THE GROWTH OF NETWORK COMPUTING: QUALITY-ADJUSTED PRICE CHANGES FOR NETWORK SERVERS*

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This article investigates the evolution of quality-adjusted prices for servers motivated by two facts. First, the recent productivity acceleration in the US is closely linked to the spread of IT of which networked computing is a large component. Second, the growth of network computing itself has been fostered by the rapid growth in the quality and quantity of server hardware and software. The preferred hedonic price index fell much more rapidly than the standard 'matched model' price index, mainly due to the selection bias in the standard model arising from the exit of obsolete models, which would have had the fastest price falls.

The slowdown of US productivity growth that began in the mid-1970s appeared to have reversed itself after the mid-1990s. This remarkable productivity acceleration is believed to be closely linked to the production and spread of information and communication technologies (ICT) bringing an end to 'Solow's Paradox' – the fact that computers appeared to be everywhere apart from the productivity statistics.[1]

A key part of the link between productivity growth and ICT is the rapid fall in quality-adjusted prices for ICT goods, especially since 1995. Unfortunately, our knowledge of this price fall is based on rather few studies.[2] In particular, there have been no comprehensive studies for *network servers*, which are a large and rapidly growing part of the corporate IT capital stock. Most papers consider computers as a whole rather than disaggregating into the different types of IT. This lacuna is surprising since the Internet relies on servers for its existence and the network effects stressed by many theories of the revolutionary effects of IT (see below) are closely linked to the development of network servers themselves. Worldwide, corporations spent $56 billion on servers in 2000 compared to $124 billion for PCs, and the growth of spending on servers has far outstripped that on PCs since 1995.[3] Furthermore, servers have been at the centre of the several competition policy debates including the European's Commission's Decision in 2004 against Microsoft (European Commission, 2004).

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[1] See *inter alia*, Jorgenson (2001).
[2] See e.g., Triplett (1989, 2004) for an extensive discussion. Doms and Forman (2003) examine quality-adjusted prices for Local Area Network equipment; van Mulligen (2003) calculates some hedonic prices for servers but only for one country (the Netherlands) and only for 1999–2001.
[3] International Data Corporation (2000*b*).

This article also tackles an important methodological issue that hampers studies of the price changes in high tech markets with many 'new goods'. It has long been recognised that just looking at unadjusted price changes can lead to underestimation of consumer benefits as there are rapid increases in quality in these sectors. The question is how to best measure the 'true' quality-adjusted price change? The standard approach to dealing with quality changes by the statistical agencies is the 'matched model' price index that compares the prices of identical models at two points of time. This has serious potential problems when there is rapid entry and exit of models. The obsolete models which exit are likely to be of systematically lower quality than the surviving models and would therefore have been subject to larger price falls had they remained in the market. Because these exiting models are not used to calculate price changes in the standard matched model approach, the statistical agencies may be missing out on some of the substantial real price falls as they are relying on a highly selected sample of data (effectively under-sampling the left tail of the price change distribution). This is particularly a problem for the server market as in a typical year over half of the models exit in our dataset.

There are several ways to address this problem, recently highlighted by Pakes (2003). The hedonic approach is based on regressing prices on characteristics so we have estimates of the prices of models even in periods when they are not available in the market. Thus, the problem of missing data from models leaving the market (and indeed entering) it can be solved by using a 'proper hedonic' index. The hedonic price regression has the disadvantage that it is a reduced form and its coefficients cannot in general be related back to primitives (see Section 2 for an example). This means that it is likely that the coefficients will be unstable over time and we must allow for this in the estimating procedure. Nevertheless, Pakes (2003) provides conditions under which the hedonic index still provides an upper bound to the compensating variation. Another disadvantage of the 'proper hedonic' approach is that there will be estimation variance introduced into the construction of the price index that is avoided in the matched model approach. My preferred index uses the matched model price change where this exists but substitutes its hedonic estimate when the model exits the market. This index, called the 'complete hybrid' by Pakes, avoids the selection bias problem of exiting models, but keeps the variance reduction property of the matched model index for surviving models. I compare across all the models for servers to show that the complete hybrid has these attractive properties in practice as well as in theory.

I estimate that the price fall for servers is something of the order of 30% per annum between 1996 and 2001 in the US. By contrast, the matched model index shows only a 15% fall per annum. I present similar calculations for Western Europe that also show these biases. Interestingly, price falls appear to be somewhat slower in Europe than in the US. This may be one reason why the diffusion of ICT and productivity growth in the late 1990s was less impressive in Europe than in the US (van Ark and O'Mahony, 2003). I also show that there are differential price trends for low-end 'work group' servers compared to high-end 'enterprise' servers. Low-end server prices have fallen much more quickly than high-end server prices.

