1 to J here, because the index 0 indicates the choice where there is no PC - and therefore no server - bought. The demand for PC operating systems is then given by $q_{OS} = q_{PC} = M \int w s_{OSt}(w) d\Gamma(w)$, where $s_{OSt} = \sum_{j=1}^{J} s_{jt}$. Let Ω be the set of server sellers k that run the server operating system sold by the same firm as the PC operating system. Then the demand for server operating systems for firm Ω is given by $q_\Omega = M \int \sum_{k\in\Omega} s_{kt}(w)d\Gamma(w)$ and the demand for all servers is given by $q_S = M \int \sum_{k=1}^{K} s_{kt}(w)d\Gamma(w)$. Let ω_{OS} be the price charged by the PC operating system company to the different sellers of PCs[6].

A PC seller j then maximizes profits:

$$(p_j - \omega_{OS} - c_j)M \int ws_j(w)d\Gamma(w) \tag{5}$$

A producer of a server $k \neq \Omega$ who does not produce his own software maximizes:

$$(p_k - \omega_k - c_k)M \int s_k(w)d\Gamma(w) \tag{6}$$

where ω_k is the price for the server operating system that runs on server k. For a producer of a server-software bundle (who does not sell his software to others) ω_k is simply the marginal cost of producing the software copy.

The PC operating system monopolist maximizes:

$$\begin{aligned}
&\sum_{j=1}^{J}(\omega_{OS} - c_{OS})M \int ws_j(w)d\Gamma(w) + \sum_{k\in\Omega}(\omega_\Omega - c_\Omega)M \int s_k(w)d\Gamma(w) \\
= \;& (\omega_{OS} - c_{OS})M \int w(1 - s_{00}(w))d\Gamma(w) + (\omega_\Omega - c_\Omega)M \int \sum_{k\in\Omega} s_k(w)d\Gamma(w) \\
= \;& (\omega_{OS} - c_{OS})q_{PC} + (\omega_\Omega - c_\Omega)q_\Omega
\end{aligned} \tag{7}$$

The condition for profitable quality deterioration will always come from a trade-off of the first term that leads to some marginal purchases of PC

[6]We could allow for price discrimination by Ω between the different PC companies by indexing, i.e. ω_j, but we suppress that possibility for the discussion below.

operating systems not being performed and from the second term, the impact on the number of own servers being sold. We discuss this further below.

This concludes the exposition of the base model. We will now explore some of the issues that arise in simplified versions of this model, which allow us to get more insight in how to interpret our regressions.

3 Theoretical Model Predictions

3.1 Analysis of a simplified model

Given the complementarity of the two products issues of move order will determine the interaction of pricing on the software and the hardware. If the software company moves first then its pricing incentives are not affected by whether the software producer charges the hardware firm or if it charges the consumer directly. However in this case, which is the typical assumption in vertically related markets, the pricing incentives of the software company have to take into account the price reactions of the hardware company.

This is different when the two companies set their prices simultaneously. In this case we have to assume that the price the software company charges is directly added to whatever price the hardware company charges for the computer. In this case the software price conditions on the expected prices for the computers, but we do not have to solve for the pricing policies of the hardware producers to analyze the pricing incentives of the software firm. Below we will take this approach first because of its greater analytical simplicity. We will then discuss the implications of the alternative approach.

The first order conditions for the seller of the PC operating system who also sells a server operating system with the subset Ω of server producers is from (7) given by:

$$\begin{aligned} q_{PC} + (\omega_{OS} - c_{OS})\frac{\partial q_{PC}}{\partial \omega_{OS}} + (\omega_\Omega - c_\Omega)\frac{\partial q_\Omega}{\partial \omega_{OS}} &= 0 \\ q_\Omega + (\omega_{OS} - c_{OS})\frac{\partial q_{PC}}{\partial \omega_\Omega} + (\omega_\Omega - c_\Omega)\frac{\partial q_\Omega}{\partial \omega_\Omega} &= 0 \end{aligned} \tag{8}$$

Denoting $\frac{\partial q_L}{\partial \omega_M}\frac{1}{q_L} = \varepsilon^L_M$, we can solve (8) for the price profit margins as:

$$(\omega_{OS} - c_{OS}) = \frac{\frac{q_\Omega}{q_{PC}}\varepsilon^\Omega_{\omega_{OS}} - \varepsilon^\Omega_{\omega_\Omega}}{\varepsilon^{PC}_{\omega_{OS}}\varepsilon^\Omega_{\omega_\Omega} - \varepsilon^{PC}_{\omega_\Omega}\varepsilon^\Omega_{\omega_{OS}}} \tag{9}$$

$$(\omega_\Omega - c_\Omega) = \frac{\frac{q_{PC}}{q_\Omega}\varepsilon^{PC}_{\omega_\Omega} - \varepsilon^{PC}_{\omega_{OS}}}{\varepsilon^{PC}_{\omega_{OS}}\varepsilon^\Omega_{\omega_\Omega} - \varepsilon^{PC}_{\omega_\Omega}\varepsilon^\Omega_{\omega_{OS}}} \tag{10}$$

To obtain an insight into the relevant elasticities, note that the elasticities of demand relative to these prices for a given type $(\alpha, \beta, \gamma, w)$ are given by:

$$\begin{aligned} \varepsilon^{PC}_{\omega_{OS}}(\alpha,\beta,\gamma,w) &= \frac{1}{q_{PC}(\alpha,\beta,\gamma,w)} wM(\alpha,\beta,\gamma,w)\frac{\partial \sum_{j=1}^J \sum_{k=0}^K s_{jk}(\alpha,\beta,\gamma,w)}{\partial \omega_{OS}} \\ &= \frac{1}{q_{PC}(\alpha,\beta,\gamma,w)} wM(\alpha,\beta,\gamma,w)\frac{\partial}{\partial \omega_{OS}}\left[\frac{\sum_{j=1}^J \sum_{k=0}^K e^{\delta_j+\eta_k}}{1+\sum_{j=1}^J \sum_{k=0}^K e^{\delta_j+\eta_k}}\right] \\ &= -w\alpha s_{oo}(\alpha,\beta,\gamma.w) \end{aligned} \tag{11}$$

and

$$\begin{aligned} \varepsilon^{PC}_{\omega_\Omega}(\alpha,\beta,\gamma,w) &= \frac{1}{q_{PC}(\alpha,\beta,\gamma,w)} wM(\alpha,\beta,\gamma,w)\frac{\partial \sum_{j=1}^J \sum_{k=0}^K s_{jk}(\alpha,\beta,\gamma,w)}{\partial \omega_\Omega} \\ &= \frac{1}{q_{PC}(\alpha,\beta,\gamma,w)} wM(\alpha,\beta,\gamma,w)\frac{\partial}{\partial \omega_\Omega}\left[\frac{\sum_{j=1}^J \sum_{k=0}^K e^{\delta_j+\eta_k}}{1+\sum_{j=1}^J \sum_{k=0}^K e^{\delta_j+\eta_k}}\right] \\ &= -w\alpha s_{00}(\alpha,\beta,\gamma,w)\frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_{PC}(\alpha,\beta,\gamma,w)} \end{aligned} \tag{12}$$

$$
\begin{aligned}
\varepsilon^{\Omega}_{\omega_{OS}}(\alpha,\beta,\gamma,w) &= \frac{1}{q_{\Omega}(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial \sum_{j=1}^{J}\sum_{k\in\Omega} s_{jk}(\alpha,\beta,\gamma,w)}{\partial \omega_{\Omega}} \\
&= \frac{1}{q_{\Omega}(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial}{\partial \omega_{OS}} \left[\frac{\sum_{j=1}^{J}\sum_{k\in\Omega} e^{\delta_j+\eta_k}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\eta_k}} \right] \\
&= -w\alpha s_{00}(\alpha,\beta,\gamma,w) \qquad (13)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon^{\Omega}_{\omega_{\Omega}}(\alpha,\beta,\gamma,w) &= \frac{1}{q_{\Omega}(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial \sum_{j=1}^{J}\sum_{k\in\Omega} s_{jk}(\alpha,\beta,\gamma,w)}{\partial \omega_{\Omega}} \\
&= \frac{1}{q_{\Omega}(\alpha,\beta,\gamma,w)} M(\alpha,\beta,\gamma,w) \frac{\partial}{\partial \omega_{\Omega}} \left[\frac{\sum_{j=1}^{J}\sum_{k\in\Omega} e^{\delta_j+\eta_k}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\eta_k}} \right] \\
&= -\alpha\left(1-\frac{\sum_{j=1}^{J}\sum_{k\in\Omega} e^{\delta_j+\eta_k}}{1+\sum_{j=1}^{J}\sum_{k=0}^{K} e^{\delta_j+\eta_k}}\right) = -\alpha\sum_{k\notin\Omega} s_k(\alpha,\beta,\gamma,w) \qquad (14)
\end{aligned}
$$

To generate the aggregate elasticities we simply need to add up the frequency weighted individual elasticities:

$$
\begin{aligned}
\varepsilon^{PC}_{\omega_{OS}} &= \int \frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} \varepsilon^{PC}_{\omega_{OS}}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} w\alpha s_{oo}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \qquad (15)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon^{PC}_{\omega_{\Omega}} &= \int \frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} \varepsilon^{PC}_{\omega_{\Omega}}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} w\alpha s_{00}(\alpha,\beta,\gamma,w) \frac{q_{\Omega}(\alpha,\beta,\gamma,w)}{q_{PC}(\alpha,\beta,\gamma,w)} dP(\alpha,\beta,\gamma,w) \\
&= -\frac{q_{\Omega}}{q_{PC}} \int \frac{q_{\Omega}(\alpha,\beta,\gamma,w)}{q_{\Omega}} w\alpha s_{00}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \qquad (16)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon^{\Omega}_{\omega_{OS}} &= \int \frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} \varepsilon^{\Omega}_{\omega_{OS}}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} w\alpha s_{00}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \qquad (17)
\end{aligned}
$$

$$\begin{aligned}
\varepsilon^{\Omega}_{\omega_\Omega} &= \int \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\varepsilon^{\Omega}_{\omega_\Omega}(\alpha,\beta,\gamma,w)dP(\alpha,\beta,\gamma,w) \\
&= -\int \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\alpha[1-s_\Omega(\alpha,\beta,\gamma,w)]dP(\alpha,\beta,\gamma,w) \qquad (18)
\end{aligned}$$

We can then determine the sign of ω_Ω and ω_{OS} by noting that (denoting $dP(\alpha,\beta,\gamma,w)$ as $dP(.)$ for brevity)

$$\begin{aligned}
\frac{q_{PC}}{q_\Omega}\varepsilon^{PC}_{\omega_\Omega} - \varepsilon^{PC}_{\omega_{OS}} &= \int \left[\frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right][w\alpha s_{oo}(\alpha,\beta,\gamma,w)]\,dP(.) \\
&= -\int \left[\frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right]\left[\varepsilon^{PC}_{\omega_{OS}}(\alpha,\beta,\gamma,w)\right]dP(.) \\
&= \int \left[\frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right]\left[\bar{\varepsilon}^{PC}_{\omega_{OS}} - \varepsilon^{PC}_{\omega_{OS}}(\alpha,\beta,\gamma,w)\right]dP(.) \qquad (19)
\end{aligned}$$

where the last equality comes from subtracting $-\int \left[\frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right]\bar{\varepsilon}^{PC}_{\omega_{OS}}dP(.) = 0$ from the second line where

$$\bar{\varepsilon}^{PC}_{\omega_{OS}} = \int \varepsilon^{PC}_{\omega_{OS}}(\alpha,\beta,\gamma,w)dP(.)$$

Hence, the price cost margin on servers will be positive if the elasticity $\varepsilon^{PC}_{\omega_{OS}}(\alpha,\beta,\gamma,w)$ is positively correlated is positively correlated with $\frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}} - \frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}$, i.e. if on average buyers with more elastic demand have higher market share in PC purchases than server purchases. If there is no heterogeneity, then this expression is zero. Note that this expression holds quite generally, even when parameters are correlated. It can be computed by specifying conditional distributions in the general case. We will specify the exact outcomes for the two type case with identical w further below.

For ω_{OS} we get that it is proportional to:

$$\frac{q_\Omega}{q_{PC}}\varepsilon^{\Omega}_{\omega_{OS}}-\varepsilon^{\Omega}_{\omega_\Omega} = \int \alpha w s_{00}(\alpha,\beta,\gamma,w)\begin{pmatrix} \frac{M(\alpha,\beta,\gamma,w)-q_\Omega(\alpha,\beta,\gamma,w)}{wM(\alpha,\beta,\gamma,w)-q_{PC}(\alpha,\beta,\gamma,w)}\frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega} \\ +\frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_{PC}(\alpha,\beta,\gamma,w)}\frac{q_{PC}(\alpha,\beta,\gamma,w)}{q_{PC}} \end{pmatrix} dP(.)$$
$$-\frac{q_\Omega}{q_{PC}}\int \alpha w s_{00}(\alpha,\beta,\gamma,w)\left[\frac{q_{PC}(\alpha,\beta.\gamma,w)}{q_{PC}}-\frac{q_\Omega(\alpha,\beta,\gamma,w)}{q_\Omega}\right]dP(.) \tag{20}$$

We can calculate the ratio for the relative mark-up (of servers to PCs)

Relative mark-up

$$\frac{\omega_\Omega - c_\Omega}{\omega_{OS}-c_{OS}} = \frac{\frac{q_{PC}}{q_\Omega}\varepsilon^{PC}_{\omega_\Omega}-\varepsilon^{PC}_{\omega_{OS}}}{\frac{q_\Omega}{q_{PC}}\varepsilon^{\Omega}_{\omega_{OS}}-\varepsilon^{\Omega}_{\omega_\Omega}} \tag{21}$$

Note that for the two type model with fixed w one can simply sum up over the two types instead of integrating. The estimated coefficient on ω_{OS} or p_j in the PC demand equation is αw.

