The role of ICT in the global investment cycle

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Abstract

Most macroeconomic forecasters underestimated global investment during the late 1990s. One potential reason was that the models they were using were insufficiently disaggregated. In this paper, an empirical model is estimated whose out-of-sample forecasts largely predicted the global investment boom of the late 1990s. The main factor behind the improved model performance is the distinction between investment in ICT assets and investment in other assets, using disaggregated investment data provided by the OECD. In line with previous studies on US and UK investment performance, ICT investment is estimated to be much more responsive to changes in the real user cost of capital. In particular, panel and seemingly unrelated regression (SUR) estimates suggest very strong relative price effects on ICT investment for all G7 countries and Australia. The data also allow an examination of the effects of possible deflator mismeasurement; but within our framework, the measurement of investment using harmonised, rather than national, deflators is not found to have a material impact on forecasting performance.

Key words: Investment, ICT, panel econometrics, G7.

JEL classification: E22, E27, C33.

Summary

Most macroeconomic forecasters underestimated the volume of global investment during the late 1990s. One potential reason was that the models they were using were insufficiently disaggregated.

We extend previous international empirical models of investment in a number of ways. Following approaches for the United Kingdom and the United States that have demonstrated the benefits from estimating disaggregated investment equations, we use a data set that enables us to disaggregate non-residential investment into information, communications and technology (ICT) and non-ICT assets for all G7 countries and Australia. Furthermore, we calculate for each country a measure of the real user cost of capital that is more richly specified than has generally been the case in cross-country studies. We employ a Hall-Jorgenson real user cost of capital measure that specifies roles (among others) for the price of investment goods relative to that of other goods in the economy; the real interest rate faced by firms (including corporate spreads); and the cost of equity finance.

The various innovations in our approach and the use of more disaggregated data result in improved econometric performance. Our estimated disaggregated system of investment equations yields out-of-sample forecasts that largely explain the global investment boom in the late 1990s. They suggest very strong relative price effects on ICT investment for all countries in our sample, and it is this sensitivity that accounts for the much improved forecasting performance of our model relative to previous approaches.

1 Introduction

Macroeconomic forecasters repeatedly underpredicted the global investment boom of the late 1990s. In the United States, for example, investment increased by an average of 8.8% per annum between 1996 and 2000. That was much higher than the 4.5% average growth of the previous 13 years; and it was well above the average two-year ahead projections made by private sector forecasters over the period 1994 to 1998 (5.2% per annum), as surveyed by Consensus Economics. (1) This picture is qualitatively similar for most G7 countries. And the investment underprediction of those Consensus forecasts is mirrored by the performance of macroeconomic models of the global economy.

The poor overall performance of aggregate investment equations in the late 1990s could be indicative of commonly experienced difficulties in estimating aggregate investment equations. Numerous authors have faced challenges in finding a significant role for the cost of capital,(2) although more compelling evidence has been presented in recent years.(3)

In this paper we develop an empirical model whose out-of-sample forecasts largely explain the global investment boom in the late 1990s, and whose econometric performance improves upon previous work. We extend previous work on investment equations in a number of ways. First, we use a data set that disaggregates non-residential investment for all G7 countries and Australia into ICT assets, consisting of IT equipment/computers, communications equipment and software, and non-ICT assets. For both the United Kingdom and the United States, previous work has demonstrated the theoretical importance of disaggregation and highlighted its role in improving the forecasting performance of investment equations as the relative price of ICT investment fell rapidly over the late 1990s.(4) The data we use provide us with the opportunity to determine if the United Kingdom and United States are special cases, or if a disaggregated approach to explaining investment is equally important in other advanced economies. The unique data set, provided by the OECD, has been previously used within a growth accounting framework to demonstrate that the marked increase in investment in nine large OECD economies in the 1990s is entirely accounted for

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(1) Consensus Economics is a private company which publishes the results of its monthly survey of the key forecast variables of over 240 financial and economic forecasters, covering more than 20 countries.
(2) See, for example, Oliner, Rudebusch and Sichel (1995), Chirinko (1993) and, for the G7 economies, Ashworth and Davis (2001).
(3) For example, Ellis and Price (2004) for the United Kingdom, and Chirinko *et al* (2004) for the United States.
(4) See Tevlin and Whelan (2003) for the United States, and Bakhshi, Oulton and Thompson (2003) for the United Kingdom.

by a global investment boom in ICT assets (see Schreyer (2000) and Colecchia and Schreyer (2002)).[(5)]

Second, the data allow us to examine the implications of marked differences in national practices with regard to the extent hedonic pricing is used to calculate ICT investment deflators. Schreyer (2000) has demonstrated that different national statistical practices may imply marked differences in measured investment deflators in the ICT sector. The OECD data also provides deflators that are calculated using a 'harmonised' methodology. Allowing for possible deflator mismeasurement, the investment boom – and the contribution of ICT assets – may have been even greater. We use the data set to calculate constant-price investment data for the G7 on both a national and harmonised basis and, in a sensitivity analysis, we examine the impact of estimating our models using the harmonised rather than national deflators.

Third, we calculate for each country a measure of the real user cost of capital that is more richly specified than has generally been the case in cross-country studies. We employ a Hall-Jorgenson real user cost of capital measure that specifies roles for the price of investment goods relative to other goods in the economy; the real cost of debt faced by firms; and the real cost of equity finance.

The various innovations in our approach yield improved econometric performance. Our seemingly unrelated regression (SUR) estimates of investment equations for the ICT and non-ICT sectors yield out-of-sample forecasts, contingent on the actual paths for output and the real user cost of capital, that largely explain the global investment boom in the late 1990s. They suggest very strong relative price effects on ICT investment for all G7 countries and Australia, and it is this sensitivity that accounts for the much improved forecasting performance of our model relative to previous approaches. These econometric findings are largely insensitive to deflator mismeasurement – perhaps not surprisingly, given that any deflator mismeasurement would affect not only our measures of the investment-output ratio, but also our fully specified Hall-Jorgenson real user cost of capital measures.

The remainder of the paper is organised as follows. Section 2 provides greater detail on the previous studies mentioned above. Section 3 presents the theoretical framework upon which we base our empirical work, while Section 4 presents the key features of our data set. Sections 5 and 6 examine

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(5) The disaggregation of the ICT and non-ICT sector across such a wide group of countries has not been available to previous authors. In this paper we distinguish ICT investment (IT equipment/computers, communications equipment, software) and non-ICT assets (non-residential buildings, other construction, transport equipment, and other non-residential, non-ICT assets). No account is taken of residential investment though government investment is included. ICT investment does not include investment in training for ICT. For more details see Colecchia and Schreyer (2002).

the statistical properties of our data and the econometric results of our analysis respectively. In doing so, we take particular care to check the robustness of our results to possible deflator mismeasurement and alternative econometric specifications. Section 7 presents the forecast evaluation and Section 8 examines some avenues for future research. Section 9 concludes.

2 What do we know from previous studies?

2.1 Cross-country analysis

Much recent cross-country research on investment relates to evidence of a new economy cycle in the late 1990s, as identified by Edison and Slok (2001). This involved a circular chain of events through which - for a while at least - rising productivity in the ICT sector implied both falling prices for ICT goods and rising equity prices of ICT producers. It is argued that purchases of such ICT goods were also associated with sizable productivity gains (actual or perceived) for other firms, leading to additional equity price rises for ICT-using as well as ICT-producing sectors. In turn, this implied increased access to funding of ICT investment, leading to further productivity gains.

Previous work on the role of the ICT sector in the global economy has focused on various links in this chain. Schreyer (2000) and Colecchia and Schreyer (2002) use a growth accounting framework to demonstrate that investment in ICT assets made a particularly marked contribution to growth across all the major economies in the late 1990s; during this period ICT investment contributed between 0.3 and 0.9 percentage points per annum to growth in the G7 economies, with the highest contribution being made in the United States. Edison and Slok (2001) focus on the roles of ICT and non-ICT equity prices in explaining overall investment trends over the 1990s. Their VAR approach yields mixed results, with investment reacting relatively less to increases in ICT than non-ICT stock market capitalisation in four of the seven economies.

2.2 Asset-level analysis

At the single-country level, recent research indicates that disaggregated models of investment may be superior, in theory and in practice, to aggregate models. Tevlin and Whelan (2003) note that aggregate models do not capture the increase in replacement investment associated with compositional shifts in the capital stock towards short-lived assets, such as computers. Further, the authors suggest that since aggregate models typically find little or no role for the real user cost of capital, they understate the impact on investment of the substantial relative price falls in assets such as computers. More formally, Bakhshi, Oulton and Thompson (2003) demonstrate that the theoretical relationship between firms' desired capital stocks (or investment) and the real user cost of capital at the aggregate level actually breaks down in the presence of trend falls in the relative price of investment goods, a key feature of certain assets in recent years.

Such research also highlights the extent to which the theoretical advantages of a disaggregated approach can translate into a superior forecasting performance. Bakhshi, Oulton and Thompson (2003) present evidence that models that distinguish between computer and non-computer investment can – unlike standard aggregate models – explain the strength of the UK investment boom in plant and machinery in the latter half of the 1990s. That is consistent with the US findings of Tevlin and Whelan (2003), who find the disaggregate modelling approach yields important gains in out-of sample forecasting performance.

Other research suggests that even greater disaggregation may be beneficial. Marquez and Wang (2003) examine aggregation residuals in the US National Accounts and investigate whether those for private investment in information technology exhibit a predictable pattern that is consistent with Hicks' composite-good theorem and that may be used for forecasting. The authors find that they are able to forecast these residuals more accurately in a model based on relative prices than in a model that ignores relative price information. More generally, Garrett (2002) has highlighted the relationship between the degree of aggregation and economic inference. The author demonstrates why regression coefficients and their statistical significance differ according to the degree of data aggregation. It is argued that this leads to different conclusions regarding economic behaviour depending upon the level of data aggregation.