This article has several links to the article by van den Berg (2006) in this Feature. First, the sharp fall in server prices I document is consistent with the idea that customers have become much better informed about (dispersed) prices over time and this has put downward pressure on vendors' prices. The fact that much of the price change is driven by the exit of obsolete models is also consistent with van den Berg's emphasis on reallocation effects. Second, my article systematically documents the rapid growth in the quantity and quality of computer networks. These networks foster improved information flow (e.g., through the development of the Internet) that have massively reduced search costs.[4] This potentially switches the economy from an inefficient equilibrium with wide price dispersion to an efficient equilibrium with lower average price and lower dispersion. These two mechanisms are self-reinforcing: server prices fall through improved information flows which, in turn, foster the growth of the server market and therefore faster information diffusion in other markets. For example, falling real server prices helped fuel the growth of websites and on-line auctions for intermediate goods. Finally, and related to the first point, it has been argued that the mid-1990s represents a structural break in the US in the sense that hedonic prices of computers fell much more rapidly than in earlier periods and this helped drive the productivity acceleration (Jorgenson, 2001). Van den Berg's model predicts such discontinuities. Although I do not have early 1990s server data to directly test this, it is unlikely that server price falls were as rapid as the 30% per annum or so falls that I document here.

The plan of the article is as follows; Section 1 gives a brief introduction to the features of network serving and discusses the data. Section 2 sketches the modelling strategy and Section 3 contains the results. Section 4 concludes.

1. Descriptive Analysis of the Server Market

1.1. Network Servers

In the late 1980s and beginning of the 1990s computing architecture went through a paradigm shift. The mainframe-orientated system was overthrown by the 'PC client/server' computer architecture that is familiar today.[5] Instead of computer intelligence being centralised and users interacting via 'dumb' terminals, processing power was more decentralised, distributed between PCs with their own operating systems and increasingly powerful servers linking these PCs together in networks.

Computing can be performed locally on stand-alone appliances such as using a laptop computer away from the office. Most computing, however, is performed on multi-user networks in which users communicate through 'clients' and in which much of the computing activity takes place behind the scenes on 'servers'.[6] The

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[4] Although much of the growth of servers has fostered information flow within companies, servers are used to host websites and act as e-mail servers, which have boosted the development of the Internet and e-commerce.

[5] See, e.g., Bresnahan and Greenstein (1996) for an economic analysis of this transition and the introduction and discussion by ter Weel (2006) at the beginning of this Feature.

[6] See, e.g., Sybex (2001) for a basic discussion of servers.

clients in a client-server network take many forms. Some are 'intelligent', such as a desktop computer; others are 'non-intelligent', such as a dumb terminal (e.g., an ATM machine). Servers vary in size and in the nature of the tasks they are asked to perform. The mixture of servers in a client-server network depends on the kinds of computing that the network is designed to support. The server requirements of a small office, for example, are considerably different than the server requirements of a large international bank.

Like all computers, servers consist of both hardware (e.g., the processors and storage facilities/memory) and software (e.g., the operating system). Server hardware is manufactured using various types of processors. Intel processors are used in many servers, and Microsoft's Windows operating system is compatible only with hardware that uses Intel processors. Novell's NetWare and SCO's UNIX variants are also designed to run on Intel processors. The leading hardware manufacturers for Intel-based servers include Compaq/HP, Dell, Gateway and IBM.

Server vendors mostly sell Intel-based systems on a non-integrated basis. An organisation usually buys server hardware from one vendor with the server operating system installed from another vendor. Server systems are also sold on an integrated basis in which the vendor supplies both the server hardware and a proprietary operating system that has been specially designed for the vendor's hardware (e.g., Sun Microsystems).

One of the principal benefits of a computer network is that it allows an organisation to share computer resources among multiple users. Clients connected to a network can share printers and files. Application programmes can be maintained on central servers and then 'served' to clients on an as-needed basis. In addition, computers connected to a network can run distributed applications. Distributed applications are computer programmes in which different blocks of the programme are executed on different computers within the network.

There are at least two tiers of network computing sometimes called the business layer (run on 'work group servers') and the data layers (run on 'enterprise servers'). Work group servers are used to perform a number of the basic infrastructure services needed for the computers in a network to share resources. Work group servers most commonly handle security (authorisation and authentication of users when they connect their clients to the network), file services (accessing or managing files or disk storage space), print services (sending print jobs to a printer managed by the server), directory services (keeping track of the location and use of network resources), messaging and e-mail, and key administrative functions in the management of the work group network. In addition to infrastructure services, work group servers also execute certain kinds of server-side applications. In many organisations, there is a pressing need to manage enormous (and growing) amounts of data that are critical to the mission of the organisation. Inventory control, airline reservations and banking transactions are just a few examples. The 'mission-critical' data used for these purposes need to be stored, updated, quality controlled and protected. They also need to be readily available to authorised users. The servers that perform these mission-critical data functions are frequently referred to as enterprise servers. Enterprise servers tend to be larger and signifi-

cantly more expensive than work group servers. A work group server usually has one (or sometimes two) microprocessors and modest memory (around four gigabytes). A work group server typically provides services for 20–30 clients. Enterprise servers, by contrast, tend to have at least eight processors, usually cost more than $25,000 and in some circumstances can cost more than $1 million. In contrast to the standardised applications that run on work group servers, application programmes for enterprise servers tend to be custom written and specific to a particular organisation.

