



Australian Government

Department of Communications,
Information Technology and the Arts

ICT AND AUSTRALIAN PRODUCTIVITY: METHODOLOGIES AND MEASUREMENT

OCCASIONAL ECONOMIC PAPER





Australian Government

**Department of Communications,
Information Technology and the Arts**

ICT and Australian productivity

Methodologies and measurement

Occasional economic paper

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There is very little disagreement that we are entering into a new stage of market-based capitalism, a stage in which the economy is more strongly and directly rooted in the production, distribution and use of knowledge than ever before. Knowledge creation and diffusion are the key driving forces for long-term economic growth and the primary basis for competitiveness.¹

How policy makers approach the new economy is crucial for whether citizens and businesses will be able to participate in, and benefit fully from the new environment. Policy makers should promote the use of the new economy throughout the economy—government, business, communities and schools—and they should promote an environment of innovation and entrepreneurship to ensure that the global technologies of the networked economy work in the local economy.²

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Foreword

This report is one of a series of occasional economic papers in which the Communications, Information Technology and the Arts portfolio examines the role of information and communication technologies (ICT) in productivity improvements in Australia. It follows the publication in 2003 by the then National Office for the Information Economy of firm-level research by Ovum on *Productivity and organisational transformation: optimising investment in ICT* (NOIE 2003), a further report by Ovum on *The Australian mining and ICT industries: productivity and industry growth*, (NOIE/DCITA 2004), and *Achieving value for ict: key management strategies* by Opticon and ANU (DCITA 2005). In addition, in-house macroeconomic studies have been prepared on *Productivity growth in Australian manufacturing* (NOIE 2004), and *Productivity growth in services* (DCITA 2005).

The above work reflects the extensive interest in the economic literature and in policy circles in the drivers of productivity growth and in particular in the role of ICT in raising productivity. Much of this economic literature deals with the deep conceptual and data issues involved in productivity measurement and in international comparisons. Nevertheless, a broad consensus is emerging among international economic organisations and in the productivity literature that ICT has played a significant role in overall productivity growth of industrialised countries in recent times. However, disentangling these from other influences including complementary influences arising from globalisation, greater economic openness, macroeconomic management, and other innovations remains a difficult task. While it is agreed that all these factors are important, and indeed play complementary roles, the relative importance of each on trend productivity at the macroeconomic level remains a matter for debate. Unravelling these influences has clear policy implications.

This occasional paper, comprising a collection of four separate research papers, is put forward as a further contribution to growth research and the ICT-productivity relationship. While not pretending to be the final answer, this research poses an alternative perspective to a difficult, albeit import policy issue, and points strongly to the benefit of continued research in this field.

The issue addressed in this paper is whether some present estimates reflect methodological assumptions that are open to question and do not take adequate account of the disequilibrium transitional characteristics of the ‘information revolution’, perhaps the most notable characteristic being the sustained rapid fall in the real price of computing over four decades. The more complex aspects of the work have been assisted by two leading international research consultancies. Taken together, these occasional papers suggests that there are good grounds for concluding that previous productivity studies using conventional methodologies may have significantly understated the influence of ICT on productivity growth.

Chapter 1 provides a brief introduction to the research. It presents the concept of a general purpose technology (GPT) and briefly outlines evidence suggesting that ICT is a ‘transforming GPT’, the sort of technology that economic historians associate with long transitional cycles of growth. This chapter also summarises key elements and findings of the studies in this volume in order to draw out the key implications from the very different and somewhat technical methodologies used. It seeks to make the technical aspects more accessible to a general audience.

Chapter 2 presents in-house research with a broad internationally-focused look at evidence relating to ICT and productivity.

Chapters 3 and 4 were prepared by the international consultants. Chapter 3 presents the research of Professor Erwin Diewert and Dr Denis Lawrence. Chapter 4 presents that of Dr Kenneth Carlaw, drawing on modelling work done jointly with Professor Richard Lipsey. These reports were presented to an international audience of productivity practitioners at Plenary Session Number 2 (ICT and productivity) of the Asia Pacific Productivity Conference 2004, held in Brisbane 15–17 July 2004.