2.3 Combining the cross-country and disaggregate approaches

Several authors have used disaggregated cross-country approaches to provide deeper insights into other aspects of investment behaviour. Campa and Goldberg (1999) show that investment responsiveness to exchange rate changes depends positively on an industry's export share and negatively in response to the share of imported inputs in production. Hughes Hallett, Peersman and Piscitelli (2003) estimate disaggregated investment equations for eleven industries in ten countries, to demonstrate that exchange rate volatility may not necessarily lead to reductions in investment, depending upon the opportunity cost of postponing investment and the price of scrapping capital.[6]

However, no previous international studies have directly investigated the potential improvements in the forecasting performance of investment equations that may be obtained through a disaggregated

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[6] Byrne and Davis (2002) use an aggregate approach and find that nominal and real exchange rate uncertainty reduces investment in the G7. Darby *et al* (1999) demonstrate that models of 'irreversible' investment show that uncertainty does not necessarily always reduce investment, as it depends upon the variability of the scrapping price and the opportunity cost of waiting rather than investing.

approach. Furthermore, these previous studies consider disaggregation by industry rather than by asset type; it is not clear that the special role played by falling relative prices for ICT investment would be captured by this analysis.(7) In this paper, we combine the cross-country and asset-level approaches in order to do so. There are a number of key advantages to this approach. First, the cross-country panel approach allows us to examine econometrically relationships between variables for which only a limited number of time-series observations are available. This is particularly pertinent for ICT investment data. Second, informational gains from the cross-country approach have motivated many studies in the past, but such gains may actually be greater in asset-level panels than aggregate panels. Aggregate investment studies typically involve the imposition of cross-country restrictions on the elasticity of the real user cost of capital with respect to investment (or capital). But this may be unrealistic for two reasons: elasticities may vary by asset (as suggested by Tevlin and Whelan (2003) for the United States and Bakhshi, Oulton and Thompson (2003) for the United Kingdom); and the asset composition of investment and capital varies across countries. To the extent that the estimated aggregate elasticity is a weighted average of the asset-level elasticities,(8) cross-equation restrictions are likely to be more appropriate at the asset level.

3 The theoretical framework

This section derives the key long-run relationship between investment and the real user cost of capital that we examine econometrically in Section 6.(9) Assuming a CES production function with constant returns to scale, the key long-run relationships explaining a single country's gross investment at the asset level are given by the first-order conditions (FOC) for different types of capital, such as ICT and non-ICT, from a profit maximising firm.(10)

$$k_{it} = y_t + \alpha_i - \beta \, rcc_{it} \qquad \textbf{(1)}$$

Here lower case denotes natural logs, K is capital, Y output, RCC the real user cost of capital, α_i a constant, and subscripts i and t denote the relevant asset and time period. Additionally, RCC is given by the (discrete time) Hall-Jorgenson formula:(11)

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(7) These cited studies also do not account for changing relative prices in the user cost of capital variable used.
(8) See Bakhshi, Oulton and Thompson (2003). The authors derive the aggregate relationship between capital and the real user cost of capital from the asset-level relationships suggested by standard economic theory, and discuss the specific pattern of weights required to aggregate the asset-level relationships.
(9) More detailed expositions of the aggregate and asset-level long-run relationships are provided by Ellis and Price (2004) and Bakhshi, Oulton and Thompson (2003) respectively.
(10) Technical progress is assumed to be only labour augmenting. If technical progress were assumed to be both labour and capital augmenting, this would imply the inclusion of a time trend in equation **(1)**. Our key findings were not found to be sensitive to this assumption, however.
(11) See Jorgenson (1963) and Hall and Jorgenson (1967). The user cost expression is derived under profit maximisation using the capital accumulation identity (equation **(3)**) and the assumption of no adjustment costs.

$$RCC_{it} = P_{it}[\rho_{it} + \delta_i(1+\pi_{it}) - \pi_{it}] \quad \textbf{(2)}$$

where P is the price of asset-level investment relative to economy-wide prices, ρ is the real cost of finance, δ is the asset-level depreciation rate,(12) and π is the growth rate of the asset-level relative price of investment.

There are two key points to note. First, investment does not appear anywhere in the relationship: rather, the long runs relate asset-level capital to output and asset-level user cost. Second, the elasticity (β) of capital with respect to the user cost is the same for each asset group, reflecting the assumed CES production technology. We discuss the extent to which the data are consistent with such a restriction later in this paper.

The capital accumulation identity states that capital in any period is equal to the depreciated amount from the previous period plus (gross) investment. This is shown in **(3)**, where *I* denotes investment and δ the depreciation rate.

$$K_{it+1} = (1-\delta_i)K_{it} + I_{it} \quad \textbf{(3)}$$

Bean (1981) used this to substitute for (aggregate) capital. In the steady state **(3)** can be written as:

$$K_{it} = \frac{I_{it}}{\delta_i + g^K_{it+1}} \quad \textbf{(4)}$$

where g^K denotes the growth rate of capital. By substituting logged **(4)** into equation **(1)**, we derive a long-run relationship **(5)** which links investment to output and the real user cost.

$$i_{it} = y_t + \alpha_i - \beta rcc_{it} + \ln(\delta + g_{it}{}^K) \quad \textbf{(5)}$$

On the assumption that the depreciation rate and growth rate of capital are stationary at the asset level, we can omit the final term in equation **(5)** when estimating the long-run cointegrating vectors:

$$i_{it} = y_t + \alpha_i - \beta rcc_{it} \quad \textbf{(6)}$$

(12) In line with Tevlin and Whelan (2003), we use a nominal aggregate depreciation rate. This avoids biases that can arise from the calculation of real aggregate depreciation rates under the chain-weighted data published in the US, for example.

As noted by Ellis and Price (2004) in an aggregate context, we can think of equation **(6)** as the reduced form of two relationships: the first-order condition linking capital, output and the real cost of capital; and the cointegrating relationship between capital and investment given by the capital accumulation identity. It is this long-run, asset-level relationship that we estimate jointly for the G7 plus Australia in Section 6.[13]

4 The data: stylised facts

Our data set contains disaggregated investment data provided by the OECD. These data have two major advances over data used in other international studies of investment. First, for each country the data are disaggregated into a number of asset types. The second is that the data set contains both national and 'harmonised' deflators, and so we are able to consider alternative means of measuring investment deflators. Table A shows that national investment deflators for ICT goods fell particularly rapidly in the late 1990s in all countries relative to the 1980s. But the alternative 'harmonised' measures (which we discuss in more detail in Appendix 3) suggest even more rapid declines over this period. We examine below the sensitivity of our data set – and econometric results – to possible deflator mismeasurement.

Table A: Average annual percentage change in ICT equipment, national and harmonised deflators

1995-2000	Australia	Canada	France	Germany	Italy	Japan	UK	US
National	-22.2	-18.3	-11.7	-6.5	-2.4	-7.8	-8.1	-22.8
Harmonised	-19.8	-22.3	-21.7	-21.7	-21.0	-20.9	-21.4	-22.8
1980-1990								
National	-10.8	-16.5	-7.1	-1.2	6.0	-3.1	-3.7	-10.2
Harmonised	-9.1	-12.5	-11.0	-12.8	-7.1	-15.0	-11.2	-10.2

Source: Colecchia and Schreyer (2002).

4.1 Investment

The baseline data set covers the period 1980 to 2000 for all of the eight countries except Australia and Japan (1980-99). For each country, we used the national deflator series to calculate alternative constant-price investment series at both the aggregate and disaggregate (ICT/non-ICT) level. In order to aggregate to this level, from the seven asset level of disaggregation contained in the OECD data set, we adopted the Tournqvist chain index aggregation approach. This is calculated as a weighted average of the growth of investment in each asset. The asset-level weights are allowed to

[13] Given that this long-run expression may not fully capture past, accumulated investment gaps, Bakhshi and Thompson (2002) include a capacity utilisation term in the equation dynamics as an 'integral control variable'. On the other hand, Bean (1981) argued that omitting such a variable may not lead to significant biases, while Ellis and Price (2004) note that output itself is linked to capital via the production function and therefore incorporates a degree of integral control. For simplicity, we exclude capacity utilisation variables from the econometric specifications estimated later in the paper.

vary over each time period, and are defined as the mean of the asset-level shares of aggregate current-price investment in two adjacent years.[14]

Investment to GDP ratios vary both across countries and also over time. Chart 1 illustrates the marked increase in the constant-price ratio of whole-economy investment (excluding dwellings) to GDP for many countries since the mid-1990s. This is true for all economies in the G7 plus Australia, with three exceptions. Japan, Germany and (to a lesser extent) France experienced rather different investment cycles, characterised by the ratio of investment to GDP peaking in the early 1990s.[15] But for all eight of the countries, there was a marked rise in the ratio of ICT investment to GDP in the latter half of the 1990s.

Chart 1: Change in investment to GDP ratio (national deflators) – aggregate versus ICT

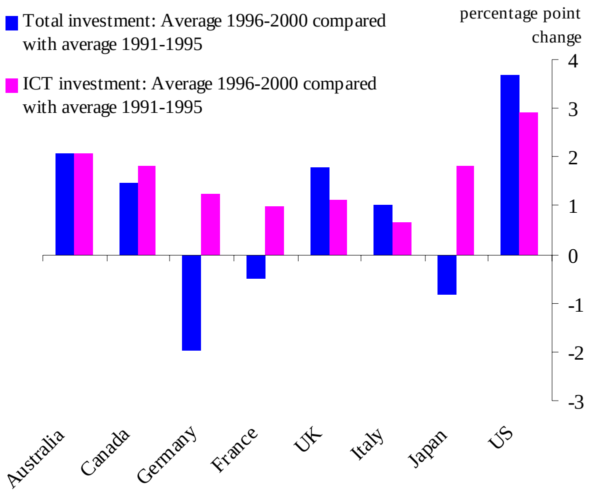
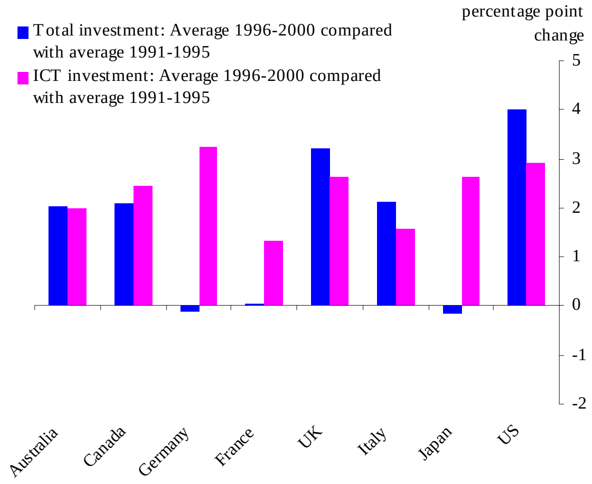


Chart 2: Change in investment to GDP ratio (harmonised deflators) – aggregate versus ICT



The data set also allows us to calculate alternative investment series based on the harmonised deflators discussed above. Chart 2 shows that use of harmonised deflators implies a more even increase in ICT investment across countries; and a more marked rise in the ratios of both ICT investment to GDP and aggregate investment to GDP outside the United States.