1.2. *Data Description*

I have used data from the International Data Corporation's (IDC) Quarterly Server Tracker database.[7] This enables me to analyse the evolution of prices, revenues and units sold of every server, between the first quarter of 1996 and the first quarter of 2001. In principle IDC covers the population of models. It gathers revenue and characteristics data from vendors in all the main regions[8] and then cross-checks the company totals with global HQs and its own customer surveys. Transaction prices (called 'street prices' by IDC) are also estimated on a region-specific, quarterly, model-by-model basis. These prices take into account the various discounts offered off the list price as well as trade-ins.

I break down the IDC data into the US and Western Europe, the main two regional markets. Looking in a cross-section I define an observation in a region as a vendor-family-model. So a typical example would be Sun's (*vendor*) Ultra-Enterprise (*family*) 3000/3500 series (*model*) – this was priced by IDC at about $65,000 in the first quarter of 2000 in the US. A model still contains some grouping across different 'versions' in the data, so I am careful to break the series whenever there is a change in average characteristics.[9]

There are a number of characteristics available in the IDC Server Tracker which include: the number of Central Processing Units (CPUs), whether the system is rack-optimised,[10] the number of rack slots, the chip architecture (RISC, CISC or IA32), motherboard type (e.g., Symmetric Parallel Processing – SMP), the types of operating system used (Windows, Unix, Netware, OS390/OS400, VMS and others – including Linux), and hardware vendor dummies. One obvious concern was that these characteristics do not pick up all the relevant variation in quality in the

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[7] More precisely, the 7th June 2001-version. For a full description of this database and the recent evolution of the market see IDC (1998, 2000*b*). Pakes (2003) and Foncel and Ivaldi (2001) have used the equivalent dataset for PCs.

[8] The regions are North America, Western Europe, Japan, Asia-Pacific and Rest of World. I have also done some analysis on the world market as a whole and in Japan; see e.g., Van Reenen (2004). The other regional data in IDC ('Rest of Asia' and 'Rest of World') appeared less reliable due to smaller sample size.

[9] I use data from the first quarter of each year. To make sure that the models are perfectly matched I define a model more precisely than IDC declaring a new model when any of the characteristics change (there are some small changes in the original IDC dataset as models are aggregations of similar versions). This left us with 1,143 models in the US between 1996 and 2001. The balance of the panel was as follows 765 models were observed for 1 year, 237 for 2 years, 86 for 3 years, 34 for 4 years, 20 for 5 years and only one for all 6 years.

[10] Rack mounted servers are designed to fit into 19-inch racks. They allow multiple machines to be clustered or managed in a single location and enhance scalability.

hedonic regressions. To address this I also collected extra data on server characteristics and matched them into the IDC data. Data were collected for the following ten major server vendors: Compaq, Digital, Tandem, Dell, Fujitsu, Hewlett, Packard, IBM, Siemens and Sun Microsystems. I used a wide variety of sources to obtain these data including the trade manual *Datasources*, company websites, back issues of computer magazines and their web pages and major resellers. I also received help by contacting some of these organisations directly. I collected a wide variety of characteristics, the most informative of which were memory, clock/processor speed and internal storage.[11] The final dataset covered 60% of the IDC models (we cover 1,143 distinct models) and over 80% of the revenues of all servers.[12]

Note that my method is slightly different from the Pakes (2003) study. Pakes uses version level models that are not reported in the IDC data but are reported in PC magazines. This has the advantage that he can use characteristics at a more finely disaggregated level than I do here. But it has the disadvantage that he relies on list prices rather than transaction prices and that he has to allocate sales arbitrarily between the different versions of the models.

The descriptive statistics in Table 1 show rapid falls in average prices but also major increases in quality over our time period. In 2001, the average server had a memory over twelve times as powerful as the 1996 average and was eight times faster. This implies that simply looking at unit values will underestimate the quality-adjusted fall in sever prices (the average model in 2001 was 60% of the price of the average model in 1996). Figure 1 and Figure 2 show the change in market share by hardware and software vendor for major vendors. Among hardware vendors the Sun (at the higher end of the market) and Dell (at the lower end

Table 1

Means of Some Key Variables over Time (US Market)

	Price	Memory (RAM)	Speed (MhZ)	Average number of Racks	Proportion Rack optimised
1996	20.71	816.62	144.91	0.035	0.035
1997	18.82	2,057.62	274.34	1.24	0.076
1998	16.43	3,146.72	424.90	2.67	0.085
1999	13.48	3,751.20	557.59	3.92	0.066
2000	13.34	6,926.81	951.44	3.78	0.200
2001	12.34	10,013.24	1245.97	3.55	0.390

Note. 1,739 observations. These are market averages – i.e., all models are weighted by the number of units shipped.

[11] Other characteristics included cache size on chip, cache size on board, list price, disc capacity in cabinet, maximum external storage, maximum Input-Output channels per processor, maximum Input-Output bandwidth. These had much less explanatory power in the hedonic regressions than the three variables I focused on.