3.2 The incentives to decrease interoperability

There is an incentive to decrease interoperability at the margin if:

$$\frac{\omega_\Omega - c_\Omega}{\omega_{OS}-c_{OS}} > -\frac{\frac{\partial q_{PC}}{\partial a}}{\frac{\partial q_\Omega}{\partial a}} \tag{22}$$

Intuitively, degrading interoperability increases Microsoft server sales but reduces PC sales. The benefit of doing this will depend on the size of the server margin relative to the PC margin (the "relative mark up" on the left hand side of equation (22)). Other things equal the larger the server OS margin $(\omega_\Omega - c_\Omega)$ relative to the PC OS margin $(\omega_{OS}-c_{OS})$ the greater the incentive to degrade. On the other hand, there is a cost as the monopolist must take into account the size of the change in demand from reducing interoperability (a down). The relative size of this change is the term $(\frac{\frac{\partial q_{PC}}{\partial a}}{\frac{\partial q_{\Omega}}{\partial a}})$ on the right hand side of equation (22)), the sensitivity of PC demand to a change in interoperability relative to the sensitivity of Microsoft server demand to such a change. The larger the increase in Microsoft server demand relative to the fall in PC demand following a drop in interoperability the more likely there are to be incentives to degrade interoperability[7]. For the two group equal w case one can explicitly calculate the relative elasticities (of the impact of a change in interoperability on PC demand relative to Microsoft server demand).

Relative Elasticity

$$\frac{\frac{\partial q_{PC}}{\partial a}}{\frac{\partial q_{\Omega}}{\partial a}} = -w\frac{\sum_n v^n s^n_{k\notin\Omega\cup\{0\}}(q^n_s - q^n_{\Omega})}{\sum_n v^n s^n_{\Omega}(q^n_s - q^n_{\Omega})} \tag{23}$$

where q^n_s is the total number of servers demanded by group n, and q^n_{Ω} is the number of Microsoft servers demanded by group n. v^n is the common marginal characteristic between servers and PCs (e.g. interoperability). We discuss this term and its identification in more detail in Appendix B. Note that equation (23) goes to zero as $s^n_{k\notin\Omega\cup\{0\}}$ (the non-Microsoft share of servers) goes to zero and s^n_{Ω} approaches $1 - s^n_{00}$. In other words, as Microsoft's market share of servers gets larger the relative elasticity term will tend towards zero and the incentive to decrease interoperability will become stronger.

[7] Note that this "relative elasticity term" is negative as enhancing interoperability (a up) increases the demand for PCs ($\frac{\partial q_{PC}}{\partial a} > 0$) but reduces the demand for Microsoft servers ($\frac{\partial q_{\Omega}}{\partial a} < 0$).

Why is the inequality sign in equation (22) not an equality? If Microsoft can control interoperability, a, why does it not simply choose an optimal level of a in every period? There are several reasons. Interoperability in the past has generally been high among server OS as most server operating systems are either open standard (e.g. Unix) or open source (e.g. Linux). When Microsoft first entered the server market it based its protocols on these open standards[8]. During this period the incentive to increase interoperability was not binding as it was already close to a maximum (we will show evidence for this in the results section). However, over time as Microsoft's server share has grown, equation (22) at some point either started to bind (or was expected to bind). Interoperability degradation began to occur, but not to the extent that Microsoft would find fully optimal for a variety of reasons. First, there are time lags between the design of the less interoperable software and its diffusion on the market. Second, other players such as Novell, Sun and more recently Linux sought to overcome the fall in interoperability through a variety of measures such as developing "bridge" products, redesigning their own software, reverse engineering, etc. Finally, since the late 1990s anti-trust action in the US and EU may have somewhat slowed down Microsoft's desire to reduce interoperability.

[8]For example, Windows NT security interface was Kerberos that was developed by researchers at MIT. Microsoft's original file system protocols, CIFs, was also an open standard.

4 Econometric Models

4.1 Basic Framework

For the purpose of estimation we adopt the empirical strategy and the econometric techniques found in recent studies of differentiated products, such as Berry (1994), Berry, Levinson and Pakes (1995) and Nevo (2000a). We extend their analysis to allow differential estimation within different segments of the PC market depending on the type of customer (home, small business, large business). Within each segment we use a structural random coefficient discrete choice model of demand for PCs, we are able to control for the endogeneity of prices, while allowing for heterogeneity in consumer preferences within each market segment. As documented in studies of other industries, the use of a random coefficient model results in a more realistic pattern of product substitutions, which is crucial for the calculation of aggregate elasticities.

For our purposes, we assume that the conditional indirect utility, $u_{ijt}(\theta)$, for consumer $i = 1, ..., I_t$ in market $t = 1, ..., T$ for product $j = 1, ..., J_t$ takes the following form

$$u_{ijt}(\theta) = \delta_{jt}(\theta_1) + \mu_{ijt}(\theta_2), \tag{24}$$

where $\theta = (\theta_1, \theta_2)$ are the model's coefficients to be estimated. In the estimation below, a market is defined as each relevant market segment at every point in time.

The first term, δ_{jt}, which represents the mean utility derived from consuming good j and is common to all consumers, is given by

$$\delta_{jt} = x_{jt}\beta - \alpha p_{jt} + \xi_{jt}, \tag{25}$$

where α is the marginal utility of income; x_{jt} and β are vectors of the observed product characteristics and the associated taste parameters, respectively; and ξ_{jt} denotes utility derived from characteristics observed to the consumers and the firms, but unobserved to the econometrician. Unobserved characteristics might include unquantifiable variables such as firm reputation for reliability, prestige effects of certain brands or after-sales service quality. The crucial point is that since these characteristics are observed by market participants, they will be correlated with the equilibrium prices and hence, the price coefficient will be biased towards zero.

The second term, μ_{ijt}, represents a deviation from that mean, which is individual specific and can be written as

$$\mu_{ijt} = \sum_{l} \sigma_l x_{jlt} \nu_{il} + \sigma_p p_{jt} \nu_{ip} + \epsilon_{ijt} \tag{26}$$

where x_{jlt} is the lth characteristic of product j in the tth market, for $l = 1, ..., L$. Each consumer i has $L+1$ idiosyncratic tastes for the L observed characteristics and the price, represented by a vector $\nu_i = (\nu_{ip}, \nu_{i1}, ..., \nu_{iL})$ of random draws from a multivariate normal distribution with zero mean and an identity covariance matrix. Finally, ϵ_{ijt} are shocks that are identically and independently distributed across products and consumers with a Type

I extreme value distribution.[9] Notice that μ_{ijt} depends on the interaction of consumer specific preferences and product characteristics. More precisely, each consumer i derives $(\beta_l + \sigma_l \nu_{ilt})\, x_{lt}$ utility from every lth product characteristic. Berry, Levinson and Pakes (1995) show that allowing for substitution patterns to depend on consumer's heterogeneous tastes (i.e. $\mu_{ijt} \neq 0$) is crucial in order to get more realistic demand elasticities.[10] The intuition behind this formulation is that consumers who attach a higher utility, for example, to laptop computers would more likely substitute towards other laptops rather than desktops.

The specification of the demand system is completed with the introduction of an "outside good". Allowing consumers the possibility of not purchasing any of the personal computers offered by these firms is essential, because otherwise a uniform price increase would not change the quantities purchased. The indirect utility of the outside option is

$$u_{i0t} = \xi_0 + \sigma_0 \nu_{i0} + \epsilon_{i0t}. \tag{27}$$

[9] This particular assumption although facilitates the estimation by insuring nonzero purchase probabilities and smooth derivatives for the market share equation, has recently being critisized. Petrin (2002), for example, shows that welfare changes from the introduction of new products are overstated due to the presence of this idiosyncatic error term. Alternative models, like the probit model of Goolsbee and Petrin (2003) are prohibited for the current application given the number of products in each period. Finally, recent work by Berry and Pakes (2002) and Bajari and Benkard (2003) that attempts to correct for the influence of this error has not yet produced a clear empirically feasible alternative.

[10] When μ_{ijt} is zero, the only source of heterogeneity among consumers is based on the i.i.d. ϵ_{ijt}'s. In terms of elasticities, that implies that all the consumers have the same expected ranking over products. In other words, consumers would substitute more towards the most popular products independently of their characteristics and the characteristics of the products that they were buying before.

where the price of the outside good is normalized to zero. Since relative levels of utility can not be identified, the mean utility of one good has to be normalized to zero. As is customary, we normalize ξ_0 to zero. The term ν_{i0} accounts for the unobserved variance of the outside alternatives and implies the presence of a random coefficient on the constant term in the utility of the inside goods.

Each consumer is assumed to purchase one good per period[11] from the available choice set that provides him with the highest utility. Given the assumption on the distribution of ϵ_{ijt}, the probability that consumer i purchases good j in market t is given by the multinomial logit choice probability (McFadden, 1973)

$$\Pr\left(j \mid x, i\right) = \frac{\exp\left(\delta_{jt} + \sum_{l=1}^{L} \sigma_k x_{jlt} \nu_{il} + \sigma_p p_{jt} \nu_{ip}\right)}{1 + \sum_{l=1}^{J} \exp\left(\delta_{mt} + \sum_{k=1}^{K} \sigma_l x_{mlt} \nu_{il} + \sigma_p p_{mt} \nu_{ip}\right)} \quad (28)$$

Market shares for each product, s_j, are obtained by aggregating over consumers and their vector of unobservable tastes. This integral is solved numerically by simulation using a technique introduced by Pakes (1986). Recall that equation (28) is estimated separately for different consumer groups (home, small businesses and large businesses).

[11] Although this assumption seems reasonable for home or small business users, it might not be applicable to the large business segment. Hendell (1999) for example observes PC data on large firms and models explicitly the choice of multiple products. Without more dissagregate information his techniques can not be applied in the current data, hence if this phenomenon is widespread this model can be seen as an approximation to the true choice model.

We do not observe the proportion of servers of different types bought by consumers buying PCs of specific types. It is not possible to recover estimates of γ_{ij}^* (valuation of server characteristics for PC purchases) and therefore the v^n without further assumptions (group specific valuation of server quality). Appendix C shows how we can do this using aggregate information on server characteristics. Essentially we recover the (group specific) time dummies from the PC demand equations and project the time dummies on our proxy for interoperability (the Windows share of server OS), server prices, other server characteristics (e.g. memory), server prices, group dummies (and interactions) and a polynomial in time. This second stage regression can be used to recover estimate of the group-specific valuations, v^n.

4.2 GMM Estimation

Our estimation strategy closely follows Berry (1994) and Berry, Levinson and Pakes (1995). In essence, the algorithm minimizes a nonlinear GMM function that is the product of instrumental variables and a structural error term. This error term, defined as the unobserved product characteristics, ξ_{jt}, is obtained through the inversion of the market share equations after aggregating appropriately the individual consumer's preferences. Standard errors corrected for heteroskedasticity are calculated taking into consideration the additional variance introduced by the simulation. More details on the estimation are given in the Appendix B.

4.3 Identification and instrumental variables

Identification of the population moment condition, detailed in Appendix B, is based on an assumption and a vector of instrumental variables. In line with other papers in this literature, we assume that the unobserved product level errors are uncorrelated with the observed product characteristics. In other words, the assumption is that the location of products in the characteristics space is exogenous.[12] For the present study, however, this assumption can be though of as being close to the reality of the industry given that most of the R&D and the components that are built in the personal computers are produced by other firms and not the PC manufacturers.

With respect to the instrumental variables, we experimented with various types of instruments that have been suggested in the recent literature. First, in the spirit of the studies by Hausman, Leonard and Zona (1994), Hausman (1996), Nevo (2000a, 2001) and Hausman and Leonard (2002) we tried to use prices of the same models of PCs in Canada[13] as instruments for the US prices. The fact that these two are neighboring countries with very close trade relationships, imply that prices of PCs in Canada have the same cost component and only demand factors are different. Moreover, they could be

[12] Endogenizing the firm's decision of which products to produce conditional on its beliefs about what other firms will produce and the state of future demand in a multidimensional differentiated products oligopoly is still an open research question and beyond the scope of this paper.

[13] Given that we examine only these top nine manufacturers, we were able to match each model with the same model sold in Canada over the same period. The dataset on the Canadian models and prices is also from IDC. These prices were also deflated using the Canadian price index.

partially immune from the Bresnahan (1996) critique of these instruments, in the sense that aggregate shocks (such as a national advertising campaigns) that affect the US demand would be uncorrelated with the Canadian demand. The obvious disadvantage, with respect to the previous studies, is the very small cross-sectional variation (only one instrument for each price).