Chapter 5 is in-house research. It presents a narrowly focused empirical review of some Australian evidence. An early version of this research was tabled at the above conference¹. Since then, it has been revised and refereed. Further work in this area is continuing and is expected to be published over coming months.

The Department of Communications, Information Technology and the Arts wishes to thank its international consultants, Professor Erwin Diewert, Dr Denis Lawrence and Dr Kenneth Carlaw for the quality of their contribution to this issue. DCITA also thanks Professors Dowrick and Diewert, and Dr Lawrence for refereeing the in-house work.²

¹ As a contributed paper.

² DCITA productivity and related research is at <http://www.dcita.gov.au/ie/environment/transformation>

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Abbreviations

ABS	Australian Bureau of Statistics
aka	also known as
ANZSIC	Australia and New Zealand Standard Industrial Classification
BLD	business longitudinal database
BLS	Bureau of Labor Statistics (US Dept of Labor)
CGE	computable general equilibrium model (aka DGE)
DCITA	Dept of Communications, Information Technology and the Arts
DGE	dynamic general equilibrium model (aka CGE)
FRB	Federal Reserve Bank (US)
GDP	gross domestic product
GFCF	gross fixed capital formation
GLS	generalised least squares
GPT	general purpose technology
HP	Hodrick-Prescott
ICT	(modern) information and communications technologies
IMFI	International Monetary Fund
IS	information systems
IST	investment specific technology
ISTC	investment specific technological change
IT	information technologies (synonymous with ICT in the USA)
LP	labour productivity
LPG	labour productivity growth
MFP	multi-factor productivity (aka TFP)
MFPA	multifactor productivity acceleration (second derivative of the MFP index and between-period change in MFPGs)
MFPG	multifactor productivity growth (the between-year change in the MFP index and the basis for the 'MFP classic cycle').
NGM	neoclassical growth model

NIPA	national income and product accounts, also see SNA.
NOIE	National Office for the Information Economy
OECD	Organisation for Economic Co-operation and Development
OLS	ordinary least squares
PC	Productivity Commission
RBA	Reserve Bank of Australia
R&D	research and development
RBC	Real Business Cycle theory to explain macroeconomic change
RNT	residual neutral technology, see RNTG
RNTG	residual neutral technology growth, ie, TFPG less ISTC
SNA	System of National Accounts, including NIPA
SNA93	System of National Accounts 1993
SSG	steady state growth (aka balanced growth)
TFP	total factor productivity, aka MFP
TFPG	total factor productivity growth
VA	value-added

Glossary ¹

Business cycles: Co-movement of macrovariables describing the general state of the economy, such that periods of prosperity are followed by phases of depression and crises.

Capital deepening: The increase in the productivity of labour that can be attributed to increased endowment of capital per worker.

Complementarity, technological: Requires that cooperating technology 'x' be redesigned for advance in technology 'y'. Contrasts with Hicksian (gross) complementarities, which require that demand for technology 'y' rises when the price of technology 'x' falls.²

Complementary factors: Activities are (Edgeworth) complements if doing (more of) any one of them increases the returns to doing (more of) the others.

e-commerce: In August 2000, the OECD put forward a statistical definition to measure the transactional aspect of e-commerce. More specifically, the OECD proposed two definitions that are characterized by the degree of openness of the technological infrastructures being used and the underlying communications protocol.

broad definition: an *electronic transaction* is the sale or purchase of goods or services, whether between businesses, households, individuals, governments, and other public or private organizations, conducted over *computer-mediated* networks. The goods and services are ordered electronically, but the payment and the ultimate delivery of the good or service may be conducted on or off-line.

narrow definition: an Internet transaction is the sale or purchase of goods or services, whether between businesses, households, individuals, governments, and other public or private organizations, conducted over Internet-protocol based networks*. The goods and services are ordered electronically, but the payment and the ultimate delivery of the good or service may be conducted on or off-line.