[12] The primary method of matching was through the model name, but I also used characteristics common to IDC and the model specification to check the accuracy of the match (e.g., maximum number of processors). Models are sometimes aggregated by IDC across several versions. IDC weights the final characteristics according to importance (i.e. by revenue). Since I did not have revenues by version I considered the minimum version, the median version and the maximum version. The results are given for the characteristics of the median version but using the minimum or maximum made little difference to the results.
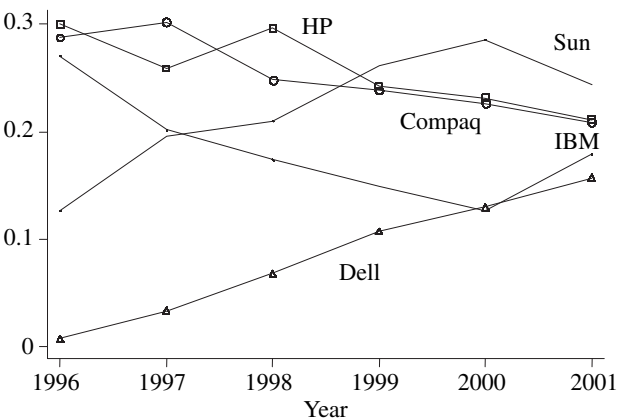
Fig. 1.   *Evolution of Market Shares for Hardware Vendors (Revenues)*
Source: IDC Quarterly Tracker Survey
Note. I have used the market structure in 2001 to allocate vendors who have been taken over (e.g., Digital and Tandem acquired by Compaq in 1998 and 1999, respectively). Fujitsu and Siemens had market shares below 1% and are not shown here.
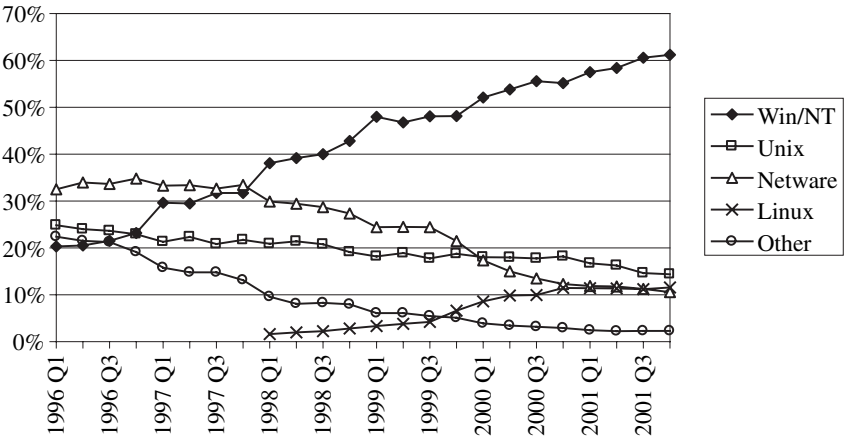
Fig. 2.   *Evolution of Market Shares for Software Vendors (Units)*
Source: IDC Quarterly Tracker Survey, World Market

of the market) have grown their market shares over the period; IBM has lost share, as have HP and Compaq (to a lesser extent). Among the operating system vendors the rapid ascent of Microsoft is particularly striking. Microsoft's increase has been almost entirely in the low-end work group segment and has been mainly at the expense of Novell's Netware.[13] Linux has also made some gains, but still only had a 12% market share in 2001.

[13] I use unit shares for software vendors as it is difficult to calculate the revenue share of an operating system – it is sold bundled with the hardware. Furthermore, since Linux is free the importance of open source would be ignored if I used revenue shares for operating systems.

2. Modelling Framework

In this Section I lay out a framework for illustrating the economic relationship between prices and characteristics for servers. I show in the context of a simple model the difficulties of interpreting the price-characteristics relationship.

Let (x_i, p_i) be the vector of characteristics and prices of good i, and (x_{-i}, p_{-i}) denote the characteristics and prices of other goods. Demand for good i is

$$D_i = D(x_i, p_i, x_{-i}, p_{-i}; A),$$

where A indexes attributes which determine distribution of consumer preferences over characteristics. Assume marginal cost is constant and given by $c(x_i)$ and all firms are single product. Under Bertrand competition equilibrium prices are given by:

$$p_i = c(x_i) + \frac{D_i(\cdot)}{|\partial D_i(\cdot)/\partial p|}, \tag{1}$$

where $D_i(\cdot)/|\partial D_i(\cdot)/\partial p|$ is the mark-up over marginal cost and will vary inversely with the elasticity of demand. The hedonic function $h(x_i)$ is simply the expectation of price conditional on x_i. From (1) this is simply

$$h(x_i) \equiv \mathrm{E}(p_i|x_i) = c(x_i) + \mathrm{E}\left[\frac{D_i(\cdot)}{|\partial D_i(\cdot)/\partial p_i|} \Big| x_i\right], \tag{2}$$

where $\mathrm{E}(\cdot|\cdot)$ is the conditional expectations operator. The hedonic function is a sum of the marginal cost function (the first element on the right hand side of (2), $c(x_i)$) and a function that summarises the relationship between mark-ups and characteristics (the second element on the right-hand side of (2)). The signs of characteristics in the mark-up function will depend on the characteristics of the competing products and the distribution of consumer characteristics in a complex way. The signs may well change over time and take different signs from those in the cost relationship.