4.2 Real user cost of capital

The asset-level real user cost is given by equation **(2)**, reproduced as equation **(7)** below.

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(14) See Bureau of Labour Statistics (1997) for further details on this aggregation approach.
(15) It is perhaps worth noting that in Germany, reunification was associated with a pickup in investment in the early 1990s.

$$RCC_i^t = P_i^t[\rho^t + \delta(1+\pi_i^t) \; - \pi_i^t] \qquad \textbf{(7)}$$

When expressed in logs, the real user cost of capital term in equation **(7)** is the sum of two components: the relative price of capital; and a non-relative price component. The former is simply the price of asset-level capital relative to the price of output. The latter conflates the real cost of finance, depreciation and relative price inflation terms.

The data set uses national deflators to calculate the relative price of investment, as well as a weighted average cost of capital (WACC) measure of the real cost of finance. The WACC is made up of a cost of debt term (a corporate bond yield measure that consists of not only the risk-free (*ex-post*) real interest rate, based on government bond yields, but also a corporate spread term) and a measure of the cost of equity (derived from a one-stage dividend discount model). The WACC variable may pick up overoptimistic expectations to the extent that these expectations are reflected in equity valuations and a lower estimated cost of finance.

$$WACC_i^t = \lambda(\cos t \; of \; debt_i^t) + (1-\lambda)(\cos t \; of \; equity_i^t) \qquad \textbf{(8)}$$

The weights on the cost of debt (λ) in each country are fixed at the average share of debt financing over the past ten years.(16) For example, the weight on debt for Canada (0.35), the United Kingdom (0.16) and the United States (0.25) is relatively low, reflecting the importance of equity finance in these countries.

The Jorgenson real user cost of capital measures are plotted in Charts 3 and 4 (on logarithmic scales).(17) These charts show that, in general, the real user cost has fallen somewhat for the economies in our sample over the 1990s. We have also examined the movements of the aggregate real user cost of capital that are due to the movement of relative prices in Chart 5.(18) This chart shows that the price of aggregate capital relative to the price of output has trended down over the sample. The non-price component - comprising the cost of finance, depreciation and relative price inflation terms - has moved broadly in line with the aggregate measure.

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(16) These data are derived from national financial accounts data, where available. In Appendix 3, we examine the sensitivity of our econometric results to a simple cost of debt measure that is more typically used in the cross-country investment literature.
(17) Note that the axes differ on Charts 3 to 5.
(18) Charts A1.1 – A1.8 (for aggregate capital) and Charts A1.9 – A1.16 (for ICT capital) show, by individual country, the real user cost and relative price data contained in Charts 3 – 7.

Chart 3: Aggregate Hall-Jorgenson real user cost of capital

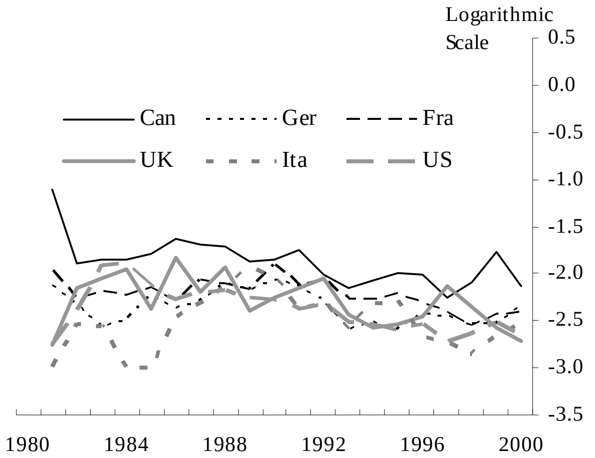


Chart 4: Aggregate Hall-Jorgenson real user cost of capital (continued)

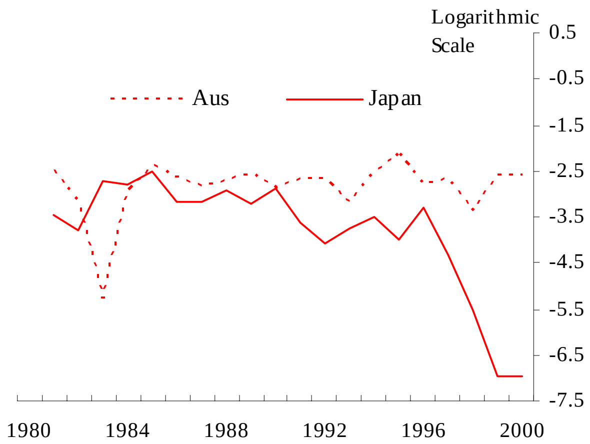
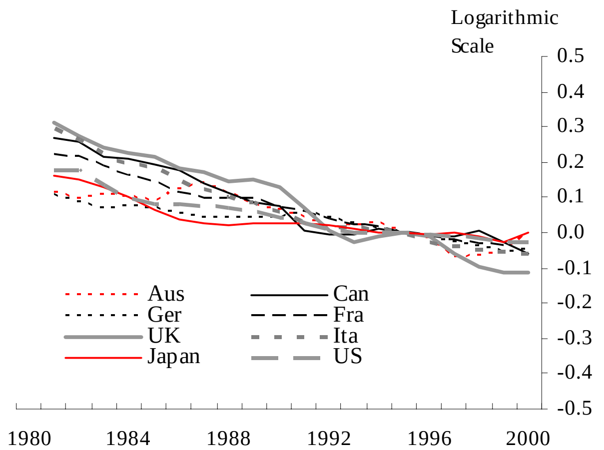


Chart 5: Relative price component of the aggregate Hall-Jorgenson real user cost of capital



The aggregate real user cost masks rather different trends at the asset level. The real user cost of non-ICT capital has remained fairly stable over the sample. But, in contrast, there has been a significant decline over time in the real user cost of ICT capital for all of the countries (Chart 6). This decline is largely the result of the declining relative price of ICT goods (Chart 7); the non-price component has remained relatively constant over time.

Chart 6: Hall-Jorgenson real user cost of ICT capital

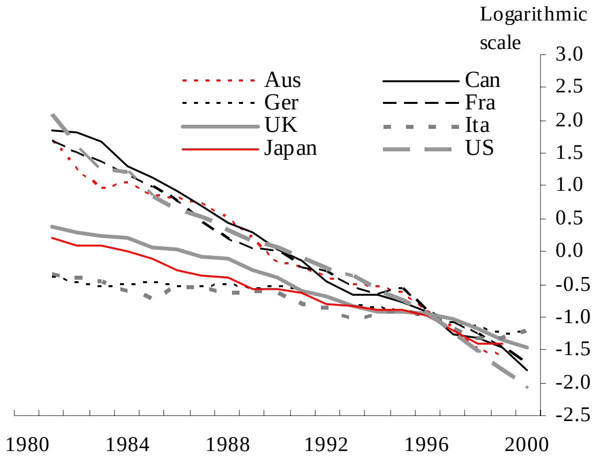
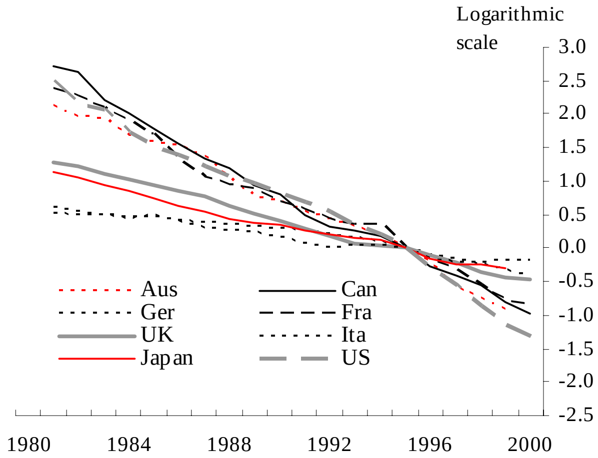


Chart 7: Relative price component of the Hall-Jorgenson real user cost of ICT capital



5 Statistical analysis

In this section we examine the statistical properties of the baseline data set.[(19)]

Unit root tests

First, we performed panel unit root tests on our data series, following Im, Pesaran and Shin (1997) – hereafter IPS.[(20)] The lag length was optimally chosen using the Schwarz-Bayesian Information Criterion with a maximum lag length of four lags. The results, reported at the top of Tables B and C, are mixed. Panel stationarity of the investment data, in aggregate and at the asset level, is rejected by the IPS tests. But the tests suggest that the non-ICT real user cost of capital series may be I(0). Given the low power of unit root tests and that we can more clearly reject non-stationarity when we difference our data (see Tables A1 and A2 in Appendix 2), we proceed on the basis that the data for the overall panel are I(1). However, if the cost of capital series does not contain a unit root, then caution is necessary in interpreting the estimated long-run cointegrating relationship.

While the tests of IPS improve on early panel unit root tests by Levin and Lin (1993) by allowing for heterogeneity in the unit root properties across countries, IPS is only of limited use in the presence of contemporaneous correlation across countries. IPS assume that this correlation is caused by time-specific effects and eliminate this effect by use of a common time dummy. As highlighted in Maddala and Wu (1999), this form of cross-correlation can be eliminated simply by de-meaning the

[(19)] For a survey of the panel unit root and cointegration literature, see Banerjee (1999).
[(20)] These tests were implemented in RATS using code made available by the authors (Im, Pesaran and Shin). We are grateful to Rebecca Driver for initial advice on implementing these tests.

data (using the cross-sectional mean).[21] Moreover, cross-correlation in a real-world application is unlikely to take the form accounted for in IPS tests.