Expansion: Phase of the business cycle dominated by the acceleration of growth. Although growth averages over a large number of sectors, the core inputs and main carriers of the technological revolution tend to register higher profit rates. This may induce speculation, as proved by the American stock market bubble of 1995-2000.

General purpose technology (GPT): A technology with widespread diffusion all over the economy, having high potential for technological improvements and enabling innovative complements.

Generic ICT: as defined by the UN, and described in the rationale for the development of WSIS, ICT is broad and inclusive of both traditional technologies (e.g. radio, TV,

¹ The definitions are largely drawn from Jones (2003). Note that the definitions of these concepts vary, and the particular definitions provided may reflect a particular usage.

² See Gelauff (2005), Carlaw and Lipsey (2001), Milgrom and Roberts (1990, 1995) and Arora *et al* (2001).

print, video/film) and newer technologies (Internet, virtual reality, distance education applications, mind-computer interface technologies, etc).

Growth accounting: Technique to decompose observed productivity growth (LPG) into its capital deepening and multifactor productivity components (MFPG)

Information revolution: The industrial revolution associated with the diffusion of microelectronics and its combination with new technologies of communication³

Information technology (IT): US references often use this term to refer to what the OECD and the Australian Government calls ICT. It includes Information technology equipment, communications equipment and software. It forms part of the economic concept of 'capital'. The addition of aggregate capital services and aggregate labour services is a measure of GDP. These aggregates are used in 'growth accounting' to measure MFPG.⁴

Modern and traditional ICT: (Information and communications technology—or technologies) is an umbrella term that includes any communication device or application, encompassing: radio, television, cellular phones, computer and network hardware and software, satellite systems and so on, as well as the various services and applications associated with them, such as videoconferencing and distance learning. ICTs are often spoken of in a particular context, such as ICTs in education, health care, or libraries. The term is somewhat more common outside of the United States. (see searchSMB.com) See also e-commerce.⁵

Multifactor factor productivity growth: The part of labour productivity growth not explained by enhanced capital formation.

Productivity paradox of the information economy: Lack of correlation between investments in information technology and reported (as opposed to actual) productivity growth gains.⁶ (p.102)

Recession: Phase of the business cycle dominated by deceleration of growth. The common technical definition presupposes two successive quarters of negative growth.

³ Louçã (2003)

⁴ Bertschek (2003)

⁵ For issues on the definition of the ICT sector, see Bruneau and Lacroix (2001)

⁶ Daveri (2003)

Chapter 1

1 Overview and implications

Information technology is best described not as a traditional capital investment, but as a 'general purpose technology' (Bresnahan and Trajtenberg, 1995). In most cases, the economic contributions of general purpose technologies are substantially larger than would be predicted by simply multiplying the quantity of capital investment devoted to them by a normal rate of return. Instead, such technologies are economically beneficial mostly because they facilitate complementary innovations. (Brynjolfsson and Hitt, 2000, p.24)¹

¹ Quoted by Gera and Gu (2004)

1 Overview and implications

1.1 Background

A broad consensus is emerging among international economic agencies and in the productivity literature that over recent times ICT has played a significant role in increasing the productivity of industrialised countries. This consensus sits alongside a growing concern among productivity researchers with the limitations of the conventional multifactor productivity methodologies used to measure productivity growth. This has sparked a debate in academic and policy circles on how best to model innovation-based growth, and, in particular, how to identify the role and contribution of transforming ‘general purpose technologies’¹ like ICT. In consequence, the development of improved methods of measuring productivity growth and an improved understanding of multi- or total factor productivity (MFP or TFP²), a traditional indicator of macroeconomic performance, has become more urgent.