In general we should not expect theory to impose any sign restrictions on (2) and we should expect parameter instability over time. The coefficients on characteristics cannot be simply mapped back into 'marginal willingness to pay' derivatives or 'cost' derivatives except in the context of very specific models. This does not mean that hedonic price functions are uninformative. They can be useful in providing 'proper' indices that give an upper bound to the compensating variation needed to make consumers indifferent between base and comparison period utility.

Consider the Laspeyres type price index for a typical matched model ('MM') index commonly used by statistical agencies (I^{MM})

$$I_t^{MM} = \sum_{i \in C_{t-1}} \left(\frac{p_i^t}{p_i^{t-1}} x \frac{p_i^{t-1} q_i^{t-1}}{\sum_{i \in C_{t-1}} p_i^{t-1} q_i^{t-1}}\right), \tag{3}$$

where q is quantity and C_t is the class of goods available at time t. This index does not need explicit data on characteristics as it simply looks at the price change

between periods t and $t-1$ of a particular model i. This is then weighted by the model's share in total revenue ('plutocratic weights').

Define a second index as the 'proper hedonic' (I^{PH}) as

$$I_i^{PH} = \sum_{i \in C_{t-1}} \left(\frac{h^t(x_i)}{h_i^{t-1}(x_i)} x \frac{p_i^{t-1} q_i^{t-1}}{\sum_{i \in C_{t-1}} p_i^{t-1} q_i^{t-1}} \right), \tag{4}$$

where $h^t(\cdot)$ is the tth period estimate of the hedonic function. Note that estimates of the implicit price of a model this will exist for all periods even if the model does not exist in that period. The lack of sales will affect the 'plutocratic' weight, however; it implies that I^{PH} will exist for only one period when I^{MM} does not exist: the period just after the model exits the marketplace (Triplett, 1989).[14]

My preferred index is the 'complete hybrid' (I^{CH}). This is the same as the matched model index of (3) for those periods when prices are observed in t and $t-1$, but uses the following definition when prices are observed in $t-1$, but not in t:

$$I_t^{CH} = \sum_{i \in C_{t-1}} \left(\frac{h^t(x_i)}{p_i^{t-1}} x \frac{p_i^{t-1} q_i^{t-1}}{\sum_{i \in C_{t-1}} p_i^{t-1} q_i^{t-1}} \right). \tag{5}$$

In my view, this combines the best of both models because

(*i*) it enables me to construct a price index for models that exit and thus deal with the selection bias in the matched model; and

(*ii*) it reduces the estimation variance endemic to the hedonic model and should therefore give more precise estimates.

I considered several functional forms for the hedonic relationship but mainly use the standard log-log form, which gives a good representation of the data:

$$\log p_i^t = a^t + \sum_j \beta_j^t \log x_{ij} + \varepsilon_i^t, \tag{6}$$

where the x_j are characteristics of models (such as speed and memory). I allow the relationship to be different across time periods as this has been found to be very important in previous studies (Berndt *et al.*, 1995; Berndt and Rappaport, 2001) and is suggested by (2). We present tests of pooling coefficients on characteristics over years and show that they are rejected.

Dropping the t subscripts, note that the prediction of the hedonic function is

$$\hat{h}(x) = \exp(\hat{a}) \prod_j x_j^{\hat{\beta}_j} \, \mathrm{E}[\exp(\varepsilon_i^2)]. \tag{7}$$

Assuming that the ε_i term is distributed normally, when estimating the level of price from the hedonic function in log-log form we need to add the standard correction of $0.5\exp(\hat{\varepsilon}^2)$ (Goldberger, 1968).

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[14] This is due to using the base weighted price index.

3. Results

Table 2 contains the full set of price regressions each year between 1996 and 2001 (and a pooled estimation in the final column). Memory, the number of racks, rack optimisation and chip types has the strongest positive association with server price. Speed is also a consistently positive predictor, although weaker in 1996–7 than between 1998 and 2001. Internal storage has a positive association, although it is generally weaker than memory or speed. Hardware dummies and operating system (OS) dummies are highly jointly significant in the pooled sample and generally jointly significant in the year-by-year regressions.

Although the signs of the characteristics are usually as expected in the sense that 'better' characteristics are correlated with higher prices, the discussion in the modelling section emphasised that structural interpretation is difficult. The coefficients show quite a bit of variation from year to year. At the foot of Table 2 we observe that the controls account for at least three-quarters of the variance in price in every year. I experimented with dropping characteristics and including higher order terms, which did change the explanatory power of the regressions but did not have a major impact on the qualitative results reported below. The exception to this statement is dropping memory and/or rack characteristics that lead to an underestimation of the price falls in the hedonic specification.[15]

Panel A at the bottom of Table 2 contains tests of restricting the coefficients to be equal across years. As with other studies of ICT I find that such restrictions are strongly rejected by the data (Berndt and Rappaport, 2001). The only restriction that I could not reject was the similarity of the coefficients in 1997 and 1996.