The second set of instruments follows directly the approach taken by Berry, Levinson and Pakes (1995). They used the sums of the values of the same observed characteristics of other products offered by each firm and the sums of the values of the same characteristics of products offered by other firms. Given the previous assumption on exogeneity, characteristics of other products will be correlated with price since the markup for each model will depend on the distance from its nearest competitors. These type of instruments have been used successfully in the study of many industries.

Lastly, we used a modified version of the previous instruments in the spirit of the study by Bresnahan, Stern and Trajtenberg (1997). They used as instruments functions of the observed characteristics segmented according to their proposed clustering of the PC market during the late eighties. Our modification is much simpler and closer to the reality of competition in the PC industry during late nineties: we calculated functions of the values of the observed characteristics of products offered by each firm and by rival firms conditional on the form factor of each computer. The intuition underlying this modification is that PCs of the same form factor would exert each other a stronger competitive pressure, given the fundamental differences in functionality between a desktop and a laptop and their technical characteristics (in our sample, laptops had always inferior on average specifications compared with their contemporary desktops).

5 Data

Quarterly data on quantities and prices between 1995Q1 and 2001Q2 was taken from the personal computer tracker (PC Tracker), an industry census conducted by International Data Corporation's (IDC). The PC Tracker gathers information both from the major vendors and component manufacturers, but also from the various channel distributors,[14] which makes it one of the best available datasources for the PC industry.[15] The need to match each observation with more detailed product characteristics led us to concentrate on the US market and on the top nine producers.[16] The unit of observation is defined as a manufacturer (e.g. Dell), brand (e.g. Optiplex), form factor (e.g. desktop), processor type (e.g. Pentium II), processor speed (e.g. 266 MHZ) combination. More detailed data information can be found in Appendix A.

A unique aspect of this dataset is that it also provides information on the identity of the PC buyers at an aggregate level, distinguishing among the following segments: Large, Medium and Small Business, Small Office, Gov-

[14] IDC claims that it covers more than 80% of the US market.

[15] Various datasets from IDC have been used both in economics (Foncel and Ivaldi, 2001; VanReenen, 2003; Pakes, 2003) and in management (Bayus, 1998; Bayus and Putsis, 1999, 2001).

[16] These manufacturers are: Acer, Compaq, Dell, Gateway, Hewlett-Packard, IBM, NEC, Sony and Toshiba. Apple was excluded due to the fact that we were unable to match more detail characteristics in the way its processors were recorded by IDC.

ernment, Education and Home.[17] Hence, in the analysis below we estimate demand not only for the market as a whole but also for each of the three following segments individually: Home, Small Business (where Small Business, Small Office and Medium Business were merged) and Large Business. The three segments account for the majority (average 89%) of all PC sales, with the biggest being the Home segment (37%), followed by the Small Business (34%) and the Large Business (17%).

Despite the large number of small producers, the PC industry is rather concentrated with the top five firms accounting for the 52% and the top ten firms for the 72% of the aggregate sales. Appendix Table 1 shows the average percentage shares of the nine firms included in our sample. They account for the 65% of total sales, with 60% and 65% for the home and small business segment, while they reach 80% in the large business segment.

Appendix Tables A2 through A5 provide sales weighted means of the variables that are used in the specifications below, both for the overall market and the different segments. These variables include quantity (in units of 1,000), price (in $1,000 units), benchmark[18] (in units of 1,000), RAM (in units of 100MB), monitor size and dummies for the CD-ROM (1 if standard, 0 otherwise), internet (1 if modem or ethernet included as standard, 0 other-

[17] According to IDC definitions a Small Office is a non-residential business site with less than 10 employees. Similarly, Small Business is a business site with 10 to 99 employees, Medium Business with 100 to 499 employees and a Large Business with 500 or more employees. The Home segment includes all the home purchases, regardless of usage (home office, work-at-home or consumer applications).

[18] This variable is a combination of the type and speed of each processor. See Appendix A for more details. Bajari and Benkard (2002) were the first to use this variable.

wise) and desktop (1 if desktop, 0 if portable). The choice of these variables was based on two criteria: first, to include characteristics that would capture technological innovation (like the benchmark and RAM) and trends in related markets (like the modem/ethernet for internet and CD-ROM for multimedia) and second, the characteristics to be relevant both for the overall market but also for the three segments individually.

Several interesting trends are evident from these tables that reveal the remarkable pace of innovation and competition in this industry. The number of products rises from 88 in the first quarter of 1995 to 277 in the second quarter of 2001, following an upward trend. At the same time, the core characteristics of the computers, benchmark and RAM, follow an amazing on average quarterly growth of 13% and 11% respectively. Also, new components, such as the CD-ROM and the internet peripherals, although installed in 68% and 51% of the new PCs at the beginning, diffuse very quickly and become virtually standards at the end of the sample. Even more spectacularly, this fast technological progress is accompanied by equally rapidly falling prices. In real terms, sales-weighted average price of PCs has fallen by 45% in the late nineties.[19] The combination of falling prices and technological improvements meant that portable computers became affordable for more consumers, which can be seen by the negative trend of the market share of desktops. Finally,

[19] There is also an extensive empirical literature using hedonic regressions that documents the dramatic declines in the quality adjusted price of personal computers. See, for example, Dulberger (1989), Gordon (1989), Triplett (1989), Berndt, Griliches and Rappaport (1995) and Pakes (2003).

there are some revealing differences among the variable means in the different segments. Large Businesses, for example, seem to buy more expensive PCs on average, with better core characteristics and with a stronger preference for portable computers, while lagging slightly behind the other sectors in the adoption of peripherals. Although these differences could be seen as indicative of the different purchasing patters that these segments follow, in order to draw any firm conclusion we need to estimate the aggregate segment elasticities.

The server data that is used in the "second stage" regressions comes from IDC's Quarterly Server Tracker. It is built in a similar way to the PC Tracker (see Van Reenen, 2004 for more details)[20]. As with the PC tracker, information on characteristics is limited so we merged in characteristics data (memory, speed, hard disk size, etc.) from a variety of other datasources. As with the PC industry there have been tremendous falls in quality adjusted prices over time for this industry. One important fact is that Microsoft's share of the work group server industry has been increasingly rapidly over the past 8 years from 20% in 1996 to 65% in 2003. This has lead to concerns that interoperability degradation was one cause of this change in market structure (European Commission, 2003).

[20] IDC's Quarterly Server Tracker is available only from 1996Q1 ro 2001Q1, a slightly shorter time series than the PC Tracker.

6 Results

We turn now on the demand estimates from the simple logit model and the random coefficients logit model for the overall market and each market segment separately, before discussing their implications in terms of the theoretical model.

6.1 Main results

The simple logit model (i.e. $\mu_{ijt} = 0$) is used in order to examine the importance of instrumenting the price and to test the different sets of instrumental variables discussed in the previous section. Table 1 reports the results obtained from regressing the difference in logarithms between each product's market share and the market share of the outside good on prices, characteristics and time dummy variables. In columns 1 and 2 ordinary least squares was used. Despite the rise in the price coefficient and the higher predictive power of the model when we include firm dummies in column 2, the majority (58.4%) of products are predicted to have inelastic demands, which is clearly unsatisfactory.

In order to correct for the endogeneity of prices, we experiment with different instrumental variables in the last five columns of Table 1. In column 3, Canadian prices of the same models were used. The coefficient on price increases, in line with previous research, but approximately a quarter of all the products has still inelastic demand. Columns 4 and 5 use the type of instruments proposed by Berry, Levinsohn and Pakes (1995) and our modified instruments in conjunction with the Canadian prices. Both the coefficient on price and the proportion of inelastic demands remain unaffected. When we use the Berry, Levinsohn and Pakes (1995) type of instruments in column 6, the coefficient on price rises significantly (leaving only 16.45% of products with inelastic demands), but fails to correct for the negative coefficient on RAM (implying that *ceteris paribus* consumers dislike higher to lower RAM) and the positive coefficient on the Desktop dummy (implying that *ceteris paribus* consumers prefer a desktop to a laptop). Also the Hansen-Sargan test of overidentification is rejected, suggesting that the identifying assumptions are not valid.

Our modified instruments seem to be more effective in controlling for the endogenous prices as can be seen from the last column of the table. All the coefficients are statistically significant and have the expected sign, correcting for the anomalies related to the coefficients on RAM and Desktop. The coefficient on price rises even further, leaving no products with inelastic demands even in this simple model. Moreover, the test of overidentified restrictions cannot be rejected at the 1% level of significance, despite the large number of observations. Similar results with respect of the validity of the instrumental variables hold for each of the three market segments as well, but for brevity are not reported here.

Table 2 reports results from the random coefficient model for the whole market. Column 1 replicates column 7 from the previous table to ease comparisons. Due to the difficulty of the full model estimation, a parsimonious list of random coefficients has been selected. As Bresnahan, Stern and Trajtenberg (1997) suggested, because of the modularity of personal computers and the ease with which consumers can re-configure their machines, not all characteristics carry the same weight. For example, consumers might choose a computer that does not have a modem or a CD-ROM as standard not because they do not value it, but simply because they can buy it afterwards and possibly arbitrage any price differences. To the extent that this reconfiguration can be easily done, we would not be able to capture consumers heterogeneous preferences along these dimensions. Hence, we focus here on random coefficients for benchmark (the combination of the type and speed of each processor) and Desktop. The argument is that these variables are essential characteristics of every computer and cannot be as easily altered as other core characteristics (such as RAM or hard disk) or peripherals (such as the modem or the CD-ROM).

Results from the full model are shown in column 2. Identification of the random coefficients is derived from observing multiple markets with changes in the distribution of observed characteristics. Despite the fact that we have a short panel of only six an a half years, the pace of the evolution of the PC market is such that gives us some confidence that we can identify these parameters. For the whole market, three out of four coefficients of the standard deviations have z-statistics greater than two. In the segment estimations (Table 3) eight out of twelve coefficients have Z-statistics greater than two. The large majority of the rest of the coefficients retain their signs and significance in the BLP estimation as in the IV regressions.

The advantage of using the random coefficient model stems from the more realistic substitution patterns among the different PCs, which in turn are crucial for the calculation of the aggregate elasticities. One way to test the implications of our estimates is to compare the estimated markups and percentage margins with some observed values. Since most of these multiproduct firms do not report separately accounting measures for their PC operations we rely on two surveys from the *Financial Times* (10/2/1996 and 4/3/1998) that estimate the gross profit margins for the whole PC industry in the order of 20% in 1996 and around 10% in 1998. Table A6 summarizes the estimated markups and margins for the different models.[21] Markups derived from the OLS regression are too high and they imply that the majority of brands have negative marginal costs. Results from the IV regression still predict an average markup of 21%, which reaches 33% percent at the 90th percentile. On the other hand, profit margins seem much more realistic in the random coefficient model with an average of 14% and a variability well within the reported values. Given that our sample includes all the big PC manufacturers, it seems that the derived elasticities are close to the reality of the market[22].

[21] These quantities are calculated based on the assumption that there exist a pure strategy Bertrand-Nash equilibrium in prices. For more details see Genakos (2004).

[22] It is worth noting that compared to the other two papers that estimate a structural demand model for the PC industry, our estimates fall somewhere in between. Foncel and Ivaldi (2001), using IDC data for the home segment only from various industrialized countries for the period 1995-1999, estimate a nested logit model and report a mean markup of 2.7 for the US in 1999. On the other hand, Goeree (2004) using also quarterly data from a different source for the US home segment between 1996-1998 reports a median

Table 3 reports the analysis broken down by segment and is our key set of results. The first three rows contain results for the home segment, the next three for the small business segment and the final three for the large business segment. Turning to the home segment first we see a qualitatively similar pattern of results to those we saw for the market as a whole. The coefficient on price is biased towards zero in OLS (column (1)) compared to the IV logit in column (2) by a large factor. This is true as we look across all three segments. There is also evidence in column (3), (6) and (9) of random coefficients for price and key characteristics justifying the use of BLP over the simple IV logit.

There is also substantial evidence of different coefficients between the three segments of customer types. Businesses seem to consistently have price coefficients closer to zero (i.e. less elastic demands) than households whatever estimation method is used. The degree of heterogeneity in the price coefficient also seems greater among large businesses (1.79) than small businesses (1.04) and households (0.88). Furthermore, businesses seem to place a higher mean valuation on quality than do households (e.g. in the BLP specification the mean value of "benchmark" is over 2 for large and small businesses and under 1.4 for households).

What does this mean in terms of the aggregate demand elasticities? Using

margin of 5% using a model similar to ours and a 19% median margin from her prefered model. Based on our estimates, the mean and median margins for the home segment are 11.4 and 10.6 percent respectively, which seem to be more realistic than the other two estimates.

the standard method of simulating a 1% increase in the price of all models we calculate aggregate elasticities for the three segments in Table 4. The upper panel gives the IV logit results and the lower panel the BLP results. The BLP aggregate elasticities are somewhat more inelastic than the IV logit results, especially for the home segment (7.9 vs. 4.7). A very consistent pattern of results emerges from both methods, however: the home segment has the most elastic demand and the large business segment the least elastic demand. For BLP the difference is about 1.8 to 1 and for the nested logit it is about 2.5 to 1. As we argued earlier, this implies that a price discriminating monopolist would have strong incentives to charge higher prices to the larger firms because they have more inelastic demand.