Aggregate MFP growth (MFPG), which is derived from the system of national accounts, assumes a productivity bonus, being the increase in aggregate output not explained by the increase in aggregate inputs. The estimation method is called ‘growth accounting’ and stems from Solow’s (1957) linking of early macroeconomic productivity index theory with microeconomic production theory.³ Growth accounting gained relevance and credibility through a close association with Solow’s (1956) formal growth model (the neoclassical growth model or NGM of steady state growth (SSG)).⁴ It was Solow who originally sparked debate about the impact of ICT on productivity growth with his famous remark that you can see the computer age everywhere but in the productivity statistics. The MFPG productivity bonus subsequently become widely known as the ‘Solow residual’, and was attributed to the influence of scientific and technological advance.⁵ Nevertheless, many economists saw SSG as an inadequate explanation of growth and took MFPG to be a measure of our ignorance.⁶

¹ Lipsey, Bekar and Carlaw (1998a) define GPTs as technologies that have massive scope for improvement, come to have pervasive range and variety of use in an economy and that have myriad technological complementarities with existing and yet to be invented technologies.

² MFP (multifactor productivity) and TFP (total factor productivity) are used synonymously in the macroeconomic literature. We generally follow that convention in this volume.

³ This study first linked the non-parametric methods of national accounting with econometric methods of microeconomics.

⁴ See Griliches (2000) and Nelson (1994).

⁵ For a historical account of the ‘residual’, see Griliches (1996 or 2000) or Balk (2001).

⁶ The argument is that the re-labelling of an unexplained ‘residual’ as ‘technological progress’ or ‘efficiency gain’ does not address the econometric misspecification or nonparametric mismeasurement that gave rise to the

Explaining MFPG has remained a challenge over the last half -century. Empirical growth accounting studies attempted to whittle away the residual by better measurement, at least until 1973 when measured US MFPG all but vanished. The research focus then changed to explaining the productivity slowdown. The revival of the MFPG in the mid-1990s with the emergence of the New Economy broadened the research focus once more, with new interest attaching to the impact of technological shocks on the short-to-medium term macroeconomic dynamics (Greenwood, Hercowitz and Krusell 1997, 2000; Pakko 2002a; Fisher 2003a,b; Mulraine 2005) ⁷.

Hall (1994, p.309) describes the paradox that the Solow Neoclassical Growth Model posed for economic theory: ‘technological progress was central to understanding advances in long-term growth yet, at that time, technological change remained the *terra incognita* of modern economics’. Hall cites the contribution of growth theorists, such as Paul Romer, to the mapping of the territory, but noted a new *terra incognita* for growth theorists: modelling ‘the sources of the revolutions in technology and economic structure’ ⁸ (Hall, 1994, p.310).

Also in 1994, Nelson set out an agenda for formal growth modelling. Addressing Nelson’s agenda is central to mapping Hall’s new *terra incognita*, and to better understanding the complexities of innovative growth. ⁹ Nelson lists the stylised facts about technological progress, facts that are acknowledged in appreciative but not formal theory. ¹⁰ Nelson holds that formal theory is an important precondition to quantifying the immediate (or proximate) sources of long-run innovative growth, which were identified by Abramovitz as long ago as 1956 as ‘technical advance, the role of the enterprise, and broader cultural and institutional factors surrounding the enterprise’.

By the mid-1990s, the growing impact of what Greenspan called the information revolution had become harder to ignore. This brought new data and new theories, re-energising old debates, and exposing the unresolved issues in measurement and in theoretical explanation.

‘residual’.(Abramovitz, 1956)

⁷ This followed earlier interest through Real Business Cycle (RBC) theorists.

⁸ For Hall, the theory needs to abandon ‘much of the smoothness and equilibrium tendency that is a feature of neoclassical analysis. ... Growth is either cyclic or jerky, driven by bursts of innovation which dramatically punctuate economic history, as in the Schumpeterian vision and take the economic system off along new paths, subject to continuous change in structure’.