Table B: Panel and univariate unit root tests

Test	Country	GDP	Total investment	ICT investment	Non-ICT investment
IPS (Panel)	**GROUP**				
ADF (Univariate)	Aus				*
	Can				
	Ger				*
	Fra				*
	UK		**	**	**
	Ita				
	Jap	*	**		**
	US				

Null of non-stationarity is rejected at *10% level, ** 5% level, * 1% level**

Table C: Panel and univariate unit root tests (continued)

Test	Country	Aggregate real cost of capital	Real cost of ICT capital	Real cost of non-ICT capital
IPS (Panel)	**GROUP**	***		***
ADF (Univariate)	Aus	***		***
	Can	***		***
	Ger	**		**
	Fra	**		***
	UK	***		***
	Ita	**		***
	Jap			
	US	***		***

Null of non-stationarity is rejected at *10% level, ** 5% level, * 1% level**

One possible improvement would be the use of another test, such as that proposed by Maddala and Wu, or the multivariate ADF test proposed by Taylor and Sarno (1998). Both of these tests allow for contemporaneous correlation of a more general form. However, as the aim of our paper is to find a long-run relationship between three non-stationary variables (albeit in a multi-country set-up), standard unit root test results should be sufficient to establish that our variables are I(1). The results

[21] Similar results were obtained using this approach.

of these tests are summarised in the remainder of Tables B and C above. Again, the results are mixed, but most variables do not appear I(0) in levels and differenced data again lends support to proceeding on the assumption that the data are I(1) (see Tables A2.1 and A2.2 in Appendix 2).

Cointegration

We next examine the existence of the long-run relationship embodied by equation **(1)** above. There are a number of tests for cointegration in a dynamic panel. The tests of Pedroni (1995, 1997) and Kao (1999), for example, are based on a null of no cointegration and use the residuals from a panel equivalent of the Engle-Granger regression. Pedroni (1999) constructs seven tests for cointegration in heterogeneous panels with multiple regressors – four are based on pooling within dimension ('panel tests') and three based on pooling between dimension ('group statistics'). The panel tests pool the residuals across countries and test the hypothesis of cointegration assuming the unit root properties of the error are the same across countries. Therefore, the panel statistics are a joint hypothesis of cointegration and homogeneity of the error process. The group statistics are preferred as they allow for hetereogeneity in the error process across countries.

Tables D and E report the initial Pedroni tests for a long-run relationship in our three systems - the aggregate system refers to our econometric estimates using data on total non-residential investment while the (non-) ICT system refers to (non-) ICT investment data. In Table D all three variables are included and the co-integrating vector is unrestricted. In Table E, investment and GDP are constrained to be a ratio in the long-run relationship. In most cases for the aggregate data, the test statistics do not allow us to reject the null of no cointegration (the exception is the group analogue of the Augmented Dickey-Fuller test for the unrestricted vector). But for the two disaggregated asset systems, there is greater evidence of long-run cointegrating relationships.[22]

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[22] One potential extension of this approach would be to attempt to deal with the complications of heterogeneous short-term dynamics. These dynamics are not easily dealt with using the Pedroni or Kao panel cointegration tests. Groen (2002) uses Monte Carlo experiments to show that applying the Pedroni tests to models with common long-run but heterogeneous short-run dynamics (and intra-cross sectional endogeneity) leads to low power against the null of no cointegration. An alternative strategy would be to use the Larsson *et al* (2001) or Groen and Kleibergen (2003) approaches. These are panel versions of the Johansen VAR-based cointegration framework. However, our current data set contains too few observations for this extension. We are grateful to Jan Groen for discussions and advice on these (and other) issues.

Table D: Panel cointegration test results (assuming no restriction on GDP)

3 variables	Aggregate system	ICT system	Non-ICT system
Panel v-stat		***	
Panel rho-stat			
Panel pp-stat		**	
Panel adf-stat	*	***	**
Group rho-stat			
Group pp-stat		**	
Group adf-stat	**	***	**

Null of no cointegration is rejected at *10% level, ** 5% level, * 1% level**

Table E: Panel cointegration test results (GDP coefficient restricted to equal -1)

2 variables	Aggregate system	ICT system	Non-ICT system
Panel v-stat		***	
Panel rho-stat		**	
Panel pp-stat		***	
Panel adf-stat		***	
Group rho-stat			
Group pp-stat		**	
Group adf-stat		***	

Null of no cointegration is rejected at *10% level, ** 5% level, * 1% level**

6 Econometric analysis

A number of important methodological issues surround the modelling of long-run cointegrating relationships in a dynamic country panel (see, eg, Pesaran and Smith (1995)). In particular, by introducing lagged dependent variables, estimates are rendered inconsistent regardless of sample size (Pesaran and Smith (1995)). However, we can estimate a system of individual equations and then gain more precision in our estimates by using restrictions across the cross-sectional dimension.

Pesaran, Shin and Smith (1999) suggest the use of a pooled mean group (PMG) estimator. This involves imposing country-specific dynamic specifications to each equation in our system, but restricting the long-run parameters to be the same across countries. The appropriateness of these imposed long-run restrictions can be tested using a Hausman test (Pesaran, Shin and Smith (1999)). This approach circumvents the problem of omitted 'group variables' which bias country-specific estimates.

Pesaran, Shin and Smith (1999) propose a maximum likelihood estimator for this approach.[(23)] Given our sample dimensions, we proceed with their approach but estimate the system using the SUR method. This takes account of any contemporaneous covariance between the residuals (unlike OLS). The equation that we estimate is of the form of equation **(9)** below:

$$\Delta i_{i,t}^{n} = \alpha + \sum_{j=0}^{m} \phi_{i,1+j}^{n} \Delta y_{t-j}^{n} + \sum_{k=1}^{p} \gamma_{i,1+k}^{n} \Delta i_{i,t-k}^{n} + \alpha_{i}{}^{n} \left(i_{i,t-1}^{n} - y_{t-1}^{n} - \beta^{n} rcc_{i,t-1}^{n} \right) \qquad \textbf{(9)}$$

where i denotes investment for a given asset, y is GDP and rcc is the asset-level real user cost of capital; n specifies the country in question and t denotes time. Lower case denotes natural logs.

The bracketed long-run term in this equation represents equation **(6)** derived in Section 3. In our benchmark system, we constrain β^n to be the same for each country. This implies that, for a given asset, the elasticity of the real user cost with respect to investment is the same in all our countries. As argued in Pesaran, Shin and Smith (1999), imposition of long-run restrictions seems more plausible than the assumption of exactly common dynamic specifications.

A further advantage of this specification is that it allows us to perform a further test of the long-run relationship suggested by our theoretical model. This is particularly useful given the low power of cointegration tests in small samples. Specifically, we take the significance of the ECM coefficients, *ß*, in our SUR equations to be evidence for a cointegrating relationship, following Banerjee *et al* (1986).

Our key results are summarised below and in Table F.

- In the **aggregate** system, the econometric estimate of the restricted elasticity term is very low and not statistically different from zero. The ECM term ranges from -0.2 to -0.5 for those countries for which it is significant (Australia, France, Italy and Japan). In Canada the elasticity is -0.1 but insignificant from zero. There is no evidence of a cointegrating relationship in Germany, the United Kingdom or United States.
- The estimates from the **non-ICT** investment system are similar to those in the aggregate investment system. The elasticity term is low and insignificantly different from zero. The ECM term is significant, ranging from -0.3 to -0.5, for France, Italy and Japan; but elsewhere, the ECM estimates are insignificantly different from zero and, for the United States and Germany, incorrectly signed.
- The disaggregated **ICT** system provides markedly different econometric results, in which there is an important role for the real user cost of capital and much greater evidence of

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(23) This estimator is available from the authors at www.econ.cam.ac.uk/faculty/pesaran/jasa.exe.

cointegration. This is consistent with the single-country findings of Tevlin and Whelan (2003) and Bakhshi, Oulton and Thompson (2003), discussed in Section 2. In particular the elasticity is -1.3 and highly significant. The ECM terms are sensible for most countries in our sample (ranging from -0.1 to -0.6 for Australia, Canada, France, the United Kingdom, the United States and Italy), but round to zero for Germany and Japan.

These findings appear robust to alternative definitions, econometric specifications and disaggregation (see Appendix 3). In all cases, the estimated elasticity for ICT assets is both highly significant and much greater than for non-ICT assets.[24]

Table F: Results for system using restricted elasticity term
(probability that coefficient is zero in italics)

Country	**Aggregate system**		**ICT system**		**Non-ICT system**	
	Elasticity	ECM term	Elasticity	ECM term	Elasticity	ECM term
Aus	**0.0**	**-0.53**	**-1.3**	**-0.06**	**0.0**	**-0.03**
	(0.8)	*(0.0)*	*(0.0)*	*(0.5)*	*(0.3)*	*(0.6)*
Can	**0.0**	**-0.08**	**-1.3**	**-0.39**	**0.0**	**-0.21**
	(0.8)	*(0.7)*	*(0.0)*	*(0.1)*	*(0.3)*	*(0.2)*
Ger	**0.0**	**0.04**	**-1.3**	**0.00**	**0.0**	**0.06**
	(0.8)	*(0.5)*	*(0.0)*	*(1.0)*	*(0.3)*	*(0.2)*
Fra	**0.0**	**-0.24**	**-1.3**	**-0.38**	**0.0**	**-0.45**
	(0.8)	*(0.0)*	*(0.0)*	*(0.0)*	*(0.3)*	*(0.0)*
UK	**0.0**	**0.07**	**-1.3**	**-0.37**	**0.0**	**0.00**
	(0.8)	*(0.2)*	*(0.0)*	*(0.0)*	*(0.3)*	*(1.0)*
Ita	**0.0**	**-0.39**	**-1.3**	**-0.41**	**0.0**	**-0.50**
	(0.8)	*(0.0)*	*(0.0)*	*(0.0)*	*(0.3)*	*(0.0)*
Jap	**0.0**	**-0.34**	**-1.3**	**0.00**	**0.0**	**-0.26**
	(0.8)	*(0.0)*	*(0.0)*	*(1.0)*	*(0.3)*	*(0.0)*
US	**0.0**	**0.04**	**-1.3**	**-0.57**	**0.0**	**0.45**
	(0.8)	*(0.7)*	*(0.0)*	*(0.0)*	*(0.3)*	*(0.2)*

[24] In Section 3, it was noted that the assumption of a CES production function implies a common elasticity across assets. The finding of very different asset-level elasticities could still be consistent with the CES assumption, given that the estimated elasticity will be greater for capital inputs where shocks to the real user cost are more persistent, compared with shocks that are temporary (Tevlin and Whelan (2003)). That explanation would be consistent with the marked differences in persistence properties across assets, discussed in Section 4.2, but not necessarily the weaker evidence of cointegration for the non-ICT system. An alternative explanation is that equation **(9)** is misspecified (Bakhshi, Oulton and Thompson (2003)), in which case we would reject cointegration in the ICT system.