We report the results of calculating the second stage regressions linking unexplained shifts in PC demand by group to server characteristics in Table 5 The BLP based estimates are in column (1) and the IV logit results are in column (2). As expected, improved server quality (indicated by the significant server memory variable) is positive correlated with PC demand. Similarly, higher server prices significantly reduce PC demand (the linear server price term is significantly negative suggesting complementarity between PC and server characteristics). PC demand for larger firms is less sensitive to server prices than for small firms[23]. The large positive and significant interaction for Microsoft's server share and large firms indicates that interoperability is

[23] Large firms' PC demand is increasing in server memory to a greater extermt than small firms. The interaction variable was not significant at conventional levels, however, so we have dropped it from the results.

valued significantly more by large firms than small firms.

6.2 Implications for the model

We use the set of parameter estimates from our model to test whether the interoperability condition hold. Recall that the condition for there to exist an incentive for degrade interoperability was given in equation (22) and is re-written below for convenience.

$$\frac{\omega_{\Omega} - c_{\Omega}}{\omega_{OS} - c_{OS}} > -\frac{\frac{\partial q_{PC}}{\partial a}}{\frac{\partial q_{\Omega}}{\partial a}} \tag{29}$$

Intuitively, degrading interoperability increases Microsoft server sales but reduces PC sales. The benefit of doing this will depend on the size of the server margin relative to the PC margin (the "relative mark up" on the left hand side of (22)). Other things equal the larger the server OS margin $(\omega_{\Omega} - c_{\Omega})$ relative to the PC OS margin $(\omega_{OS} - c_{OS})$ the greater the incentive to degrade. On the other hand, there is a cost as the monopolist must take into account the size of the change in demand from reducing interoperability (a down).

We use the common w and two group case (large and small firms). The formula for the relative mark-up is given in equation (21) and the formula for the relative elasticity is given in equation (23). We use a combination of the estimated parameters and market conditions in the United States in 2001Q1 to calculate all the values in equation (22) (Appendix D has the details)[24].

[24] Note that the calculation of the relative elasticity term is computationally much eas-

Table 6 contains the results. In the baseline model (row 1, column 1) we find that the mark-ups among servers are almost six times larger than the mark-ups on PCs. This may seem high, but is not surprising. Analysis of the accounts of server vendors generally finds much higher mark-ups than for PC vendors. Server OS are considerably more complex than PC OS and so generate higher willingness to pay by firms (the marginal costs for both PC and server OS are probably close to zero as most costs are fixed in R&D and marketing). The relative elasticity term is 4.09, much lower than the relative mark-up suggesting that there do exist incentives to degrade interoperability.

The other rows of the table examine various changes in the assumptions used to generate the numbers in order to test the sensitivity of our claims. Our baseline estimates uses the estimated parameters on price, but an alternative is to use the simulated aggregate elasticities of Table 4. This should only make a minor difference and we see that this is the case - the mark up rises only slightly (to 5.86) in row 2. The next two rows examine different assumptions over the average number of PCs to servers in a workgroup (w). We fixed this to be 20 in the baseline but increase this to 30 in row 3 and decrease it to 10 in row 4. Increasing w causes the absolute value of both the relative mark-up and the relative elasticity terms to rise (and vice versa), but the mark-up term still dominates the elasticity term in both cases. Another assumption we have to make in logit estimation is the size of the size of the

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ier than the relative mark-up term as it involves observed quantities and w. The only estimated component are the group specific server valuations. The relative mark-up terms involve all the PC price parameters.

potential market and there is uncertainty over the exact number (see Ivaldi and Verboven, 2001)[25]. To test the sensitivity of the results we increase the potential market by a factor of 10 in row 5. This reduces the mark-up slightly to 5.7 from 5.8 (presumably because this increases the degree of price sensitivity for PCs). Reducing the size of the potential market by a factor of 10 in row 6 increases the mark-up more substantially (to 6.6). In neither case, however, does the incentive to reduce interoperability disappear.

In the final row we reduce Microsoft's share of the server market to what it was in the mid 1990s prior to the accusations that it was degrading interoperability. Interestingly (and consistent with the analytical results in sub-section 3.2) we find that when Microsoft's share was only 30% of the work group server market, the relative elasticity term was very high (almost 30) as the cost of a shift in PC demand was much greater than the benefits of increased Windows NT server demand. In this case there was no incentive to degrade interoperability. This suggests that the incentive to increase interoperability has grown with Microsoft's share of the server market. In the early stages of entry Microsoft's incentives appear to be lower as it penetrated the market, probably for reasons unrelated to interoperability. As it has grown to dominate the market, however, the incentives to exclude rivals has become very strong.

[25] We have used the population of US workers, but this may be an over-estimate as some agents will never buy PCs or servers. It may also be an underestimate as some firms may buy several per worker - e.g. laptops and PCs.

7 Conclusions

In this paper we examine the incentives for a monopolist to degrade interoperability in order to monopolize a complementary market. This is the main concern in the European Commission's recent decision against Microsoft in the work group server market. The incentive to reduce rival quality in a secondary market comes from the desire to more effectively extract rents from the primary market that are limited *inter alia* by the inability to perfectly price discriminate. We have detailed a general model of heterogeneous demand in a logit framework (encompassing Berry et al, 1995, for example) and consider in detail a simplified version of this general model designed to capture the essential features of the empirical application (for PCs and servers). We derived the conditions under which a monopolist would have incentives to degrade interoperability and showed that these conditions are open to econometric investigation.

We implemented our method in the PC OS by estimating demand parameters using several methods including an extension to Berry et al (1995) to allow for different customer segments. We found that the ranking of the demand elasticities for the three segments (large firms had the lowest sensitivity to price, and households the greatest sensitivity).Using estimates from this model we showed that there did appear to be strong incentives for Microsoft to decrease interoperability, and that these incentives have grown stronger over time. In our view, the combination of theory with strong microfoundations and detailed demand estimation is the correct way to confront complex issues of market abuse and should be used more often.

There are limitations over what we have done and many areas for improvement. First, our model is entirely static, whereas it is likely that dynamic incentives are also important in leveraging. Appendix E has some indications of such a dynamic model and an important challenge is how to effectively confront such theoretical models with econometric evidence. Second, data limitations prevented us from fully exploiting the server information, but there are many ways that this could be used more efficiently (see Davis et al, In Process), especially if we have more detailed micro-information on the demand for different types of servers. Finally, the full structure of the random coefficients approach is only partially exploited in our theoretical framework. Although we have gone some of the way in the direction of endogenising characteristic choice (interoperability decisions) there is still a long way to climb.

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Table 1
Results from Logit Demand for PCs in all segments[a]

	OLS		IV				
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Price	-0.33**	-0.47**	-0.69**	-0.68**	-0.70**	-0.78**	-2.74**
	(0.030)	(0.031)	(0.048)	(0.049)	(0.048)	(0.267)	(0.505)
Constant	-9.22**	-9.49**	-8.89**	-8.91**	-8.87**	-8.64**	-3.08**
	(0.177)	(0.187)	(0.220)	(0.233)	(0.221)	(0.772)	(1.456)
Benchmark	0.32**	0.32**	0.44**	0.44**	0.45**	0.49**	1.61**
	(0.088)	(0.084)	(0.086)	(0.082)	(0.086)	(0.176)	(0.308)
RAM	-0.35**	-0.31**	-0.16*	-0.16*	-0.15*	-0.09	1.28**
	(0.090)	(0.089)	(0.095)	(0.096)	(0.095)	(0.207)	(0.377)
CD-ROM	0.09**	0.13**	0.15*	0.15*	0.15*	0.16*	0.29**
	(0.076)	(0.077)	(0.079)	(0.081)	(0.079)	(0.082)	(0.120)
Internet	0.22*	0.34*	0.32**	0.32**	0.32**	0.31**	0.16*
	(0.058)	(0.055)	(0.055)	(0.055)	(0.055)	(0.060)	(0.088)
Monitor Size	-0.02**	-0.02**	-0.02**	-0.02**	-0.02**	-0.02**	-0.05**
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.010)
Desktop	0.62**	0.57**	0.41**	0.41**	0.40**	0.34*	-1.12**
	(0.057)	(0.056)	(0.062)	(0.063)	(0.062)	(0.203)	(0.384)
5^{th} Generation	0.36**	0.33**	0.38**	0.38**	0.38**	0.40**	0.89**
	(0.111)	(0.117)	(0.122)	(0.131)	(0.122)	(0.139)	(0.222)
6^{th} Generation	0.26*	0.27*	0.47**	0.46**	0.48**	0.55*	2.35**
	(0.149)	(0.150)	(0.156)	(0.161)	(0.156)	(0.285)	(0.512)
7^{th} Generation	1.00**	0.97**	1.05**	1.05**	1.05**	1.08**	1.79**
	(0.263)	(0.262)	(0.262)	(0.286)	(0.262)	(0.274)	(0.442)
Firm Dummies	no	yes	yes	yes	yes	yes	yes
Fit/Test of Over	0.130	0.229	-	31.39	63.61	31.24	18.064
Identification[b]			-	(16.81)	(20.09)	(15.08)	(18.47)
1^{st} Stage R^2			0.461	0.4628	0.464	0.0166	0.0084
1^{st} Stage F-test			4043.8	777.2	452.68	210.2	5.02
Instruments[c]							
Canada prices			X	X	X		
IV				X		X	
IV2					X		X
Own price elasticity							
Mean	-0.68	-0.99	-1.43	-1.42	-1.45	-1.61	-5.69
Standard	0.29	0.42	0.61	0.60	0.62	0.69	2.42
Median	-0.64	-0.92	-1.33	-1.32	-1.35	-1.51	-5.32
% of inelastic demands	88.44	58.38	23.79	24.29	22.74	16.45	0

[a] Dependent variable is $\ln(S_{jt})-\ln(S_{0t})$. Based on 4,767 observations for the whole market. All regressions include time dummy variables. Asymptotically robust s.e. are reported in parentheses.
* Z-statistic>1.
** Z-statistic>2.
[b] Adjusted R^2 for the OLS regressions and the Hansen-Sargan test of over identification for the IV regressions with the 1% critical values in parentheses.
[c] Canada prices are the prices of the same models in Canada; IV are the characteristics, the sums of the values of the same characteristics of other products offered by the same firm, the sums of values of the same characteristics of all products offered by other firms, the number of products belonging to the same firm and the number of products of other firms; IV2 are the same as IV, except that we also condition them on the form factor.

Table 2
Results from the random coefficients model for the whole market[a]

	IV[b]	Random coefficient[c]
Variables	(1)	(2)
Means		
Price	-2.74**	-5.94**
	(0.505)	(1.386)
Constant	-3.08**	-1.24
	(1.456)	(4.190)
Benchmark	1.61**	2.59**
	(0.308)	(0.967)
RAM	1.28**	1.71**
	(0.377)	(0.732)
CD-ROM	0.29**	0.32**
	(0.120)	(0.156)
Internet	0.16*	0.11*
	(0.088)	(0.112)
Monitor Size	-0.05**	-0.06**
	(0.010)	(0.023)
Desktop	-1.12**	-5.14*
	(0.384)	(3.990)
5th Generation	0.89**	1.35**
	(0.222)	(0.339)
6th Generation	2.35**	3.84**
	(0.512)	(0.907)
7th Generation	1.79**	2.25**
	(0.442)	(0.735)
Standard Deviations		
Price		1.26**
		(0.604)
Constant		2.50*
		(2.143)
Benchmark		0.13
		(3.122)
Desktop		3.88*
		(2.954)
GMM Objective (df)		3.52 (3)

[a] Based on 4,767 observations for the whole market. All regressions include firm and time dummy variables. Asymptotically robust s.e. are reported in parentheses.
* Z-statistic>1.
** Z-statistic>2.
[b] This is the same as column (7) in Table 1
[c] Parameters estimated via the two-step GMM algorithm described in the estimation section. The standard errors reported take into account the variance introduced through the simulation by bootstrapping the relevant component of the variance in the moment conditions.