⁹ For example, Nelson (1994, p.25) notes the new growth theories treated the dynamics of technological advance mechanically, repressing the cumulative learning process by which a new technology develops towards its potential and finds its range of fruitful uses. ‘This limits the ability of formal theorising to engage with appreciative theorising about, for example, long waves or the long time lags that are often involved before a major new technology affects productivity (David, 1991)’

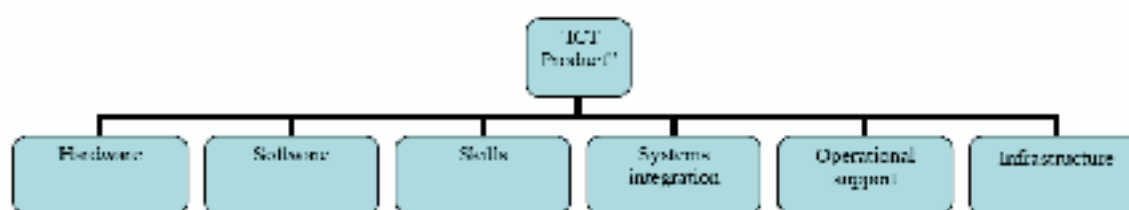
In addition Nelson notes a general mismatch between the appreciative and formal theories of growth in the treatment of uncertainty, with the then new growth theorists (inappropriately) treating uncertainty as ‘correctly understood risk’. He argues that when ex post selection determines the technology that ultimately comes to dominate in a field, then variables like the number and diversity of competitors, and the extent to which some (at least) propose radical departures from the status quo influence technical advance as well as the total R&D investment. ... In turn, such a perspective could lead to an attempt to model ‘institutions’ that tended to support or hinder diversity and creativity.’ Also see Nelson (1995).

¹⁰ Nelson and Winter (1982) were the first make the distinction between appreciative and formal theory.

The new productivity estimates further exposed the weakness in the SSG theories of the NGM. Advances in, and the diffusion of, ICT provided evidence to demonstrate that economic impact of technological advances need not have the horizontal uniformity and vertical predicability that accords with economic theory (Basu, Fernald, Oulson and Srinivasan 2003). Moreover, it dramatically emphasised the importance of the ‘embodiment’ of new knowledge.

The ICT experience is that technological gains are accessed through upgrading, that is replacing older vintage ICT and Information Systems with new ones that embody the latest technological advances (Ahn 2003) and is much broader than the computerisation of most plant and equipment. The complementary skills, management systems, organisational structures and strategies are upgraded to match. Figure 1 illustrates the nature of ICT as a composite good, supporting business operations and business models.

Figure 1: ICT is a composite good



Source: Tuomi (2004)

Embodied technological advance is known as investment specific technology change or ISTC. The increase in computing power per dollar spent is a measure of the ISTC deriving from the R&D and innovation of the global ICT industry. However the underlying phenomenon, termed technological drift¹¹ affects not only computers but extends to most modern equipment, and has been accelerated with the building-in of ‘intelligence’ deriving from the embedded ICTs.¹²

The last 10 years have also seen significant advances in the measurement and theory of growth and productivity. Measures of capital that better reflect economic principles have been adopted by some national statistical offices, including Australia’s ABS. To better capture the extent of ‘quality’ gain in ICTs, the US BLS replaced traditional matched sampling with econometric methods.¹³ In the late 1990s, the ABS implemented the new

¹¹ For a discussion of technological drift and hedonic price index methods used to capture it in the ICT sector, see Pakko 2002b,c and Gordon 1990.

¹² A side-effect is increasing obsolescence, and probably a significant downward bias in the relative contribution of ICT and upward bias in non-ICT capital services to MFPG, as unaccounted-for general obsolescence overstates the use of non-ICT capital services.

¹³ The extensive variation in ICT models and prices enabled the econometric techniques to determine the value

System of National Accounts (SNA93), and introduced new processes that *inter alia* allowed for embodied technological change and replaced capital stock by capital services.¹⁴

This new treatment of technology embodied in capital goods significantly affected the productivity accounting, dramatically reducing MFPG, increasing capital deepening, but leaving unchanged labour productivity growth (LPG)—the traditional indicator of progress in living standards. Which of these (MFPG, LPG) is the better key performance indicator for productivity is debatable. These ABS changes have implications for this debate and raise concerns about the empirical research employing the old MFP estimates.