Table 3 contains our main results (for the US). Columns (1)–(5) are associated with changes between the years indicated. Column (1), for example, has the change in quality-adjusted prices between the first quarter 1997 and of 1996. Column (6) reports the unweighted average of the changes in the price index up to 2000 and column (7) extends this through to 2001.[16]

The first three rows of Table 3 simply report the number of observations available to construct the different indices. The main point to notice is the high degree of attrition between years, ranging between 47% and 79%. There is a large amount of exit and entry of server models. Since the matched model index can only use the price data on those models, which are available in both periods there is ample room for selection bias. For example in constructing the 2000/1999-index the matched model uses 156 observations, whereas the complete hybrid uses twice as many (all 314 models available in 1999).

The lower part of Table 3 reports different price indices. The fourth row labelled 'unit values' just uses the change in the mean market price across all models (see Table 1 for the means). Average prices fall by about 10% per annum even before making any adjustment at all for quality change. The fifth row uses the matched model approach of (3). The matched model index falls on average by

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[15] For example, the adjusted R^2 fell from 0.840 to 0.778 in 2001 when we dropped memory.
[16] Note that the index for 2001/2000 is by construction the same for the matched model and the complete hybrid, as hedonic prices cannot be computed for 2001 (we would need the price regression in 2002, which is outside my sample).

Table 2

Major Coefficients in Hedonic Price Regressions, 1996–2001

	(1) 1996	(2) 1997	(3) 1998	(4) 1999	(5) 2000	(6) 2001	(7) Pooled
Constant	−1.328	−6.492	−7.253	−6.600	−7.135	−6.795	−4.393
	(0.775)	(0.114)	(0.755)	(0.506)	(0.591)	(0.450)	(0.193)
Ln(Memory, MB RAM)	0.402	0.487	0.460	0.435	0.467	0.421	0.440
	(0.084)	(0.106)	(0.086)	(0.079)	(0.071)	(0.071)	(0.030)
Ln(speed, MhZ)	−.018	0.162	0.446	0.384	0.448	0.341	0.280
	(0.165)	(0.158)	(0.132)	(0.109)	(0.134)	(0.104)	(0.050)
Ln(Internal Storage, GB)	0.125	0.056	0.023	−0.001	0.064	0.197	0.028
	(0.070)	(0.070)	(0.082)	(0.069)	(0.065)	(0.054)	(0.023)
Ln (number of racks)	–	1.641	1.311	1.205	0.737	0.820	0.906
		(0.330)	(0.191)	(0.130)	(0.122)	(0.134)	(0.057)
Rack-optimised	–	2.193	1.791	0.676	0.405	0.710	0.656
		(0.439)	(0.343)	(0.170)	(0.136)	(0.119)	(0.061)
Risc	1.037	0.953	1.229	1.764	1.870	2.041	1.447
	(0.170)	(0.192)	(0.185)	(0.162)	(0.214)	(0.204)	(0.076)
SMP	0.412	0.032	−0.201	0.073	0.020	−0.245	0.031
	(0.126)	(0.165)	(0.152)	(0.133)	(0.210)	(0.189)	(0.059)
Hardware Vendors (Compaq is base) p-value of joint significance	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dell	0.086	0.200	0.579	0.309	0.432	0.077	0.206
	(0.152)	(0.178)	(0.190)	(0.095)	(0.095)	(0.150)	(0.045)
Tandem	0.009	−0.059	−0.187				−0.245
	(0.209)	(0.241)	(0.252)				(0.077)
Fujitsu	−0.564	0.444		0.335			−0.252
	(0.520)	(0.269)		(0.149)			(0.364)
Fujitsu- Siemens					0.944	0.017	0.489
					(0.196)	(0.297)	(0.252)
HP	0.498	0.363	0.525	0.361	0.600	0.533	0.383
	(0.172)	(0.181)	(0.209)	(0.097)	(0.125)	(0.117)	(0.052)
IBM	0.691	0.406	0.350	0.408	0.561	0.447	0.290
	(0.181)	(0.196)	(0.204)	(0.104)	(0.117)	(0.131)	(0.054)
Packard-Bell	0.118	0.245	0.355				0.333
	(0.245)	(0.242)	(0.161)				(0.080)
Sun	−0.028	0.169	−0.219	−0.399	−0.084	−0.760	−0.109
	(0.363)	(0.253)	(0.280)	(0.220)	(0.240)	(0.239)	(0.100)
Digital	2.355	1.959					1.406
	(0.366)	(0.383)					(0.253)
Operating System (Novell is base) p-value of joint significance	0.307	0.020	0.002	0.087	0.180	0.557	0.030
Windows	−0.018	−0.027	−0.081	−0.118	−0.047	0.005	−0.062
	(0.113)	(0.111)	(0.092)	(0.094)	(0.093)	(0.087)	(0.042)
Unix	0.178	0.188	0.021	−0.043	0.125	−0.084	0.069
	(0.124)	(0.130)	(0.103)	(0.100)	(0.111)	(0.110)	(0.047)
VMS	0.284	0.166	−0.428	−0.392	−0.107	−0.306	−0.134
	(0.384)	(0.339)	(0.185)	(0.254)	(0.232)	(0.211)	(0.128)
OS390/400	0.382	1.038	1.042	0.254	−0.204	−0.589	0.720
	(0.297)	(0.345)	(0.375)	(0.327)	(0.253)	(0.433)	(0.169)
Linux (and others)	0.125	0.128	0.171	0.150	0.119	−0.025	0.093
	(0.123)	(0.127)	(0.100)	(0.093)	(0.093)	(0.083)	(0.044)
1997 dummy							−0.472
							(0.067)
1998 dummy							−0.768
							(0.068)