Table 3
Results of the demand estimation for the different segments

	Home Segment			Small Business Segment			Large Business Segment		
	OLS	IV	Random Coefficients	OLS	IV	Random Coefficients	OLS	IV	Random Coefficients
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Means									
Price	-0.76**	-5.07**	-6.410**	-0.36**	-3.09**	-5.831**	-0.30**	-1.58**	-5.771**
	(0.071)	(0.534)	(1.123)	(0.033)	(0.498)	(2.002)	(0.034)	(0.313)	(1.566)
Constant	-10.64**	1.28	1.284	-8.56**	-0.71	1.138	-9.56**	-5.83**	-6.008
	(0.327)	(1.529)	(1.944)	(0.199)	(1.469)	(4.001)	(0.202)	(0.939)	(6.654)
Benchmark	0.27**	2.73**	1.372	0.26**	1.71**	2.714**	0.38**	1.12**	2.263**
	(0.130)	(0.346)	(1.523)	(0.095)	(0.294)	(0.781)	(0.097)	(0.213)	(0.799)
RAM	-0.08	0.83**	0.755**	-0.34**	1.47**	2.083**	-0.42**	0.48*	0.615*
	(0.156)	(0.255)	(0.270)	(0.091)	(0.392)	(0.696)	(0.093)	(0.254)	(0.387)
CD-ROM	0.04	0.46**	0.377*	0.27**	0.28**	0.234*	0.28**	0.35**	0.340**
	(0.136)	(0.184)	(0.214)	(0.076)	(0.127)	(0.170)	(0.080)	(0.100)	(0.128)
Internet[a]	1.20**	0.83**	0.761**	0.14**	0.96**	1.314**	0.08*	0.32**	0.365**
	(0.079)	(0.120)	(0.125)	(0.065)	(0.195)	(0.386)	(0.070)	(0.102)	(0.182)
Monitor Size	-0.01*	0.02*	0.026**	-0.03**	-0.07**	-0.085**	-0.06**	-0.08**	-0.082**
	(0.008)	(0.013)	(0.013)	(0.007)	(0.012)	(0.019)	(0.007)	(0.009)	(0.018)
Desktop	1.30**	-2.57**	-7.115*	0.24**	-1.96**	-8.568*	0.40**	-0.53**	-2.597*
	(0.101)	(0.493)	(4.159)	(0.058)	(0.407)	(5.587)	(0.064)	(0.233)	(1.500)
5^{th} Generation	0.34*	1.66**	1.808**	0.37**	1.05**	1.510**	0.29**	0.63**	1.207**
	(0.184)	(0.321)	(0.418)	(0.118)	(0.250)	(0.481)	(0.121)	(0.182)	(0.424)
6^{th} Generation	0.76**	4.69**	5.101**	0.30**	2.81**	4.433**	0.04	1.22**	2.673**
	(0.238)	(0.589)	(0.745)	(0.154)	(0.523)	(1.418)	(0.162)	(0.342)	(0.899)
7^{th} Generation	1.79**	3.53**	3.609**	0.58**	1.90**	2.511**	0.02	0.58*	1.025**
	(0.363)	(0.614)	(0.648)	(0.279)	(0.499)	(0.863)	(0.291)	(0.361)	(0.511)
Standard Deviations									
Price			0.882**			1.042*			1.792**
			(0.444)			(0.609)			(0.712)
Constant			0.759			2.377			4.399*
			(1.179)			(2.652)			(3.810)
Benchmark			1.377**			0.051			0.102
			(0.647)			(1.885)			(5.285)
Desktop			4.374*			5.370*			2.555*
			(2.327)			(4.003)			(2.043)

Notes: All regressions include firm and time dummy variables. Asymptotically robust s.e. are reported in parentheses. * Z-statistic>1. ** Z-statistic>2. Parameters for the random coefficients are estimated via the two-step GMM algorithm described in the estimation section and the standard errors reported take into account the variance introduced by simulation.
[a] Internet dummy equals one if the PC includes as standard a modem for the home segment or an ethernet card for the Small and Large business segment.

Table 4
Estimated Mean Aggregate Elasticities

	Overall Market	Home Segment	Small Business Segment	Large Business Segment
IV Logit	(1)	(2)	(3)	(4)
1995-2001	4.95	7.94	5.93	3.17
Random Coefficient Logit				
1995-2001	3.94	4.70	4.17	2.62

Notes: Aggregate demand elasticity is calculated as the percentage change in total market share from a one percent increase in the price of all products in the market. Results for the overall market and each segment separately are based on the estimated coefficients in Tables 2 and 3.

Table 5
Server characteristics and PC demand

		BLP	IV Logit
		(1)	(2)
Large*Windows	Large*A	22.022	19.646
		(2.746)	(1.737)
Windows	A	-21.592	-8.248
		(7.191)	(3.331)
Server Price*large	Large*P	3.602	3.129
		(1.402)	(0.894)
Server Price	p	-5.185	-2.572
		(1.402)	(0.708)
Server memory	y	2.269	1.492
		(0.532)	(0.233)
Trend	T	-0.832	-0.630
		(.171)	(0.076)
Large	g = large	-13.464	-11.440
		(4.130)	(2.659)

Notes: Dependent variable is group specific period dummies estimates from Tables 3 (42 observations), standard errors are clustered for time period. Large and small firms only (i.e. home dropped because they do not purchase servers).

Table 6
Interoperability Incentives?

	(1) Relative Mark Up	(2) Relative elasticity	(3) Incentive to degrade?
1. Baseline	5.81	4.09	Yes
2. Simulated elasticities	5.86	4.09	Yes
3. w=30(instead of 20)	8.71	6.14	Yes
4. w=10(instead of 20)	2.90	3.05	Yes
5. Potential market*10	5.71	4.09	Yes
6. Potential market/10	6.59	4.09	Yes
7. Microsoft share 30% (instead of 65%)	6.59	29.76	No

Notes: See text for details. Relative mark-up is Microsoft server mark-up relative to PC mark-up. Relative elasticity is the sensitivity to PC demand to interoperability compared to the sensitivity of server demand to interoperability. Theoretical model calibrated with empirical estimates and data from US 2001Q1.

Appendices

A Appendix: Estimation

The estimation strategy closely follows Berry (1994) and Berry, Levinsohn and Pakes (1995). The error term is defined as the unobserved product characteristics, ξ_j, that enter the mean utility. In order to compute these unobserved characteristics, we solve for the mean utility levels, δ, by solving the implicit system of equations

$$s\,(x, p, \delta; \theta_2) = S \tag{30}$$

where $s\,(.)$ is the vector of the calculated market shares and S is the vector of the observed market shares. Essentially, this finds the vector δ, given the nonlinear parameters θ_2, that matches the predicted to the observed market shares. Berry (1994) shows that this vector exists and is unique under mild regularity conditions on the distribution of consumer tastes and in this model it is numerically calculated using BLP's contraction mapping algorithm. Once this inversion has been computed, the error term is calculated as $\xi_j = \delta_j\,(x, p, S; \theta_2) - (x_j\beta + \alpha p_j)$.

Given a set of instruments, $Z = [z_1, ..., z_M]$, a population moment condition can be written as $E[Z'\xi(\theta^*)] = 0$, where $\xi(\theta^*)$ is the above defined structural error term evaluated at the true value parameters. Then, following Hansen (1982), an optimal GMM estimator takes the form

$$\widehat{\theta} = \arg\min_{\theta} \widehat{\xi}(\theta)' Z A^{-1} Z' \widehat{\xi}(\theta), \tag{31}$$

where $\widehat{\xi}(\cdot)$ is the sample analog to $\xi\,(\cdot)$ and A is a consistent estimate of the $E\,[Z'\xi\xi' Z]$.

The intuition behind this procedure is straightforward. The structural residuals were defined above as the difference between the mean utility and the one predicted by the linear parameters, $\theta_1 = (\alpha, \beta)$. The purpose of the GMM estimator is simply to minimize the distance between these two predictions. At the true parameter value θ^*, the population moment condition is equal to zero, so the estimates would set the sample analog of the moments, i.e. $Z'\widehat{\xi}$, equal to zero. If there are more independent moment equations than parameters, we can not set all the sample analogs exactly to zero, but as close to zero as possible. By using the inverse of the variance-covariance matrix of the moments, we give less weight to those moments that have the higher variance. The weight matrix is calculated using the usual two step procedure, starting with an initial matrix given by $Z'Z$. The minimization of the GMM function was performed using both the Nelder-Mead nonderivative search method and the faster Quasi-Newton gradient method based on an analytic gradient. For more details see the appendix in Nevo (2000b).

Finally, using the results in Berry, Linton and Pakes (2003), the number of simulation draws was more than ten times larger than the average number of products in our sample in order to obtain consistent and asymptotically normal estimators for the parameters.

The asymptotic variance of $\sqrt{n}\left(\widehat{\theta}-\theta^{*}\right)$ is given by

$$\left(\Gamma'\Gamma\right)^{-1}\Gamma'\left(\sum_{i=1}^{3}V_i\right)\Gamma\left(\Gamma'\Gamma\right)^{-1} \tag{32}$$

where Γ is the gradient of the moments with respect to the parameters, evaluated at the true parameter values and approximated by its sampling analog. There are three possible sources of variance: the process generating the product characteristics, V_1, the consumer sampling process, V_2, and the simulation process, V_3. The first component is given by the variance of the moment conditions and approximated using its sampling analog. Given that the sample size is taken to be the household population of the US, the contribution of the second component is assumed to be negligible. Moreover, to account for the variance introduced by the simulation, we calculated the third component by bootstrapping fifty times the moment conditions to obtain an estimate of their variance across different sets of simulation draws.[26] Due to the large number of initial draws, the error due to simulation was minimal.

[26] Due to the fact that firm and processor generation specific dummy variables are included in the estimation and also there is a high turnover of products (see also Pakes, 2003, p. 1586), I do not aggregate over moment restrictions for models across any dimension.

B Appendix: The effects of server quality on PC demand

An obvious issue is that our theoretical framework incorporates the impact of server characteristics on the demand for PCs, whereas our PC demand system detailed in the last sub-section is primarily in terms of PC prices and characteristics. Assume for the moment that for a well defined group of buyers (in our case small businesses or large businesses, we supress the group identier n for notational simplicity) there is no unobserved heterogeneity except for the servers (including the server operating system) that they buy. The utility for buyer i purchasing w PCs from firm j and a server from firm k can be written as:

$$u_{ijkt}(w) = \delta_j(x_{jt}, p_{jt}, \xi_{jt}) + \mu_k(y_{kt}, p_{kt}, \xi_{kt}) + \mu_{jk}(y_{kt}, \xi_{jkt}) + \varepsilon_{ijkt} \tag{33}$$

where δ_j is the mean utility obtained for all i purchasing PC j independently of the server they buy. μ_k is the mean utility over different PC users from using server k, i.e. $\mu_k = A_k y_k \bar{\gamma} - \alpha p_k + \xi_k$, where $\bar{\gamma} = \frac{1}{K+1}\sum_{k=0}^{K}\gamma_j$. The term $\mu_{jk} = A_k y_k(\gamma_j - \bar{\gamma}) + \xi_{jk}$ captures the way in which observed and unobserved characteristics of a server j are valued differently for a user of $PC\ j$ relative to the mean. This allows for the possibility of a PC of brand j to work better with the hardware of a server of a specific brand[27]. Note that all possible compatibilities between software are already taken care of in the matrix A_k and that these will not be PC specific because all PCs run the same operating system in our model. Note that all heterogeneity that comes from buyers tastes are captured in the ε_{ijkt} term as in a standard logit model. However, there will be some heterogeneity among the buyers of the $PC\ j$ in terms of the server the buy. To derive demands, we will further assume that ε_{ijk} has an extreme value distribution. Then the market share of firm j in PCs is simply given by:

$$s_j = \sum_k s_{jk} = \sum_{k=0}^{K} \frac{e^{\delta_j + \mu_k + \mu_{jk}}}{1 + \sum_{l=1}^{J}\sum_{k=0}^{K} e^{\delta_l + \mu_k + \mu_{jk}}} = e^{\delta_j} \frac{\sum_{k=0}^{K} e^{\mu_k + \mu_{jk}}}{1 + \sum_{l=1}^{J}\sum_{k=0}^{K} e^{\delta_l + \mu_k + \mu_{jk}}} \tag{34}$$

Taking logs we obtain:

$$\ln s_j - \ln s_{00} = \delta_j + \ln \sum_{k=0}^{K} e^{\mu_k + \mu_{jk}}$$

[27] The simplest example for this would be laptops vs. desktiops.

Consider estimating equation (34) with data across PCs but no server characteristics. The residual, v, (used in equation (23)) can then be constructed as:

$$v = (\ln s_j - \ln s_{oo} - \frac{1}{J}\sum_{j=1}^{J}\left(\ln \sum_{k=0}^{K} e^{\mu_k + \mu_{jk}}\right) - \beta x_j + \alpha p_j) \tag{35}$$

The error then contains theoretically the term $\xi_j + \ln \sum_{k=0}^{K} e^{\mu_k+\mu_{jk}} - \frac{1}{J}\sum_{j=1}^{J}\left(\ln \sum_{k=0}^{K} e^{\mu_k+\mu_{jk}}\right)$. This is nothing else but the j specific deviation from the average. Note that $\frac{1}{J}\sum_{j=1}^{J}\left(\ln \sum_{k=0}^{K} e^{\mu_k+\mu_{jk}}\right)$ is a constant across firms j (for a specific customer group in a specific time period) and can therefore be taken care of by allowing a period specific dummy in each customer group specific demand equation[28].

In the cross-sectional analysis there is no advantage of obtaining any data on the server characteristics. The server parameters can simply not be identified. However, with a panel such as the data here, variations over time in server characteristics can be exploited to identify the server related parameters. We will assume that $\mu_{jk} \simeq 0$ (i.e. that there are few brand specific hardware complementaries between servers and PCs[29]) so that

$$\ln(s_j/s_{00}) = \delta_j + \ln \sum_{k=0}^{K} e^{\mu_k}$$

Approximating the log of the sums by the sum of the logs gives

$$\ln(s_j/s_{00}) \simeq \delta_j + \overline{\mu}_k \tag{36}$$

We could enter the aggregate server characteristics directly into the PC demand equation, but in order to control for all other aggregate influences on PC demand we capture$\overline{\mu}_k$ with a full set of group specific period dummies (τ_t^n). Thus the PC demand system can be estimated consistently without explicitly including server characteristics. In a "second stage" we project the estimated period dummies on variables determining $\overline{\mu}_k$.Empirically our specification is of the form

$$\widehat{\tau}_t^n = \overline{\gamma}_0^n \overline{A_t} + \overline{y}_t \overline{\gamma}_1^n - \overline{\alpha}^n \overline{p}_t + g^n + T(t) + \varsigma_t^n \tag{37}$$

where $\overline{y}$ are mean server characteristics (such as server memory), $\overline{p}_t$ is average server price, g^n are group dummies, $T(t)$ is a polynomial in time

[28]Note that in the absence of an interaction between PC and server quality in the preferences of the consumer only ξ_j would appear in the error term.