Growth theorists also sought to address the challenges that new technology posed for explaining the growth processes, and especially the roles of embodied and disembodied ICT. Some have incorporated the insights of economic historians into their models, drawing parallels between the modern information revolution and past eras of revolutionary growth, using the concept of a GPT. Others, in the real business cycle (RBC) tradition, have examined macroeconomic disturbances associated with technology shocks. The new dynamic general equilibrium (DGE) models abandon the smoothness and equilibrium tendency of neoclassical steady-state equilibrium to model technological shocks which mark the often-long transitional phases of the historic growth.

By year-end 2003, the transforming impact of ICT was generally accepted. Firm-level studies in a number of countries had firmly established the complementarity between investment in ICT and organisation change—the productivity performance of firms that invested in both was higher than those that invested in only one.¹⁵ At the macro level, the complementarity between technology and macro-level organisational/management innovation (including institutional and economic reform) was increasingly recognised, perhaps most significantly in the policy directions recommended by the OECD following their growth project in 2001. The ‘stick to fundamentals’ prescription of mainstream economics was joined with a policy emphasis on innovation, enterprise, skills, and on *realising the potential of ICT*.

Shortly after, the most prominent and long-standing of the New Economy critics, Professor Robert Gordon, accepted in August 2003 that the persistence of the US productivity growth could be taken as confirming the revolutionary nature of ICT (see Gordon 2003a) and modified conventional growth accounting to take account of the GPT characteristics of ICT (Gordon 2003b). This can be seen as marking the end of the US controversy as to the key role

share of the characteristics, eg memory size and type, that for example make up a computer. This enables faster, and more robust capture of the cross-period performance gains in computing power than would be available through the alternative approach of comparing matched samples. The approach is termed hedonic pricing. Australia used the US hedonic prices estimates modified for exchange rate effects.

¹⁴ As recommended by the Canberra Group on Capital Measurement, an international body of experts responsible for improvements in the measurement of capital.

¹⁵ The International Monetary Fund (IMF, 2001) sees the advances in ICT as underlying the ‘Information Revolution’, a label that makes explicit its similarities to such earlier periods of technological advance as printing, the industrial revolution and electrification.

of ICT in productivity growth. Nevertheless, disagreements over the details of productivity measurement have persisted.

The four studies of this volume address the complex issues that ICT raises for productivity measurement and interpretation including the complementary nature of the composite ICT product (figure 1 above) and the transformative impacts associated with evolution and diffusion of broadly defined ICT. The rapid rate of technological change, as evidenced in the persistent and rapid price falls in the cost of computing power, is a source of ongoing uncertainty, necessitating learning and potentially generating externalities in the long run. The studies address these issues from different but complementary perspectives, and with an Australian focus. Two studies were prepared by consultants, and two were prepared in-house.

The first of the two consultancy studies was undertaken for DCITA by Prof Erwin Diewert and Dr Denis Lawrence. Professor Diewert is a Canadian-based world authority in capital and productivity measurement, while Dr Lawrence is a long-established Australian-based productivity practitioner. Their paper is very much focused on measurement, improving the macroeconomic statistics that are so critical for macroeconomic analysis. Their work is very much in the spirit of the early measurement-focused economists who initiated the development of the modern system of National Accounts.¹⁶ It explores how the ICT-productivity estimates might change when assumptions of conventional growth accounting are relaxed to take account of disequilibrium characteristics of ICT.

The second consultancy study was undertaken by Dr Kenneth Carlaw, a member of the research team now associated with the GPT concept (see David and Wright, 1999). The concept of a GPT has its roots in historical and evolutionary economics dating back to Schumpeter (1934). The modern concept owes much to economic historian Paul David (1991), although the term, GPT, was first coined by empirical researchers (Bresnahan and Trajtenberg, 1995). A whole body of research now uses GPT theory in a wide-ranging variety of economic applications (see Helpman, 1998). Today, Lipsey Carlaw and Bekar are prominent in unifying and developing GPT theory.