7 Forecasting performance

In this section, we investigate the extent to which the theoretical advantages of the disaggregated approach translate into a superior forecasting performance. Specifically, we re-estimated the systems presented in Section 6 over a shortened sample period (1980 to 1995); and then generated dynamic out-of-sample forecasts over the following six years (1996-2001), conditional on the actual path of the real user cost and output. These forecasts extend one year beyond the period covered by our data set (which ends in 2000), given that all explanatory variables are lagged by at least one period in our econometric specification (see equation **(9)**).[25] The country-level forecasts were then aggregated (using PPP exchange rates) to derive forecasts for annual investment growth for the G7 plus Australia.

The forecasting results indicate that the disaggregate model is much more successful than the aggregate model at capturing the key features of the investment boom. Chart 8 shows out-of-sample forecasts for the G7 plus Australia from the aggregate and disaggregate models, estimated under the common elasticity restriction and using the baseline data set.[26] Table A2.3 in Appendix 2 reports the corresponding root mean squared errors (RMSEs) of our forecasts for the G7 plus Australia, as well as those for individual country forecasts. (Interestingly, the disaggregate model tends to outperform the aggregate model for individual countries, although Germany and Japan are notable exceptions - perhaps related to country-specific developments.) Our findings appear broadly unaffected by the choice of econometric specification: similar results were obtained under an alternative pooled system (in which equality of dynamic and long-run coefficients was imposed) discussed in Appendix 3.[27]

Both aggregate and disaggregate models struggle to capture the precise dynamics of whole-economy investment (excluding dwellings).[28] But unlike the forecasts from the aggregate equations, the profiles for whole-economy investment (excluding dwellings) implied by the disaggregate equations are broadly in line with the strong outturns of the latter half of the 1990s. And that is consistent with

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(25) Given the lack of deflator data for Australia and Japan in 2000, the 2001 forecasts for these countries are based on the assumption that deflators in 2000 changed at the average rate of the previous five years. We also include a 1990 dummy for Germany in all of our forecasting systems.

(26) In other words, we impose an equal elasticity of the real user cost with respect to investment across countries in the aggregate model; and in the disaggregate model, an equal elasticity for ICT assets and an equal elasticity for non-ICT assets. In the aggregate model, the estimated ECM coefficient was incorrectly signed in equations for Germany and the US. We therefore dropped the levels terms from those equations and re-estimated the aggregate system. Including the levels terms results in an even worse performance of the aggregate model.

(27) These alternative results are not reported here, but are available on request.

(28) For example, the disaggregate models overpredict investment in 1998 (largely reflecting overpredictions for the United States and Japan). To a large extent, this is offset by previous underpredictions – the forecast errors in 1996 and 1997 are, together, around two thirds of the absolute size of that for 1998 – such that the disaggregate model broadly captures the strength of investment over the period as a whole.

previous analysis by Tevlin and Whelan (2003) for the United States and by Bakhshi, Oulton and Thompson (2003) for the United Kingdom. The aggregate and disaggregate systems project more similar growth estimates towards the end of the forecast horizon.

Chart 8

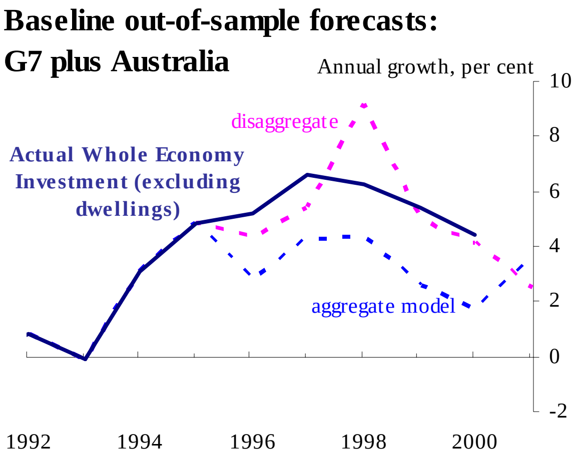
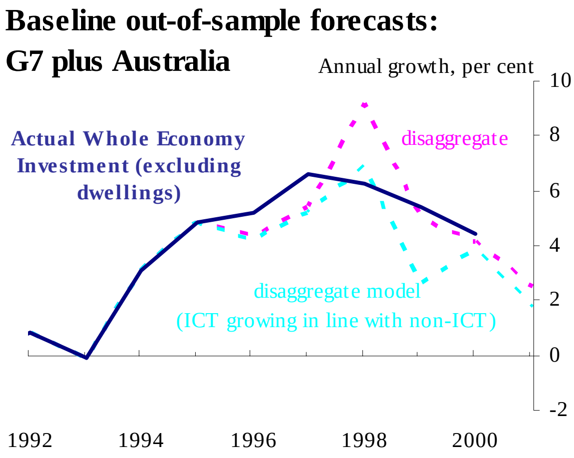


Chart 9



In the same way that the strength of actual aggregate investment outturns in the latter half of the 1990s tended to be driven by ICT assets, the strength of the disaggregate model forecast largely reflects a strong projection for ICT assets. Chart 9 shows the disaggregate model forecast with an alternative forecast in which ICT investment was assumed to grow in line with the non-ICT forecast. The alternative forecast tends to underpredict aggregate investment over this period. That too suggests gains from modelling ICT and non-ICT assets separately.

The strength of the ICT investment projection is driven by declines in the relative price of ICT assets. Chart 10 shows the alternative forecast, with ICT growing in line with non-ICT investment, together with another alternative derived under the assumption that the relative price of ICT was unchanged over the forecast period. In both cases, the alternative forecasts tend to underpredict aggregate investment. And the forecast based on unchanged ICT relative prices is almost, but not quite, as weak as the forecast in which ICT investment was assumed to grow in line with the non-ICT forecast. That indicates that the large declines in the relative price of ICT assets accounts for much, but not all, of the strength of the baseline projections for ICT investment projection - and, hence, plays a crucial role in explaining the disaggregate model's projection for whole-economy investment (excluding dwellings).

Finally, forecasting performance is little affected by the use of harmonised deflators (see Appendix 3 for further details). The disaggregate model is better able than the aggregate model to capture the strength of investment in the latter half of the 1990s (see Chart 11 and Table A2.3 in Appendix 2) -

but not markedly better when we use harmonised deflators rather than national deflators. This is perhaps unsurprising. Deflator mismeasurement affects not only estimates of the (constant-price) investment-GDP ratio, but also our estimates of the real user cost of capital. And in our framework, it is the user cost that determines the investment-GDP ratio in the long run. In other words, mismeasurement associated with national deflators will tend to lead us to understate both actual and 'equilibrium' investment-GDP ratios, and does not necessarily have a material impact on forecasting performance.

Chart 10

Baseline out-of-sample forecasts: G7 plus Australia

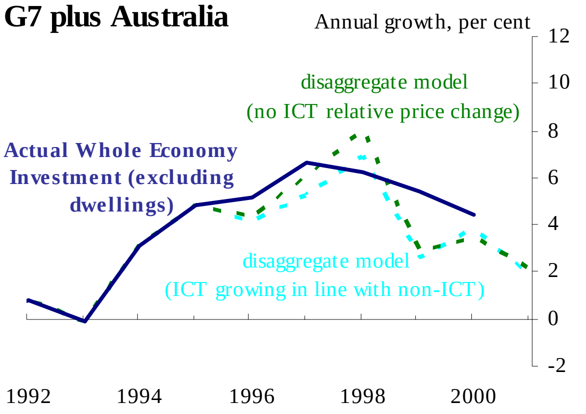
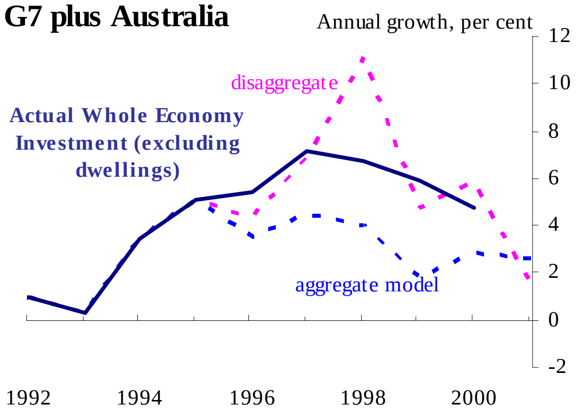


Chart 11

Harmonised out-of-sample forecasts: G7 plus Australia



8 Further research

One unanswered question is how well the aggregate and disaggregate models perform beyond the end of our sample period. For the asset-level model, that is difficult to assess, given the lack of timely ICT data for the majority of countries in the sample. The models are consistent with a slowing of investment growth post-2000, given the accelerator effect of weakening GDP growth and (in the disaggregate model in particular) the impact of equity price falls on the cost of finance. But the continued declines in the relative price of investment goods – most notably ICT assets – would have implied only a relatively modest easing. Indeed, a preliminary analysis of the investment downturn, based on the estimated models discussed above and investment outturns for 2001 and 2002 from an updated OECD asset-level data set, suggests that neither the aggregate or disaggregate models can explain the entire slowdown.[29]

[29] The updated data set was kindly provided by the OECD. Of course, this data set could imply different model coefficients to those reported in this paper. Robust analysis of the performance of these models during the investment slowdown would require the application of our entire data testing and estimation procedures on the updated data set.