[29]We can test the importance of this assumption by looking at surveys of customer purchasing patterns using alternative micro datasources.

and ς_t^n is an error term to capture other omitted factors driving the time dummies. A_t is the indicator of whether the server is Windows based (so $\overline{A_t}$ is Microsoft's market share of servers[30]) and $\overline{\gamma}_0^n$ indicates how much different groups value having Microsoft servers linked to Microsoft PCs (other things held constant). Server prices need to be instrumented in equation (37) and we use supply side cost shifters to do this (i.e. quality adjusted prices of semi-conductors).

C Appendix: Data

As noted in the Data section, quarterly data on quantities and prices[31] between 1995Q1 and 2001Q2 was taken from the PC Tracker census conducted by International Data Corporation's (IDC). The available dataset provided disaggregation by manufacturer, brand name, form factor,[32] chip type (e.g. 5th Generation) and processor speed bandwidth (e.g. 200-300 MHz). However, during the late nineties, there was a surge in the number and variety of new processors, with Intel trying to achieve greater market segmentation by selling a broader range of vertically differentiated processors. At the same time the rise of the internet and the proliferation of the multimedia meant that PCs were differentiated in a variety of dimensions that would be essential to control for. For that purpose we concentrated on the US market and focused on the top nine manufacturers, who represented the majority of sales and for whom reliable additional information could be collected.

Therefore, we matched each observation in the IDC dataset with more detailed product characteristics from various PC magazines.[33] In order to be consistent with the IDC definition of price, we assign the characteristics of the median model per IDC observation if more than two models were available. The justification for this choice is that we preferred to keep the transaction prices of IDC, rather than substitute them with the list prices published in the magazines. An alternative approach followed by Pakes (2003) would

[30] We are also experimenting with alternatives to this such as explicit interoperability indices.

[31] Prices are defined by IDC as "the average end-user (street) price paid for a typical system configured with chassis, motherboard, memory, storage, video display and any other components that are part of an "average" configuration for the specific model, vendor, channel or segment". Prices were deflated using the Consumer Price Index from the Bureau of Labor Statistics.

[32] Form factor means whether the PC is a desktop, notebook or ultra portable. The last two categories were merged into one.

[33] The characteristics data was taken from PC magazines (PC Magazine, PC Week, PC World, Computer Retail Week, Byte.com, Computer User, NetworkWorld, Computer World, Computer Reseller News, InfoWorld, Edge: Work-Group Computing Report, Computer Shopper) and Datasources.

be to list all the available products by IDC observation with their prices taken from the magazines and their sales computed by splitting the IDC quantity equally among the observations. Although, clearly, both approaches adopt some ad hoc assumptions, qualitatively the results would be the same. Both list and transaction prices experienced a dramatic fall over this period and the increase in the number and variety of PCs offered would have been even more amplified with the latter approach. Finally, instead of using the seventeen processor type dummies and the speed of each chip as separate characteristics, we merge them using CPU benchmarks[34] for each computer. Our final unit of observation is defined as a manufacturer (e.g. Dell), brand (e.g. Optiplex), form factor (e.g. desktop), processor type (e.g. Pentium II), processor speed (e.g. 266 MHZ) combination with additional information on other characteristics such as the RAM, hard disk, modem/ethernet, CD-ROM and monitor size.

The potential market size for the Home segment is assumed to be the number of US households (taken from the Current Population Survey), whereas for the Small and Large business is the total number of employees as reported in the Statistics of US Businesses. We performed various robustness checks by reducing the market sizes or by fitting different diffusion curves (not reported here). None of the results change in any fundamental way.

D Appendix: Matching results with the model

We use estimates from various datasources in addition to the parameter estimates. Our calibration is to the situation in the most recent quarter for which we have full information in all datasets (2001Q1). The estimates for the total numbers of PCs by customer type are from the IDC PC Tracker and the total server numbers are from the IDC Quarterly Server Tracker. Following the European Commission (2004) we define the workgroup server market as all servers priced under $25,000 (although nothing changes if we use all servers). The potential market is fixed by the total number of workers in the US. We use an average PC to server ratio of 20 (and compare numbers between 10 and 30 in the sensitivity analysis). The proportion of Microsoft PCs bought by small firms is estimated from using Harte-Hanks survey data on computer usage by business type.

Note that we consider only small firms and large firms and assume that Micorosft can perfectly price discriminate between the home and business segments. Although Microosft does charge a higher price for the Home and Professional editions of XP, it is unlikely that this is perfect price discrimination due to some arbitrage. If we allowed for some restraint on price dis-

[34]CPU benchmarks were obtained from *The CPU Scorecard* (www.cpuscorecard.com). They are essentially numbers assigned to each processor-speed combination based on technical and performance characteristics.

crimination between home and business segments then this would obviously increase Microosft's incentives to degrade interoperability as there would be evene more unexploited rents from the PC operating system.

E Appendix: The long run anti-competitive effects of interoperability degradation

Even when the one monopoly profit theory holds in the short run it is now well recognized that in a world with incomplete contracts there can be important incentives for exclusionary conduct like the degradation of interoperability because of their impact on long run market power. This is similar to Bernheim and Whinston's paper on exclusive dealing which makes the basic mechanism that generates incentives for exclusionary conduct particularly transparent. The important contribution their paper is precisely in making the mechanism transparent. The fact that they look at exclusivity clauses in contracts as one particular exclusionary strategy and that they use an exit mechanism to increase the market power of the firm using the exclusionary strategy in the future are secondary modelling issues. The basic mechanism unveiled is applicable to any strategy with short run exclusionary effects and any mechanism by which the long run competitiveness of the firm that suffers the exclusionary practice is reduced.

In the economic literature exclusionary effects, be they complete through exit or partial through a reduction of the competitiveness of the rival, always rely on two ingredients. First, there has to be some (potentially costly) activity that could potentially directly shift market share to the firm that is trying to generate an exclusionary effect. Secondly, this shift in market share somehow has to reduce the ability of a rival to compete in the future. We will now show that it is a simple exercise to translate these mechanisms into a formal model that is driven by the particular conditions in the software industry.

E.1 A Model of long run exclusion based on applications network effects.

We will simplify the model above a little to have the simplest one monopoly profit model imaginable, but extend it by allowing other complementary products offered by third parties: server specific applications. All buyers have the same value for the overall product: $v + a_i f(n_i)$, where v is the intrinsic value of the PC OS, a_i is the quality parameter for the server OS interoperating with the PC OS. $f(n_i)$ scales this quality by the number of applications n_i that are available, where we assume that $f(0) = 1$. We assume that $f(n)$ is increasing, strictly concave and the Inada conditions hold.

The interaction with server quality parameter a_i indicates a complementarity between server functionality and applications. We also assume that there are no customers that only want the PC OS.

We now look at a dynamic game. In the first stage the PC OS monopolist that also owns the server OS 1 can decide to degrade interoperability with server OS 2. Then both firms compete for customers that will use the operating systems for two periods. In the third stage independent outside companies decide whether or not to invest in developing an applications software for one or the other server OS. Then server operating systems are improved through an exogenous (stochastic) process. We assume that any quality increase in the server OS will be available at no cost to customers who have already bought the software through an upgrade to the old server OS.[35] In the fourth stage the PC OS monopolist and its rival in the server OS market again market their products to a new generation of demand. Finally, in stage 5, applications developers market their applications by setting prices to the final customers.

The last stage of this game can be trivially solved by noting that every application software developer can extract the marginal benefit of his software from a buyer for whose server OS he has written the software. This follows because all buyers who own a given system in the last period will have the same preferences. Hence, the outcome is the same whether we have uniform pricing or buyer specific pricing. Hence, $p_{n_i} = a_i f'(n_i)$ will be the price an applications developer can obtain for each copy in the last period market.

In the fourth stage of the game, the sellers of operating systems face two different customer groups. There is a group that has already purchased an operating system. We assume for simplicity that they will be out of the market. Then there is a new group of customers that newly enter the market (either a new generation or people who were not active as buyers in the previous period because of existing equipment whose equipment has now fully depreciated). Let $\theta_i a_{i1}$ be the server OS quality level achieved by stage 4, where $\theta_i \geq 1$ represents the exogenous quality improvement of the server since stage 2 and a_{i1} the initial quality level. The equilibrium at this stage can then be derived by exactly the same arguments as in section 2 of this paper. We obtain:

Lemma 1 *Let $A_i(\theta_i, n_i) = \theta_i a_i \left[f(n_i) - f'(n_i)n_i\right]$, then: (i) If $A_1(\theta_1, n_1) > A_2(\theta_2, n_2)$, then the PC OS monopolists makes all sales in period 4 of both the PC OS and the server OS extracting the whole value $v + A_1(\theta_1, n_1)$ from the consumer. (ii) If $A_1(\theta_1, n_1) < A_2(\theta_2, n_2)$, then in an equilibrium that does not involve strictly dominated strategies, the PC Os monopolist extracts*

[35] This assumption is inessential for our results but simplifies notation. The assumption also means we do not have to separately look at cases of uniform prices of application software across generations or price discrimination. Again such distinction would make no difference for the qualitative results.

a rent of $v + A_1(\theta_1, n_1)$ from each customer, sets server price $p_1 = 0$, and firm 2 sells the server OS at price $A_2(\theta_2, n_2) - A_1(\theta_1, n_1)$.

Proof. Note that given n_1 applications are being developed for server OS 1 and n_2 applications for server OS 2, buyers anticipate buying all of these applications at a total expense of $\theta_i a_i f'(n_i) n_i$. Hence, their willingness to pay for the bundle i is given by $v + \theta_i a_i [f(n_i) - f'(n_i)n_i]$. Then the whole problem is just like the one in the first section only with $\theta_i a_i [f(n_i) - f'(n_i)n_i]$ replacing the quality parameter of the particular server. The result then follows. ■

A central ingredient in this model is stage 3 at which applications developers have to decide whether to invest into developing an applications software and for which of the server OSs they want to develop the software. We normalize the size of the total population of each generation to a mass of 1. Let s_{it} be the (expected) market share of server OS i in generation t. We assume that applications developers are monopolistically competitive so that they do not perceive an impact of their investment on the total number of applications written for each server OS. The cost of developing an applications software is F. Hence, a software developer will have an incentive to invest in an application for server OS i if and only if:

$$E_{n_i, a_i} \{p_{n_i}(a_i) x_i\} \geq F$$

where x_i is the number of applications sold. With a continuum of potential applications developers and letting s_{i1}be the first period market share, the equilibrium condition becomes

$$\left(s_{i1} E\{\theta_i\} + \int_1^{\infty} \int_{\hat{\theta}_i}^{\infty} \theta_i dG(\theta_i) dG(\theta_j) \right) a_i f'(n_i^*) = F \tag{38}$$

where $\hat{\theta}_i = \max\{1, \theta_j \frac{a_j \left[f(n_j^*) - f'(n_j^*) n_j^*\right]}{a_i \left[f(n_i^*) - f'(n_i^*) n_i^8\right]}\}$. Note that the left hand side of (38) becomes arbitrarily large as $n_i \to 0$. Furthermore, as $n_i \to \infty$, $f'(n_i) \to 0$ and, since the expression in brackets cannot exceed $(s_{i1} + 1) E\{\theta_i\}$, the left hand side converges to zero. Hence, there exists a solution n_i^* to this equation. Note that on the left hand side of these equations an increase the number of applications written for a specific server OS generates two countervailing effects on the marginal returns of further investments into applications for that server. First there is the direct marginal benefit effect. This is always negative. The second comes in through a network effect. More applications increase the probability that the server type for which the software was written will be the one that is sold in period 4. Now note that at an equilibrium the marginal direct effect must always outweigh the marginal network effect of entry because otherwise a marginal firm could enter and generate strictly positive profits. Hence, we have:

$$\left(s_{i1}E\{\theta_i\} + \int_1^\infty \int_{\hat{\theta}_i}^\infty \theta_i dG(\theta_i)dG(\theta_j)\right) \frac{f''(n_i^*)}{f'(n_i^*)} + \frac{\partial \hat{\theta}_i}{\partial n_i} \int_1^\infty \hat{\theta}_i g(\hat{\theta}_i)dG(\theta_j) < 0$$

at an optimal entry decision given n_j^*. We will assume for the sake of technical simplicity that there exists only a single n_i^* for any given n_j^* that satisfies the equation above. From this we can now directly sign the changes in incentives that result from changes in the parameters applications developers face:

Lemma 2 *The number of applications for server i increases in s_{i1} and a_i and decreasing in n_j^* and a_j.*

Proof. Let $L(n_i^*, v)$ be the left hand side of the free entry condition above and v one of the parameters. Then comparative statics with respect to a variable v are given by:

$$\frac{dn_i^*}{dv} = -\frac{L_v}{L_{n_i^*}},$$

where $L_{n_i^*} < 0$ by the second equilibrium condition. Then the result follows from the fact that $L_{s_{i1}} > 0, L_{a_i} > 0$, $L_{n_j^*} < 0$ and $L_{a_j} < 0$. ■

A higher market share in the first period implies that there is a higher customer base when the applications have been written. This is a direct effect of first period purchases on second period demand for applications. The other comparative statics effects are mediated through the impact on second period server sales. Essentially, increasing the relative quality of one server OS will increase the marginal benefit from writing for that server OS because it becomes more likely to be adopted by the new generation. This relative quality increase can come first because an earlier quality advantage may make it more likely that quality is also better in the future and, secondly, that more applications will also increase the probability that the product is adopted, leading to a positive feedback (network effect) on the incentives for developing applications. Indeed, these comparative statics carry over to the equilibrium behavior.