Table 2

Continued

	(1) 1996	(2) 1997	(3) 1998	(4) 1999	(5) 2000	(6) 2001	(7) Pooled
1999 dummy							−1.190
							(0.071)
2000 dummy							−1.423
							(0.091)
2001 dummy							−1.624
							(0.098)
Observations	223	228	287	314	342	345	1,739
Adj R^2	0.775	0.783	0.768	0.806	0.772	0.840	0.779

Panel A
Some Tests of Restrictions Across Years

	Test of parameter equality	p-value
Equality of coefficients across all years	$F(96, 1614) = 3.27$	0.00
Equality of coefficients 1996 and 1997	$F(20, 1614) = 0.63$	0.90
Equality of coefficients 1996 and 1998	$F(20, 1614) = 1.64$	0.04
Equality of coefficients 1996 and 1999	$F(19, 1614) = 3.29$	0.00
Equality of coefficients 1996 and 2000	$F(19, 1614) = 4.80$	0.00
Equality of coefficients 1996 and 2001	$F(18, 1614) = 4.63$	0.00

Note. Estimation by OLS. Standard errors (in brackets) are robust to arbitrary heteroscedacity (White, 1980). Regressions are run on data of the first quarter of indicated year. The final column also includes time dummies. Firm dummies are missing in some years because of merger and acquisition activity (e.g., Digital taken over by Compaq in 1998). All regressions also include a dummy variable if the server was uni-processor. I also included dummy variables if the server had no racks or had a missing variable for storage (the relevant continuous variable was set zero in these few cases).

16.6% per annum between 2000/1999 and 1997/1996. This is impressive and much faster than the simple mean price, indicating that some control for quality has successfully been made. Our preferred index however is the 'complete hybrid' and this falls much faster than the matched model – by about 30% per annum. The difference is mainly due to attrition, with the exiting models being on average those likely to show the largest price falls if they had survived. The difference is very dramatic in some years. In 1997/96 for example, the matched model index falls by only 4% whereas it falls by 45% in the hedonic price index. The reason for this is that the matched model suffers from substantial selection bias – about 80% of the models in 1996 have exited by 1997. Since the exiting models are likely to be the ones made obsolete, this will lead to significant upwards bias in the matched model price index.

Why was there so much churning in 1996? Industry reports suggest that in 1997 there were several important changes in the business environment facing server vendors. First, the rapid diffusion of 'rack mounted' servers that were more easily scalable became widely available: this lead to the exit of the less scalable models. Table 1 shows that the mean number of racks was only 0.03 in 1996 whereas this figure jumped to 1.23 in 1997. Second, memory improved more dramatically than in any other year in our sample, by about 250% between 1996 and 1997. This was the fastest increase in any year of the sample. Finally, Dell computers began a rapid

Table 3

Alternative Price Indices for Servers, US Market

	(1) 1997/ 1996	(2) 1998/ 1997	(3) 1999/ 1998	(4) 2000/ 1999	(5) 2001/ 2000	(6) Average annual growth rate (2000/99– 1997/96)	(7) Average annual growth rate (2001/00– 1997/96)
Observations							
1. Base year	223	228	287	314	342	1,052	1,394
2. Comparison year	46	121	131	156	140	454	594
3. Attrition rate	79%	47%	53%	50%	59%	–	–
4. Unit values	−0.096	−0.136	−0.198	−0.010	−0.078	−0.109	−0.103
5. Matched model	−0.041	−0.279	−0.253	−0.089	−0.142	−0.166	−0.161
6. Complete hybrid	−0.449	−0.365	−0.290	−0.090	−0.142	−0.299	−0.267
(inc. Firm dummies)	(0.065)	(0.035)	(0.055)	(0.073)	(0.068)	(0.028)	(0.024)
7. Proper hedonic	−0.449	−0.315	−0.238	−0.123	−0.142	−0.281	−0.253
	(0.065)	(0.047)	(0.060)	(0.038)	(0.068)	(0.024)	(0.023)
8. Complete hybrid	−0.563	−0.383	−0.321	−0.107	−0.142	−0.343	−0.303
(no correction for +5exp(σ^2))	(0.078)	(0.038)	(0.055)	(0.075)	(0.068)	(0.031)	(0.026)
9. Complete hybrid,	−0.383	−0.366	−0.272	−0.081	−0.142	−0.275	−0.249
no firm dummies	(0.059)	(0.037)	(0.054)	(0.071)	(0.068)	(0.026)	(0.023)

Note. All prices indices are of the Laspeyres type, annual (based on first quarter); standard errors in brackets after estimates (they are estimated by a bootstrap based on 200 replications). Matched model uses only price information for models that are in existence. Complete hybrid uses hedonic imputation only when model has exited in previous four quarters and uses actual price (i.e., same as matched model) otherwise. Proper hedonic uses hedonic imputation in all periods. Attrition rate is the proportion of models that exist in year t that exit in year $t + 1$.

ascent in market share with its 'direct to customer' inventory model (see Figure 1). All these factors contributed to the exit of less competitive brands.[17]

The index from the complete hybrid model is similar to that in the proper hedonic model (that uses predicted prices in every period in row 7). For example, the average annual growth rate was –28% for the proper hedonic compared to −30% for the complete hybrid between 1996 and 2000.