This suggests that other factors, not captured by these models, may have been important. For example, our models do not contain an explicit balance sheet channel. Although our cost of finance measures do capture the direct effect of stock market valuations on the real user cost of capital, they may not fully capture financial accelerator effects from the sharp decline of equity prices in late 2000 and in 2001 – or, indeed, the preceding sharp rise in equity values in the late 1990s (Bernanke (2003a)). Similarly, the investment cycle could have been accentuated by changes over time in asset-level depreciation rates (assumed constant in our models). Effective asset-level depreciation rates, reflecting factors such as obsolescence, might have declined over the investment slowdown, as companies retained ICT equipment for longer periods than in the past. Also, unrealistic expectations of the productive potential of new ICT equipment could have resulted in over-investment in the late 1990s, only to be followed by re-assessment and a period of subdued investment. Bernanke (2003b) presents evidence that our ability to explain the US investment slowdown is improved by augmenting a model such as that used above with analysts' long-term earnings expectations, a proxy for those expectations. Y2K-related investment could have had similar effects in accentuating the investment cycle. Future research into the impact of such factors – within the context of a disaggregate modelling approach – could be particularly important in developing our understanding of this period.

9 Conclusions

Most macro forecasters of investment during the late 1990s underestimated global investment. One potential reason was that the models they were using were insufficiently disaggregated. In this paper, we have developed an empirical model whose out-of-sample forecasts, conditioned on the actual paths of output and the real user cost of capital, largely predict the global investment boom of the late 1990s. The main factor behind the improved model performance is that we distinguish investment in ICT assets from other investment, using disaggregated investment data provided by the OECD. In line with previous studies on US and UK investment performance, our SUR estimates suggest that ICT investment is much more responsive than other investment to a given change in relative prices and, hence, the real user cost of capital. Combined with the marked falls in the price of ICT assets of recent decades, that points to very strong relative price effects on ICT investment for all G7 countries and Australia.

The paper has also examined the potential impact of deflator mismeasurement on the estimation, and forecasting performance, of investment models. Our results are relatively insensitive to whether we measure investment using harmonised, rather than national, deflators. That highlights the important role played by our fully specified real user cost of capital measures. In our framework, the choice of deflator affects not only actual investment, but also estimates of equilibrium investment – and, as such, deflator mismeasurement does not necessarily have a material impact on forecasting performance.

Future research could extend this work in a number of ways. Disaggregation by sector, as well as by asset, could prove fruitful if the impact of relative price movements differs between companies producing ICT assets and those consuming them, for example. Although there remain data and econometric limitations to any increase in the dimensions of our panel, such an extension could be particularly relevant for our analysis given the varying importance of ICT production across countries. Alternatively, further analysis might focus on the more recent behaviour of investment. As highlighted above, certain extensions to the model, such as incorporation of explicit balance sheet channels or measures of firms' earnings expectations, could be particularly important in developing our understanding of this period.

Nonetheless, the general conclusion of our research is clear. When relative prices of different investment assets change rapidly, forecasting accuracy can be improved markedly by taking into account such differences.