Proposition 3 *In the best and worst equilibrium from the point of view of firm i, n_i^* increases and n_j^* decreases as s_i and a_i increase and as a_j decreases.*

Proof. Equilibrium conditions are the same as in a two player game in which player i maximizes payoffs

$$\int_0^{n_i^*} \left[\left(s_{i1}E\{\theta_i\} + \int_1^\infty \int_{\hat{\theta}_i}^\infty \theta_i dG(\theta_i)dG(\theta_j)\right) a_i f'(n_i) - F\right] dn_i$$

over n_i^*. This game is supermodular in $(n_i^*, -n_j^*)$ and has positive first differences in (n_i^*, s_i), (n_i^*, a_i) and $(n_i^*, -a_j)$ as well as in $-n_j^*$ and these three parameters. Hence, by Milgrom and Roberts (1991) the claimed comparative statics properties follow. ■

While there may be multiple equilibria, the set of equilibrium outcomes systematically moves with first period market share and first period quality. The first one is the most fundamental effect, since it occurs because operating systems are a durable good that will generate a stock of demand for complements in the future (see Kühn and Padilla 1996 for a basic discussion of the demand creating role of durables for complementary goods in the future). The second effect comes about because of any effects of quality provided to the first generation on quality provided to the next generation. If this relationship were completely random there would be no such effect. If the state of technology determines to some degree how likely the possibility of overtaking the rival in quality is, then first period quality differences will be amplified through the third period applications development decisions.

It may be argued that any quality degradation initially could be reversed later on, so that interoperability decisions would have no systematic direct effect on third period applications investment decision. Even then the indirect effect through the established market share of a server OS i initially will have a systematic effect. For this reason our results will not be affected if we would allow the period 1 decision of the PC OS monopolist to be reversed before stage 3.

We are now in a position to analyze competition between the suppliers of server OSs for the first generation of customers. Customers will be forward looking and anticipate the development of applications in the future. Hence, their value of purchasing the PC OS together with a server OS from firm i is given by:

$$2v + a_i[1 + E\{\theta_i\}[f(n_i^*) - f'(n_i^*)n_i^*]] - w - p_i$$

Note that n_i^* will depend not only on a_i and a_j, but also on s_i, the market share a buyer expects server OS i to have in the market in his own generation. This implies that there is a network effect among buyers of the same generations. A buyer of server OS i wants other buyers to purchase that server OS as well because this improves the provision of applications software in the future.

Define $\Psi_i(s_1) = a_i[1 + E\{\theta_i\}[f(n_i^*(s_1) - f'(n_i^*(s_1)n_i^*(s_1)]]$. First generation Customers will purchase from firm i, if

$$2v + \Psi_i(s_1(p_i, p_j)) - p_i > 2v + \Psi_j(s_1(p_i, p_j)) - p_j$$

and

$$2v + \Psi_i(s_1(p_i, p_j)) - p_i \geq w$$

where $s_1(p_i, p_j)$ is the market share of firm 1 if server prices p_i and p_j are charged. Clearly, the coordination issue between buyers complicates the analysis here, because a price cut may induce a switch away from the price cutting firm if buyers expect other buyers to switch away as well.

To analyze this game we also need to specify the precise payoffs of the firms. The payoff of the PC OS monopolist is given by:

$$w + s_1 p_1 + v + E_{\theta_1}\{A_1(\theta_1, n_1^*(s_1))\}$$

The firm gets w from all buyers in the first period and p_1 from those that purchase its server OS. Furthermore, we have shown in Lemma 1 that its profits from the second generation of consumers is $v + E_{\theta_i}\{A_1(\theta_1, n_1^*(s_1))\}$. Hence the PC OS monopolist gains both from first generation customers from increased market share in the standard way, but also benefits because his expected profits are rising in the number of second period customers. The payoffs of firm 2 are given by:

$$(1 - s_1)p_2 + E_{\theta_1,\theta_2}\{\max\{A_2(\theta_2, n_2^*(s_1)) - A_1(\theta_1, n_1^*(s_1)), 0\}\}$$

Again, winning market share today leads to higher profits from first generation customers but also allows a larger extraction of rents from second period customers as well. The following Proposition repeats the basic results of the simple model of section 2:

Proposition 4 *(i) Suppose $\Psi_1(1) > \Psi_2(1)$, then in any equilibrium in which all first generation customers purchase from the same firm, $p_1^* \leq \Psi_1(1) - \Psi_1(1)$, and firm 1's equilibrium profits are $3v + \Psi_1(1) + E_{\theta_1}\{A_1(\theta_1, n_1^*(1))\}$. (ii) Suppose $\Psi_2(1) > \Psi_1(1)$, then in any equilibrium in which all first generation customers purchase from the same firm, $p_2^* = \Psi_2(1) - \Psi_1(1)$, and firm 1's equilibrium profits are given by $3v + \Psi_1(1) + E_{\theta_1}\{A_1(\theta_1, n_1^*(0))\}$.*

Proof. Consider an equilibrium in which all first generation customers buy from one of the two firms and let $\Psi_i(1) - \Psi_j(1) > 0$. Suppose firm j makes the sales at a price $p_j \geq 0$. Then firm i could lower the price to $p_j + \Psi_i(1) - \Psi_j(1) - \varepsilon > 0$ and obtain a strict profit in the first period and also increase its second period profit. Hence, firm i makes the sale. Since $p_j \geq 0$, it can make the sale at any price $p_i \leq \Psi_i(1) - \Psi_j(1)$. If $i = 2$ the firm will charge at least $\Psi_i(1) - \Psi_j(1)$ in equilibrium. If $i = 1$ it could charge a price below $\Psi_1(1) - \Psi_1(1)$ and increase the whole sale price w to make up the difference. Suppose firm i would charge more than $\Psi_i(1) - \Psi_j(1)$. Then firm j could induce all customers to switch at a price $p_j > 0$, contradicting the claim that this is an equilibrium. Existence of such an equilibrium is also straightforward to see. ∎

This proposition is entirely analogous to the equilibrium characterization result in section 2. Relative to the first generation of consumers the PC OS monopolist can extract the same surplus independently of whether his server OS is purchased or not. However, his extraction possibilities relative to the second generation depend on his market share in the first generation market.[36] Hence, if the PC OS monopolist looses the first stage competition, his profits will be strictly lower, than when he wins it. It should be noted that it is possible to have some other equilibria in this model in which the two firms share the market. However, any such equilibria would be sustained by beliefs that a price cut by a firm would induce customers to switch away from that firm. Such switch would be made credible for each customer by the quality enhancing effect of the switch of others. Such equilibria rely on a perverse coordination effect where, locally, firms face upward sloping residual demands at equilibrium. We believe for practical purposes it is safe to assume that firms expect residual demand for a product never to decrease if the price for that product falls. Then the equilibria we have characterized here are the only equilibria in this market.

E.2 The incentive to degrade interoperability

It is now easy to see that degradation of interoperability can be a profitable strategy for the monopolist. This works through two channels. First, if the degradation of interoperability in stage 1 is permanent and reduces the quality of the rival's product in the future this will shift investment in applications software away from firm 2 and two firm 1. This could also happen if the reduction in interoperability reduces the likelihood that firm 2 will produce an overtaking innovation in stage 4. As far as information about existing technology increases the ability to innovate further, this is a realistic issue in this market. Secondly, the PC OS monopolist also has an incentive to degrade interoperability when its rival has a better server product in terms of the expected net present value to buyers. By degrading interoperability the monopolist can inefficiently switch the choices of the first generation. The incentive to do this comes from the ability to extract more surplus from second generation buyers in the future. We will discuss in the next section, that this is precisely the type of mechanism that Bernheim and Whinston employ in their exclusive dealing paper.

Proposition 5 *The PC OS monopolist has strict incentives to degrade interoperability with the server OS of firm* 2*. If second period quality is not*

[36] This result depends on the assumption that firms cannot set negative prices. If arbitrarily negative prices could be set the bidding process would bring the prices of firm 1 down to its opportunity costs of loosing business in the second generation market and a neutrality result would occur. However, this is would be a highly questionable model given that at negative prices everyone would want to buy the OS even if it is not used.Furthermore, many slight variations of the model will make the PC monopolist care about his margin in the server OS market (as for example in our model that demonstrated the short run effect or in a model with some product differenbtiation) and the qualitative results of such extensions are better captured in the model with the assumption that price cannot become negative.

directly affected by current restrictions on interoperability, reductions in interoperability will still be profitable if firm 2 is more efficient and the reduction in interoperability is large enough.

Proof. The profits of firm 1 in this market are given by $\Pi_1(a_2) = 3v + \Psi_1(1) + E_{\theta_1}\{A_1(\theta_1, n_1^*(s_1))\}$. Let a_2^u be the undegraded quality level and a_2^d be the quality level after degradation of interoperability. Clearly,

$$\begin{aligned}\Pi_1(a_2^u) - \Pi_1(a_2^d) &= -\int_{a_2^d}^{a_2^u} \frac{d\Psi_1(1)}{da_2} da_2 - E_{\theta_1}\{\int_{a_2^d}^{a_2^u} \frac{\partial A_1(\theta_1, n_1^*(s_1))}{\partial n_1^*} \frac{\partial n_1^*(s_1)}{\partial a_2} da_2 \\ &\quad + \left[E_{\theta_1}\{A_1(\theta_1, n_1^*(a_2^d, 1))\} - E_{\theta_1}\{A_1(\theta_1, n_1^*(a_2^d, s_i))\}\right]\end{aligned}$$

where the first line of the right hand side is the effect that comes from the degradation of future quality of the rival through current reduction in interoperability, keeping the initial market share constant. The second line is the impact of a change in current quality of the rival through current reductions in interoperability. This effect is clearly zero if the PC OS monopolist was already making all the sales of the server OS. However, if the rival were to sell the server OS in an equilibrium without quality degradation, the PC OS monopolist always has the choice of reducing interoperability so much that using the rival server Os is useful. This will clearly increase second period profits by increasing the ability to extract rents from second period customers. It has no costs in terms of first period sales, on the contrary, if the current quality degradation also lowers future quality of the rival server OS this effect will be reinforced. ■

It should be stressed that we started from a one period model in which the one monopoly profit theory holds. As soon as in a two period framework it is not possible to extract all the benefits firm 1 could get as a monopolist without competition, there is an incentive to degrade the rival's server OS quality in order to achieve extraction possibilities in the last period. The way first period market shares matter for second period profit extraction possibilities is through the well recognized applications network externality present in markets for operating systems. Any artificially generated shift in first period market share is translated into greater relative investments in applications for the PC Os monopolist's server OS. This same effect could equally be generated through increasing the cost of the rival, because it simply works through the resulting market share effect. Similarly, this effect will work if it is sufficiently costly to counteract rivals sabotage through interoperability decisions, so that it is unprofitable to overcome the quality degradation induced by degraded interoperability. These are results that should be regarded as very robust and are fully in line with recent work on exclusionary strategies by Bernheim and Whinston (1998), Rey, Tirole, and Seabright (2001), Cremer, Rey, and Tirole (2000), and Carlton and Waldman (2000).

E.3 An extension covering broader claims

The model we have developed above has much broader interpretations than the literal interpretation given in the model exposition section. First, the modelling of interoperability degradation as a direct reduction in the quality of the rival server OS is just for modelling convenience: it makes the verbal discussion more transparent because we only have to talk about the different server OSs and their qualities and not of the "qualities of the PC OS/server OS bundles". In reality Microsoft does, of course, not degrade the quality of the rival server OS. Instead it degrades the quality of its own PC OS whenever that PC OS interoperates with a Microsoft server. The model should make clear that such a distinction is only semantic. All that matters for the arguments in our models is that by reducing interoperability the overall quality of the PC OS/rival server OS system is reduced. We could formulate this explicitly, but mathematically the two models would be identical. Quite generally, this is an access problem to the functionalities of the PC OS and the models show that discriminatory access quality degradation is a real possibility in such markets.

This discussion should also make clear that our choice of letting the applications network effect run through server applications is an arbitrary one. In particular, the story of defensive leveraging against rival server OSes becoming a substitute for future editions of the Microsoft PC OS is covered by this analysis. All we need is that there is an interaction term between interconnection (i.e. server quality) and the value of applications run on either the server or the PC. In this slight modification of the model, applications producers would decide to either write applications to run on the Microsoft PC OS or as thin client applications on the rival server OS. Just as Netscape combined with Java could be used as an alternative platform for applications software writers, a server OS could be used as a platform for applications that only require minimal functionality on the PC desktop. It should be clear to the reader that the model could simply be reinterpreted in that way given that the a_i term can be treated as the quality of a specific bundle solution regardless of where applications are run. However, it should be pointed out that there is an additional effect that strengthens the argument even more. When applications are written to the server OS as thin client applications, customers have no need of upgrading the PC OS. Hence, there is the additional effect that such applications development will reduce the demand for PC OSs in the future, creating additional incentives for early exclusion of rival server OSs. Foreclosure via exclusive dealing arrangements is the most appropriate analogy for understanding the foreclosure effects of degraded interoperability.