Some robustness tests are shown in the last two rows of Table 3. Failing to correct for the bias associated with predicting prices from the log functions leads to even more dramatic price declines (34% on average between 1997 and 2000). Dropping the vendor dummies leads to slightly slower price declines (27.5% on average between 1997 and 2000).

Table 4 presents results from Western Europe. The qualitative pattern is similar to the US – the matched model index falls much more slowly than the complete hybrid (or the proper hedonic). In Europe the complete hybrid falls at about 22% per annum up to 2000 compared to just fewer than 10% for the matched model. It is often assumed that there is a single world price for ICT – these results suggest that this may not be wholly correct. There is evidence in many other markets of the failure of the law of one price to hold and of pricing to market behaviour by

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[17] For descriptions of these market developments see International Data Corporation (1998, 2000*a*, *b*).

Table 4

Alternative Price Indices for Servers, Western Europe

	(1) 1997/6	(2) 1998/7	(3) 1999/8	(4) 2000/1999	(5) 2001/2000	(6) Average annual growth rate (2000/99– 1997/96)	(7) Average annual growth rate (2001/00– 1997/96)
Observations in base year	203	224	252	313	397		
Observations in comparison year	39	110	115	150	192		
Attrition rate	80%	49%	54%	51%	52%		
Matched model	0.141	−0.119	−0.209	−0.199	−0.011	−0.096	−0.079
Complete hybrid	−0.169	−0.222	−0.291	−0.191	0.011	−0.218	−0.172
	(0.081)	(0.044)	(0.063)	(0.043)	(0.053)	(0.026	(0.023)
Proper hedonic	−0.168	−0.327	−0.349	−0.061	0.011	−0.226	−0.179
	(0.081)	(0.059)	(0.059)	(0.034)	(0.053)	(0.026)	(0.025)

Note. All prices indices are of the Laspeyres type, annual (based on first quarter); Standard errors in brackets after estimates (they are estimated by a bootstrap procedure based on 200 replications). Matched model uses only price information for models that are in existence. Complete hybrid uses hedonic imputation only when model has exited in previous four quarters and uses actual price (i.e., same as matched model) otherwise. Proper hedonic uses hedonic imputation in all periods.

producers (Knetter, 1989). The standard practice in productivity studies of using the US hedonic price index for the EU is suspect in this case. Slower falls of server (and other ICT) prices may be a reason for slower diffusion of ICT in Europe and therefore slower productivity. On the other hand, European tastes for different computers (whose prices fell more slowly) is also part of the story.

I also compared price falls in the low end ('work group') and high end ('enterprise') of the server market. Although the qualitative pattern noted before still holds up, the falls of prices (and their time series pattern) have been different for work group servers than for at the low end of the market than at the high end. The complete hybrid shows a price fall of 30% per annum for work group servers compared to 20% per annum for high-end enterprise servers.[18] This is suggestive (although hardly conclusive) of different market segments for low-end and high-end servers; see e.g., Ivaldi and Lorinz (2004) or Van Reenen (2004) for more on market definition.

4. Conclusions

The rapid growth of network computing and the Internet has been fostered by remarkable falls in the quality-adjusted prices of servers. Much of the fall in server prices is probably due to falls in the prices of inputs such as semi-conductor chips, but some of the fall may also be due to better information flows. In turn, the

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[18] A concern with this conclusion is that segments are defined on the basis of initial prices so that is a problem of endogenous sample truncation. This is mitigated because I select on initial not current price. Nevertheless, re-estimating using truncated regression (Hausman and Wise, 1977) leads to similar results to those reported here.

development of the network server market helps lower search costs and reduce prices elsewhere, maybe even shifting the equilibrium of the economy (as suggested by van den Berg, 2006).

In this article I have presented some estimates of hedonic price indices for network servers using a large database of transaction prices and quantities. I find that quality-adjusted prices have fallen dramatically – something on the order of 30% per annum for our preferred index between 1996 and 2001 in the US. This dramatic decline is underestimated by using the standard 'matched model' method used by most statistical agencies. Matched model indices, by contrast, fall by only 15% per year in the US. This is likely to be due to the high degree of exit by those models whose prices would have fallen much more rapidly than average had they remained in the market. The implication is that statistical agencies may well be underestimating price falls for ICT products and therefore the contribution of ICT to productivity.

I also find that the conclusions over price falls hold for Western Europe as much as the US, with the preferred hedonic index falling twice as fast as the matched model.

There are several directions future work should take. One is to understand the demand side of the server market in more detail in order to investigate the reasons for the growth of the market and what explains such changes such as Microsoft's rapid growth in market share – was this innovation or anti-competitive degradation of interoperability? Secondly, analysing the dynamics of the market such as the welfare impact of the introduction of new goods is important. Finally, a major challenge is to link the empirical work this more rigorously with the equilibrium theories of the impact of IT on the economy.

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