Appendix 1: The baseline real user cost of capital data

Chart A1.1: Australia - real user cost of capital

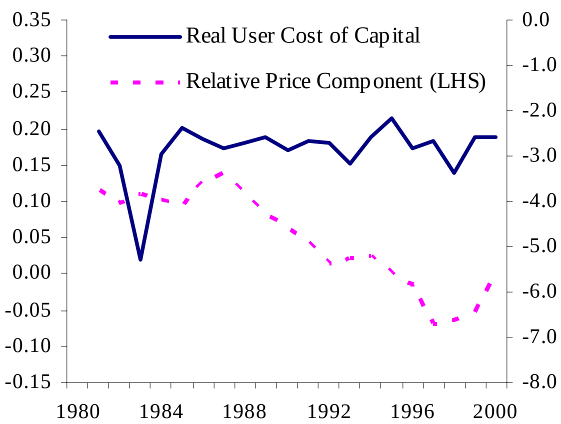


Chart A1.2: Canada - real user cost of capital

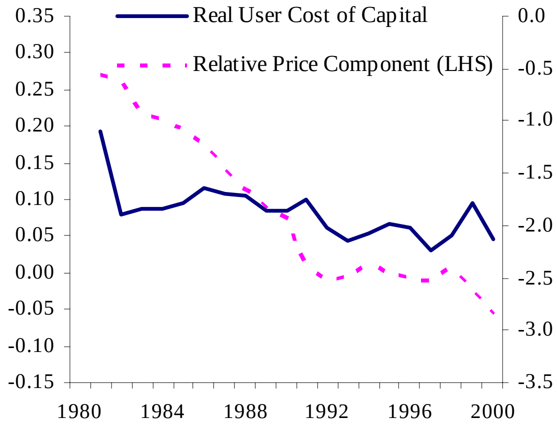


Chart A1.3: Germany - real user cost of capital

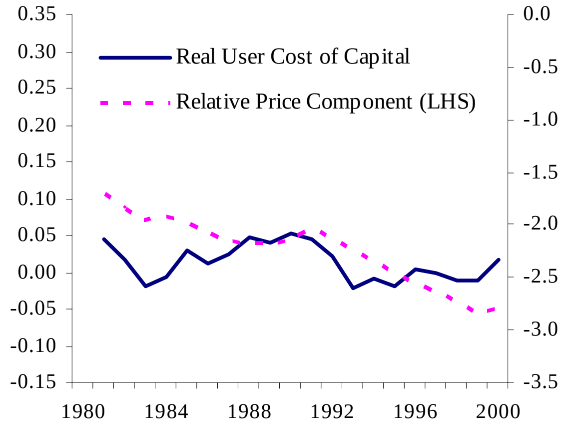


Chart A1.4: France - real user cost of capital

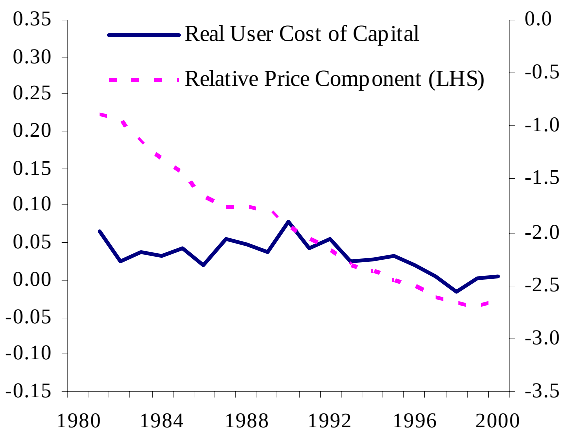


Chart A1.5: UK - real user cost of capital

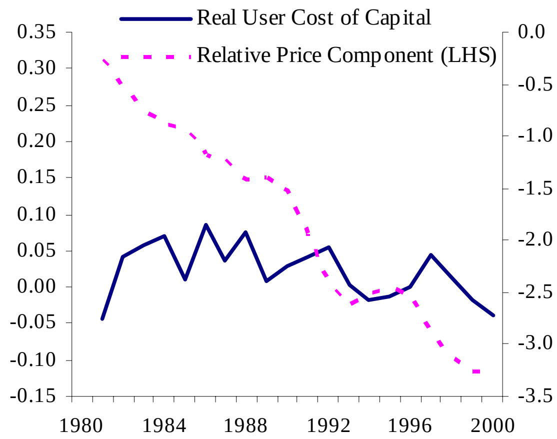


Chart A1.6: Italy - real user cost of capital

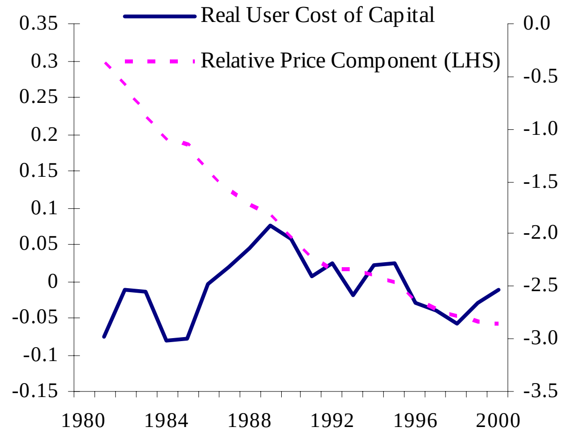


Chart A1.7: Japan - real user cost of capital

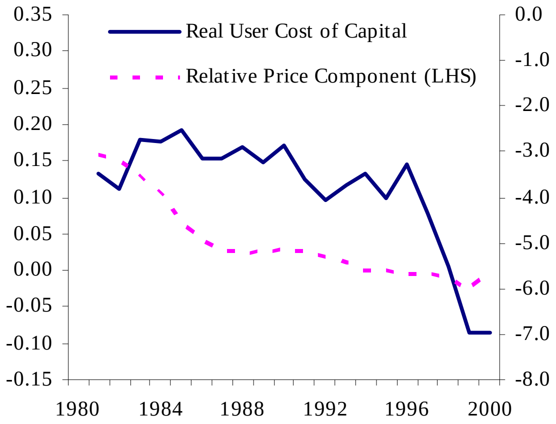


Chart A1.8: US - real user cost of capital

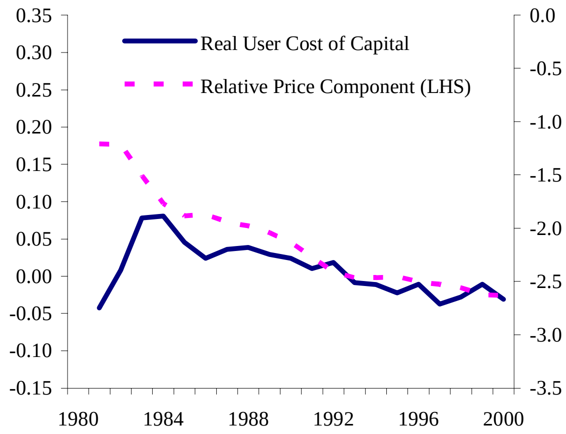


Chart A1.9: Australia - real user cost of ICT capital

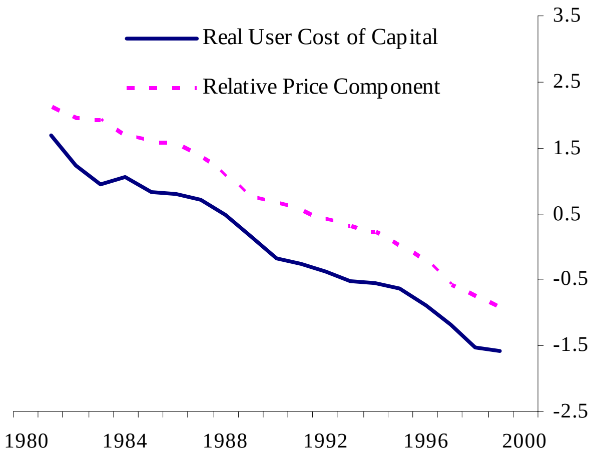


Chart A1.10: Canada - real user cost of ICT capital

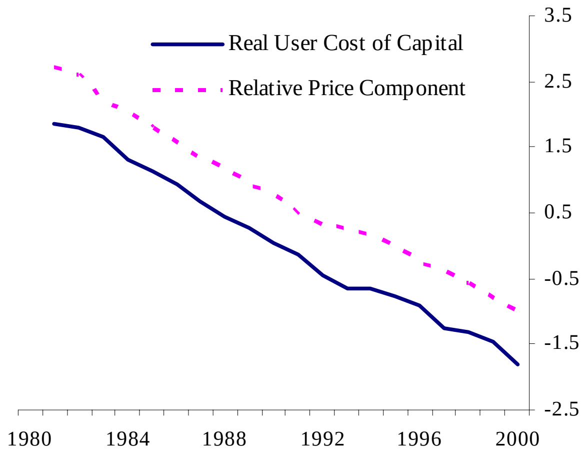


Chart A1.11: Germany - real user cost of ICT capital

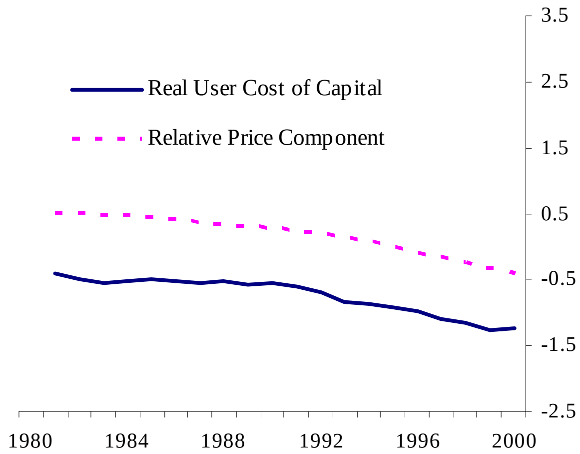


Chart A1.12: France - real user cost of ICT capital

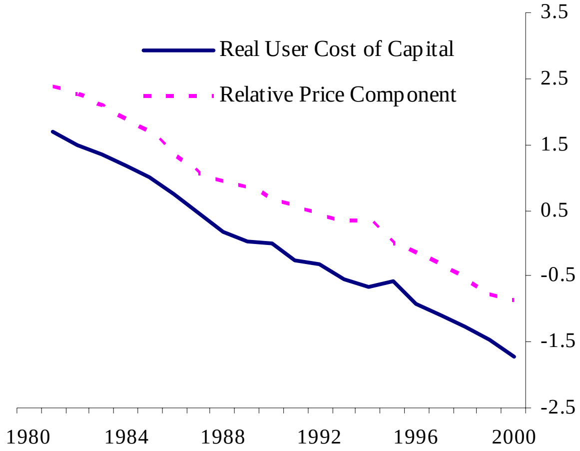


Chart A1.13: UK - real user cost of ICT capital

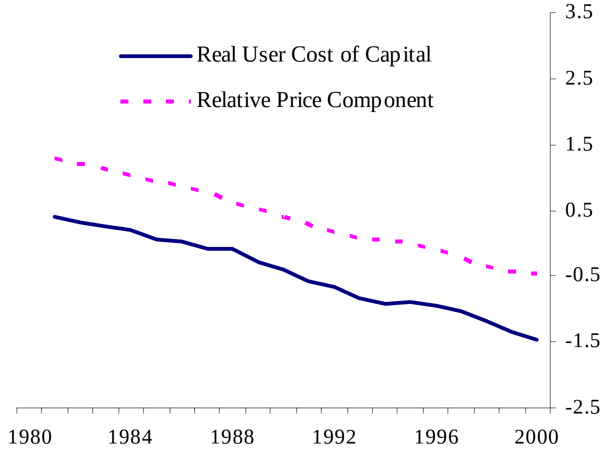


Chart A1.14: Italy - real user cost of ICT capital

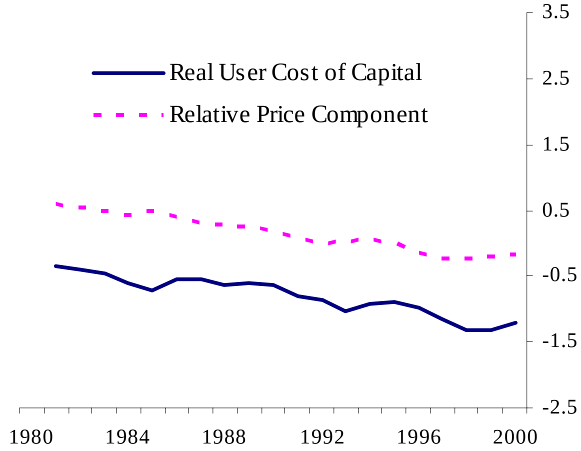


Chart A1.15: Japan - real user cost of ICT capital

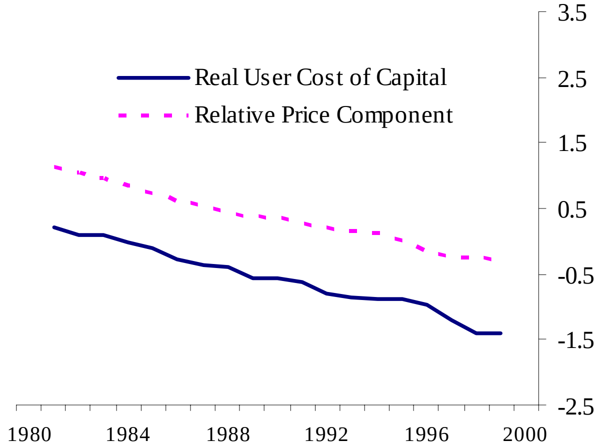
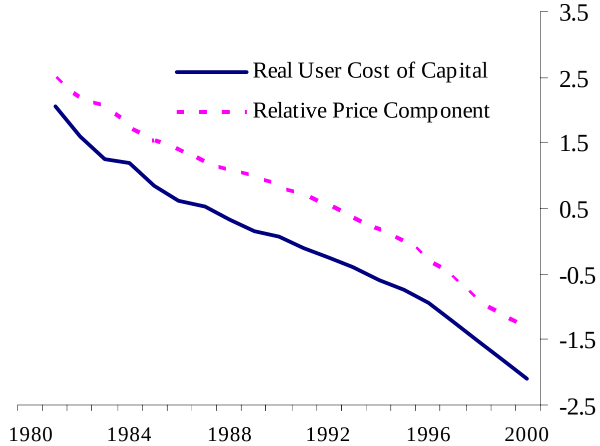


Chart A1.16: US - real user cost of ICT capital



Appendix 2: Econometric results

Table A2.1: Panel and univariate unit root tests on differenced data

Test	Country	Δ GDP	Δ Total investment	Δ ICT investment	Δ Non-ICT investment
IPS (Panel)	**GROUP**	***	***	***	***
ADF (Univariate)	Aus	***	***	***	***
	Can	***	***	***	***
	Ger	***	***	**	***
	Fra	**	**	**	**
	UK	***	***	***	***
	Ita	***	***	***	***
	Jap	**	***	***	***
	US	***	***	***	***

Null of non-stationarity is rejected at *10% level, ** 5% level, * 1% level**

Table A2.2: Panel and univariate unit root tests on differenced data (continued)

Test	Country	Δ Aggregate real cost of capital	Δ Real cost of ICT capital	Δ Real cost of non-ICT capital
IPS (Panel)	**GROUP**	***	***	***
ADF (Univariate)	Aus	***	***	***
	Can	***	***	***
	Ger	***	***	***
	Fra	***	***	***
	UK	***	***	***
	Ita	***	***	***
	Jap	***	***	***
	US	***	*	***

Null of non-stationarity is rejected at *10% level, ** 5% level, * 1% level**

Table A2.3[30]

Dynamic forecast errors, 1996-2000

	Australia	Canada	Germany	France	UK	Italy	Japan	US	G7 plus Australia
Root mean squared errors using national deflators									
Disaggregate model	0.043	0.069	0.078	0.040	0.028	0.114	0.095	0.027	0.017
Aggregate model	0.034	0.089	0.020	0.046	0.032	0.166	0.045	0.044	0.029
Root mean squared errors using harmonised deflators									
Disaggregate model	0.044	0.088	0.051	0.042	0.029	0.122	0.129	0.028	0.012
Aggregate model	0.052	0.079	0.019	0.058	0.048	0.117	0.028	0.042	0.028

(30) In both the aggregate model based on national deflators and the one based on harmonised deflators, the estimated ECM coefficient was incorrectly signed in equations for Germany and the US. We therefore dropped the levels terms from those equations and re-estimated the aggregate system. In the ICT system based on harmonised deflators (but not the system based on national deflators), the estimated ECM coefficient was incorrectly signed for Germany and the UK. Again, we dropped the levels terms from those equations and re-estimated the system.

Appendix 3: Sensitivity analysis

As a robustness check, we also examined the sensitivity of the findings reported above to four measurement and estimation issues.

Deflator mismeasurement: The baseline data set in this paper is based on national investment deflators. But our data set also contains 'harmonised' deflators, allowing us to test the implications of adopting alternatives. This could be important if, as argued by Wyckoff (1995), observed differences between computer price indices in OECD economies could to a large extent be attributed to differences in methodologies. In particular, some countries (eg the United States) employ hedonic pricing of ICT capital goods to a much greater extent than others and have recorded much sharper declines in investment price deflators. Schreyer (2000) suggests that cross-country comparisons will be more realistic when investment deflators are harmonised. To produce harmonised estimates, the author first calculates a benchmark differential between the smoothed investment deflators of ICT and non-ICT goods for the United States, a country that uses relatively advanced hedonic techniques to estimate its ICT investment price deflator. The differential is assumed to be equal in all countries and is then applied to non-ICT deflators in order to derive harmonised ICT deflators. This approach could have disadvantages. The author acknowledges that in cleansing the cross-country data of some biases, others may be introduced. And harmonisation ignores genuine differentials in prices that may arise from different composition in ICT investment, market barriers and taxation. In this appendix, we simply examine the sensitivity of our results to the choice of deflator, rather than judging which approach may be the more appropriate. Specifically, we re-estimated our models using an alternative data set based on harmonised deflators, and compared the resulting coefficients with those of the models reported in the main text.