Appendix Table A1
Sample Market Coverage

Firm	Average Percentage Unit Share			
	Whole Market	Home Segment	Small Segment	Large Segment
Acer	3.31	2.16	5.32	2.89
Compaq	14.75	13.67	13.02	20.51
Dell	12.65	3.96	15.81	22.71
Gateway	7.61	10.52	5.28	3.92
Hewlett-Packard	7.46	9.25	5.84	9.40
IBM	7.37	4.51	9.49	10.80
NEC	7.18	12.98	4.07	3.29
Sony	0.74	1.23	0.67	0.18
Toshiba	3.60	1.46	5.04	5.89
Overall	64.66	59.74	64.53	79.58

Notes: Numbers shown are average firm market shares for the period 1995Q1-2001Q2 in the overall market and in each segment separately.

Table A2
Descriptive Statistics for the whole market

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Internet	Monitor size	Desktop
1995Q1	88	28.701	2.410	0.140	0.103	0.678	0.513	12.050	0.815
1995Q2	106	23.083	2.370	0.155	0.114	0.690	0.516	11.636	0.799
1995Q3	112	27.673	2.222	0.176	0.130	0.784	0.578	12.390	0.839
1995Q4	118	31.433	2.208	0.192	0.133	0.796	0.597	12.212	0.834
1996Q1	127	25.287	2.285	0.221	0.142	0.847	0.604	12.376	0.813
1996Q2	125	26.559	2.264	0.237	0.150	0.879	0.617	12.367	0.791
1996Q3	124	32.358	2.260	0.264	0.158	0.931	0.665	12.930	0.786
1996Q4	143	31.272	2.108	0.293	0.177	0.933	0.670	13.421	0.780
1997Q1	160	24.719	2.116	0.363	0.219	0.931	0.643	12.169	0.773
1997Q2	195	20.984	2.038	0.413	0.245	0.943	0.659	12.069	0.781
1997Q3	222	22.629	1.998	0.476	0.277	0.977	0.711	11.336	0.792
1997Q4	241	22.572	1.912	0.525	0.313	0.962	0.731	11.672	0.816
1998Q1	245	19.502	1.939	0.609	0.375	0.941	0.783	12.189	0.817
1998Q2	253	18.217	1.903	0.708	0.434	0.961	0.749	12.414	0.795
1998Q3	250	22.883	1.801	0.792	0.489	0.968	0.770	12.898	0.802
1998Q4	182	36.279	1.758	0.915	0.600	0.939	0.845	13.313	0.808
1999Q1	156	37.409	1.674	1.051	0.724	0.944	0.812	15.058	0.811
1999Q2	156	39.256	1.607	1.119	0.771	0.931	0.835	15.822	0.790
1999Q3	136	48.581	1.536	1.259	0.857	0.941	0.889	16.083	0.791
1999Q4	149	48.340	1.465	1.447	0.946	0.944	0.879	15.980	0.795
2000Q1	203	33.184	1.411	1.753	0.958	0.982	0.869	14.060	0.797
2000Q2	226	28.448	1.437	1.933	1.018	0.977	0.855	14.234	0.753
2000Q3	237	32.061	1.381	1.995	1.016	0.978	0.875	14.267	0.752
2000Q4	287	26.080	1.337	2.171	1.056	0.978	0.887	14.868	0.775
2001Q1	249	24.715	1.324	2.390	1.103	0.980	0.871	15.069	0.765
2001Q2	277	19.326	1.331	2.725	1.231	0.975	0.886	15.225	0.730
ALL	4767	27.804	1.752	1.114	0.624	0.934	0.777	13.706	0.789

Note: All the entries in the last seven columns are sales weighted means.

Table A3
Descriptive Statistics for the Home Segment

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Modem	Monitor size	Desktop
1995Q1	67	16.206	2.065	0.147	0.105	0.735	0.673	14.139	0.917
1995Q2	78	11.614	1.992	0.161	0.113	0.765	0.681	13.995	0.891
1995Q3	85	15.477	1.916	0.181	0.129	0.859	0.767	14.263	0.927
1995Q4	87	19.069	1.929	0.197	0.134	0.867	0.787	14.196	0.926
1996Q1	76	16.962	2.032	0.223	0.147	0.928	0.842	14.689	0.946
1996Q2	82	12.720	1.996	0.231	0.148	0.929	0.808	14.545	0.920
1996Q3	83	18.474	2.036	0.264	0.160	0.974	0.856	14.635	0.924
1996Q4	92	19.611	1.729	0.291	0.174	0.988	0.892	15.040	0.955
1997Q1	101	15.157	1.747	0.364	0.228	0.986	0.875	12.607	0.956
1997Q2	125	10.517	1.641	0.393	0.238	0.991	0.900	13.265	0.944
1997Q3	141	12.655	1.665	0.460	0.263	0.998	0.919	11.561	0.950
1997Q4	153	13.882	1.663	0.521	0.306	0.997	0.908	12.971	0.967
1998Q1	150	11.551	1.730	0.620	0.366	0.999	0.901	13.852	0.965
1998Q2	163	8.674	1.702	0.731	0.443	0.999	0.867	13.703	0.961
1998Q3	167	11.356	1.660	0.824	0.514	0.999	0.873	13.423	0.955
1998Q4	134	18.841	1.575	0.933	0.623	0.998	0.849	13.132	0.930
1999Q1	117	19.906	1.485	1.030	0.798	0.983	0.888	15.059	0.922
1999Q2	119	17.462	1.395	1.125	0.886	0.941	0.914	15.538	0.887
1999Q3	107	23.779	1.325	1.243	0.940	0.924	0.949	16.041	0.904
1999Q4	114	29.071	1.278	1.425	0.978	0.923	0.914	16.231	0.902
2000Q1	167	19.321	1.229	1.755	0.876	0.988	0.874	14.147	0.900
2000Q2	169	14.631	1.226	1.891	0.938	0.981	0.860	14.674	0.857
2000Q3	179	17.442	1.151	1.906	0.904	0.976	0.878	14.701	0.863
2000Q4	199	16.198	1.112	2.112	0.988	0.973	0.861	15.688	0.886
2001Q1	167	13.873	1.097	2.361	1.059	0.971	0.806	16.739	0.874
2001Q2	195	9.285	1.122	2.727	1.221	0.959	0.798	16.799	0.828
ALL	3317	15.494	1.504	1.118	0.627	0.957	0.863	14.602	0.913

Note: All the entries in the last seven columns are sales weighted means.

Table A4
Descriptive Statistics for the Small Business Segment

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Ethernet	Monitor size	Desktop
1995Q1	88	11.010	2.576	0.135	0.100	0.643	0.085	10.737	0.754
1995Q2	106	9.487	2.528	0.151	0.112	0.655	0.109	10.592	0.755
1995Q3	112	10.543	2.400	0.172	0.128	0.741	0.115	11.312	0.783
1995Q4	118	11.642	2.398	0.190	0.132	0.752	0.112	10.948	0.770
1996Q1	127	9.864	2.389	0.218	0.139	0.789	0.131	11.060	0.736
1996Q2	123	11.960	2.345	0.240	0.151	0.852	0.196	11.524	0.746
1996Q3	119	13.389	2.374	0.263	0.157	0.905	0.204	12.125	0.714
1996Q4	137	12.787	2.328	0.294	0.179	0.899	0.167	12.577	0.678
1997Q1	153	9.844	2.312	0.361	0.214	0.898	0.068	12.072	0.669
1997Q2	189	9.076	2.203	0.422	0.248	0.922	0.108	11.685	0.711
1997Q3	214	9.235	2.143	0.482	0.282	0.966	0.158	11.326	0.709
1997Q4	229	9.013	2.049	0.527	0.315	0.946	0.197	10.971	0.726
1998Q1	231	8.185	2.031	0.598	0.375	0.918	0.319	11.454	0.739
1998Q2	242	8.268	1.975	0.698	0.429	0.949	0.296	11.926	0.730
1998Q3	242	10.091	1.864	0.776	0.473	0.956	0.349	12.783	0.721
1998Q4	172	15.181	1.856	0.897	0.581	0.913	0.335	13.412	0.722
1999Q1	154	13.706	1.791	1.062	0.677	0.922	0.321	15.011	0.727
1999Q2	153	15.047	1.723	1.109	0.719	0.926	0.329	15.840	0.721
1999Q3	136	17.252	1.672	1.263	0.811	0.950	0.297	16.033	0.704
1999Q4	146	15.667	1.628	1.452	0.904	0.952	0.308	15.771	0.686
2000Q1	200	10.536	1.571	1.722	1.008	0.986	0.323	14.325	0.683
2000Q2	223	10.480	1.559	1.929	1.051	0.977	0.367	14.291	0.667
2000Q3	233	11.496	1.535	2.040	1.086	0.980	0.390	14.354	0.657
2000Q4	281	9.058	1.476	2.223	1.106	0.978	0.380	14.783	0.682
2001Q1	241	9.045	1.436	2.399	1.137	0.980	0.415	14.757	0.681
2001Q2	267	7.782	1.415	2.720	1.225	0.974	0.489	14.762	0.644
ALL	4636	10.737	1.902	1.077	0.604	0.918	0.277	13.279	0.707

Note: All the entries in the last seven columns are sales weighted means.

Table A5
Descriptive Statistics for the Large Business Segment

Period	No. of models	Quantity	Price	Benchmark	RAM	CD-ROM	Ethernet	Monitor size	Desktop
1995Q1	74	6.365	2.839	0.133	0.105	0.616	0.127	9.936	0.708
1995Q2	88	6.083	2.697	0.152	0.117	0.626	0.150	9.605	0.726
1995Q3	93	6.484	2.541	0.172	0.133	0.705	0.155	10.416	0.757
1995Q4	98	6.901	2.510	0.187	0.132	0.712	0.154	9.915	0.735
1996Q1	104	6.439	2.550	0.221	0.138	0.799	0.187	10.388	0.703
1996Q2	103	7.823	2.437	0.240	0.151	0.863	0.254	11.089	0.706
1996Q3	99	8.946	2.441	0.266	0.157	0.905	0.279	11.426	0.674
1996Q4	114	8.034	2.437	0.294	0.178	0.889	0.236	11.845	0.628
1997Q1	129	7.116	2.409	0.363	0.213	0.896	0.091	11.596	0.637
1997Q2	156	6.807	2.255	0.424	0.248	0.919	0.127	11.209	0.692
1997Q3	181	6.979	2.210	0.489	0.287	0.963	0.177	11.035	0.698
1997Q4	193	6.486	2.123	0.531	0.321	0.931	0.217	10.626	0.709
1998Q1	204	5.660	2.101	0.609	0.388	0.892	0.378	10.898	0.723
1998Q2	219	5.453	2.019	0.695	0.430	0.936	0.335	11.705	0.708
1998Q3	215	6.428	1.885	0.775	0.483	0.947	0.417	12.382	0.734
1998Q4	143	10.259	1.896	0.914	0.595	0.884	0.453	13.447	0.749
1999Q1	131	10.657	1.810	1.069	0.670	0.914	0.436	15.128	0.755
1999Q2	124	14.063	1.705	1.124	0.701	0.926	0.454	16.137	0.763
1999Q3	113	15.190	1.663	1.279	0.796	0.955	0.446	16.213	0.741
1999Q4	122	13.124	1.619	1.487	0.938	0.973	0.401	15.757	0.727
2000Q1	152	9.228	1.592	1.792	1.073	0.963	0.384	13.461	0.731
2000Q2	179	9.047	1.585	2.001	1.091	0.972	0.418	13.481	0.719
2000Q3	194	9.266	1.554	2.085	1.109	0.977	0.440	13.385	0.703
2000Q4	233	7.366	1.555	2.206	1.110	0.986	0.513	13.453	0.707
2001Q1	197	8.413	1.493	2.417	1.120	0.993	0.517	13.143	0.721
2001Q2	222	6.598	1.472	2.730	1.252	0.995	0.623	13.936	0.732
ALL	3880	8.085	1.919	1.165	0.651	0.920	0.363	12.917	0.718

Note: All the entries in the last seven columns are sales weighted means.

Table A6

Estimated Markups and Margins for the whole market (1995Q1-2001Q2)

	OLS Logit	Instrumental Variable Logit		Random Coefficient Logit	
Statistic	(1)	(2)	(3)	(4)	(5)
Median	2113.20	366.38	18.86%	250.38	13.39%
Mean	2114.30	366.56	20.95%	269.59	14.11%
10%	2109.40	365.70	11.61%	201.91	10.36%
90%	2121.80	367.86	33.24%	355.46	18.75%
Standard Deviation	4.64	0.80	9.39%	85.80	3.89%

Notes: Columns (1), (2) and (4) give the estimated markups from the various estimations over the whole sample (4,767 observations). Columns (3) and (5) give the margins, defined as markups divided by observed prices. Both Markups and margins are calculated assuming a Bertrand-Nash equilibrium in prices. All prices have been deflated using the CPI.