Disaggregation: Our baseline data set disaggregate total investment into ICT and non-ICT assets. But the precise asset coverage of such categories could vary across countries. And arguably, these differences could be greater for broad categories than for narrower categories. We examined whether such coverage issues could have a material impact on our econometric findings, by re-estimating our disaggregate models using an alternative data set that disaggregates total investment into the narrower category of IT (computer) equipment and non-IT equipment. See Schreyer (2000) for further definitional details.

Cost of finance: As discussed in Section 4.2, the cost of finance term in our baseline data set is a weighted average cost of capital (WACC) measure. Unlike many cross-country investment studies, this allows for the impact of stock market movements on the cost of equity and, hence, the cost of capital. But our results could, in principle, be sensitive to any errors we might have made in the choice of weights attached to the cost of equity and the cost of debt finance (which we estimate using national financial accounts data). We examined this issue by re-estimating our systems using a simple cost of debt measure (the *ex-post* real government bond yield) as the cost of finance term in our real user cost of capital series. This is a measure more typically used in the cross-country investment literature.

Alternative econometric specifications: Finally, results might also be sensitive to estimation approach. We examined an alternative specification: a fully pooled system in which all long-run and dynamic parameters are restricted to be the same across countries, though we do allow for country-specific fixed effects. This was estimated, using SUR, on our baseline data set; estimated elasticities are reported in Table A3.1 below. We also estimated a fully unrestricted SUR system with country-specific long-run and dynamic parameters. (The results are not reported here, but are available on request.) Although precise estimates varied markedly across countries, the broad findings correspond to those reported in Section 6 for the baseline systems. For most countries, the models suggest that ICT investment is much more responsive to a given change in the real user cost of capital than investment in other assets.

Our econometric results could, in principle, be sensitive to all four of these issues. But in practice, the impact on our results was limited.(31) Table A3.1 shows the estimated long-run elasticities - the elasticities of the asset-level real user cost of capitals with respect to asset-level investment - in our restricted ICT and non-ICT SUR systems. Compared to the baseline case (also reported in Table F), our findings appear fairly insensitive to the four alternative approaches discussed above: the alternative data set based on harmonised, rather than national, deflators; the narrower 'IT equipment' category rather than 'ICT'; the pooled rather than SUR econometric specification; and the simpler cost of finance measure. The former finding is striking, given the marked differences in harmonised and national deflators. But as discussed in Section 7, it is perhaps not surprising - deflator mismeasurement affects not only our measures of the investment-output ratio but also our fully specified Hall-Jorgenson real user cost of capital measures.

(31) Detailed results are available from the authors on request.

Table A3.1: Alternative estimates of long-run elasticities in the disaggregate SUR system

	ICT	**Non-ICT**
Baseline	-1.3	-0.0
Harmonised deflators	-1.0	-0.0
Narrower ICT definition	-1.1	-0.0
Pooled system	-1.3	-0.0
Simple cost of finance	-1.3	-0.0

References

Ashworth, P and Davis, E P (2001), 'Some evidence on financial factors in the determination of aggregate business investment for the G-7 economies', *National Institute of Economic and Social Research Discussion Paper no. 187*.

Bakhshi, H, Oulton, N and Thompson, J (2003), 'Modelling investment when relative prices are trending: theory and evidence for the United Kingdom', *Bank of England Working Paper no. 189.*

Bakhshi, H and Thompson, J (2002), 'Explaining trends in UK business investment', *Bank of England Quarterly Bulletin*, Spring, pages 33-41.

Banerjee, A (1999), 'Panel data unit roots and cointegration: an overview', *Oxford Bulletin of Economics and Statistics*, Vol. 61, pages 607-30.

Banerjee, A, Dolado, J J, Hendry, D F and Smith, G (1986), 'Exploring equilibrium relationships through static models: some Monte Carlo evidence', *Oxford Bulletin of Economics and Statistics*, Vol. 48(3), pages 253-77.

Bean, C (1981), 'An econometric model of manufacturing investment in the UK', *Economic Journal*, Vol. 91, pages 106-21.

Bernanke, B (2003a), 'Balance sheets and the recovery', remarks at the 41st Annual Winter Institute, St. Cloud State University, St. Cloud, Minnesota, 21 February 2003. Available at: www.federalreserve.gov/boarddocs/speeches/2003/20030221/default.htm.

Bernanke, B (2003b), 'Will business investment bounce back?', remarks before the Forecasters Club, New York, 24 April 2003. Available at: www.federalreserve.gov/boarddocs/speeches/2003/200304242/default.htm#fn2.

Bureau of Labour Statistics (1997), *Handbook of methods*.

Byrne, J and Davis, E P (2002), 'Investment and uncertainty in the G7', *National Institute of Economic and Social Research Discussion Paper no. 198.*

Campa, J M and Goldberg, L (1999), 'Investment, pass-through and exchange rates: a cross-country comparison', *International Economic Review*, Vol. 40, No. 2, May.

Chirinko, R (1993), 'Business fixed investment spending: a critical survey of modelling strategies, empirical results, and policy implications', *Journal of Economic Literature*, Vol. 31, pages 1,875-911.

Chirinko, R, Fazzari, S and Meyer, A (2004), 'That elusive elasticity: a long-panel approach to estimating the price sensitivity of business capital', *Center for Economic Studies and Ifo Institute for Economic Research Working Paper no. 1240.*

Colecchia, A and Schreyer, P (2002), 'The contribution of information and communication technologies to economic growth in nine OECD countries', *OECD Economic Studies, No. 34*, 2002/1.

Darby, J, Hughes Hallett, A, Ireland, J and Piscitelli, L (1999), 'The impact of exchange rate uncertainty on the level of investment', *Economic Journal*, Vol. 109, C55-C67.

Edison, H and Slok, T (2001), 'New economy stock valuations and investment in the 1990s', *IMF Working Paper WP/01/78*, June.

Ellis, C and Price, S (2004), 'UK business investment and the user cost of capital', Manchester School, Vol. 72, pages 72-93.

Garrett, T (2002), 'Aggregated vs. disaggregated data in regression analysis: implications for inference', *Federal Reserve Bank Of St. Louis Working Paper Series, Working Paper 2002-024B.*

Groen, J J J (2002), 'Cointegration and the monetary exchange rate model revisited', *Oxford Bulletin of Economics and Statistics*, Vol. 64, pages 361-80.

Groen, J J J and Kleibergen, F (2003), 'Likelihood-based cointegration analysis in panels of vector error-correction models', *Journal of Business and Economic Statistics*, Vol. 21, Issue 2, pages 295-318.

Hall, R E and Jorgenson, D W (1967), 'Tax policy and investment behavior', *American Economic Review*, Vol. 57, pages 391-414.

Hughes Hallett, A, Peersman, G and Piscitelli, L (2003), 'Investment under monetary uncertainty: a panel data investigation', *Bank of England Working Paper*, forthcoming.

Im, K S, Pesaran, M H and Shin, Y (1997), 'Testing for unit roots in heterogeneous panels', *revised version of University of Cambridge DAE Working Paper*, No. 9526.

Jorgenson, D (1963), 'Capital theory and investment behavior', *American Economic Review*, Vol. 53, pages 247-56.

Kao, C (1999), 'Spurious regression and residual based tests for cointegration in panel data', *Journal of Econometrics*, Vol. 90, pages 1-44.

Larsson, R, Lyhagen, J and Löthgren, M (2001), 'Likelihood-based cointegration tests in heterogeneous panels', *Econometrics Journal*, Vol. 4, pages 109-42.

Levin, A and Lin, C F (1993), 'Unit root tests in panel data: new results', University of California, San Diego, *Discussion Paper No. 93-56.*

Maddala, G S and Wu, S (1999), 'A comparative study of panel data unit root tests and a simplified test', *Oxford Bulletin of Economics and Statistics*, Special Issue.

Marquez, J and Wang, S-Y (2003), 'IT investment and Hicks' composite-good theorem: the U.S. experience', *International Finance Discussion Papers* # 233, Board of Governors of the Federal Reserve System.

Oliner, S, Rudebusch, G and Sichel, D (1995), 'New and old models of business investment: a comparison of forecasting performance', *Journal of Money, Credit and Banking*, Vol. 27, pages 806-26.

Pedroni, P (1995), 'Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis', Indiana University, *Working Paper in Economics*, No. 95-013.

Pedroni, P (1997), 'Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis: new results', Indiana University, *mimeo*.

Pedroni, P (1999), 'Critical values for cointegration tests in heterogeneous panels with multiple regressors', *Oxford Bulletin of Economics and Statistics*, Vol. 61, pages 653-70.

Pesaran, M H, Shin, Y and Smith, R (1999), 'Pooled mean group estimation of dynamic heterogeneous panels', *Journal of the American Statistical Association*, Vol. 94, pages 621-34.

Pesaran, M H and Smith, R (1995), 'Estimating long-run relationships from dynamic heterogeneous panels', *Journal of Econometrics*, Vol. 68, pages 79-113.

Schreyer, P (2000), 'The contribution of information and communication technology to output growth: a study of the G7 economies', *OECD STI Working Paper*, 2000/2.

Taylor, M and Sarno, L (1998), 'The behaviour of real exchange rates during the post-Bretton Woods period', *Journal of International Economics*, Vol. 46, pages 281-312.

Tevlin, S and Whelan, K (2003), 'Explaining the investment boom', *Journal of Money Credit and Banking*, Vol. 35, Issue 1, pages 1-22.

Wyckoff, A W (1995), 'The impact of computer prices on international comparisons of productivity', *Economics of Innovation and New Technology*, pages 277-93.