Dr Carlaw's focus on the development of explanatory theory contrasts with the measurement focus of the first study. Carlaw addresses Nelson's (1994) call for a closer integration of appreciative and formal growth theory. The study presents a formal modelling of technological change that incorporates critical features of innovative growth. Using simulation techniques, it examines the likelihood of a positive relationship between technical change and a 'true' measure of the MFPG 'productivity bonus'. It checks whether the Australian ICT experience is consistent with a GPT-based theory of growth.

¹⁶ These economic pioneers include Moris Copeland (1937) and Jan Tinbergen (1942). For the historical record on the residual, the reader is referred to Abramovitz (1956), Griliches (1996, 2000) and Balk (2001).

The DCITA research is in two parts: the first is a broadly focused examination of the international evidence on ICT and productivity; the second reviews the detailed measures and methodologies that underlie current Australian findings.

As a whole, the studies in this volume, taken together with earlier DCITA work support claims that ICT has played a major role in Australia's strong productivity performance. Many of Australia's competitor economies have also pointed to ICT having played a major role in their growth (US, UK¹⁷, Canada, Finland, Sweden, Ireland, EU, Singapore).

Cross-country comparison of multi-factor productivity performance with aggregate national accounts data, by sector and in aggregate, have proved problematic.¹⁸ In consequence to better explain the impacts of ICT, the OECD in 2000 invited member states to contribute firm-level studies to an OECD workshop on ICT and Business Performance in December 2002. Australia contributed a study by Gretton, Gali and Parham that established complementarity at firm level between ICT take-up and other innovations using data from the ABS 'Growth and Performance Survey', a longitudinal survey of small business between 1994-95 and 1997-78. This was one of the first non-US studies to establish a link between ICT investment and aggregate productivity. As detailed in chapter 5 the study estimated that ICT contributed about 0.2 percentage points of MFP acceleration on average over the survey period.

However, Gretton et al did not establish the relative contribution of ICT to Australia's MFP acceleration over this period. To do so requires an estimate of the total MFP acceleration for the period. Consequently, the analysis in chapter 5 is chiefly focused on the performance of the aggregate MFP time series for Australia, particularly around this period. The possibility examined is that part of the difference between the average MFP growths for the two cycles reflected non-permanent cyclical influences rather than a change in the underlying trend MFP. This possibility parallels concerns of Professor Robert Gordon, who asked whether the US productivity lift in the late 1990s had a significant cyclical component.

The issues raised by the DCITA empirical review complement and extend the broad conceptual and measurement issues raised in the other studies.

¹⁷Bakhshi and Larsen (2000), Bank of England economists, report that 'Our results suggest that despite ICT being only a relatively small component of the overall capital stock, ICT investment-specific technological progress contributes very significantly to labour productivity growth along the balanced growth path of our model of the UK economy, accounting for around 20%-30% of labour productivity growth.'

¹⁸ OECD (2004) shows that 'ICT is having substantial impacts on economic performance and the success of individual firms, in particular when it is combined with investment in skills, organisational change and innovation. These impacts can be observed in firm-level studies for all OECD countries, but have not yet translated in better economic performance at the industry or economy-wide level in many OECD countries.' This gap between firm-level and aggregate performance might be explained by aggregation effects, time lags or measurement.

1.2 THE STUDIES AND THEIR FINDINGS

1.2.1 In-house research: surveying the global ICT scene

Chapter 2 ‘ICT’s productivity credentials’, the first of the in-house contributions, takes a broad perspective, reflecting the global nature of ICT and the extensive across-country literature. It examines the evidence that led to ICT being accepted, after twenty-two years of slowdown, as the source of the US productivity revival in 1995.

1.2.2 Erwin Diewert and Denis Lawrence

The Diewert and Lawrence study (chapter 3) modifies the traditional tools of conventional productivity analysis so as to take account of the unique characteristic of ICT, including the sustained and rapid falls in the real price of computing. It directly addresses the concern that the equilibrium assumptions that underlie conventional growth accounting are ill-suited to measure the ‘information revolution’ characteristics of ICT. Using a recent advance in leading-edge productivity methodology, it tests the appropriateness of two traditional productivity assumptions (constant returns to scale technology, and ‘perfectly competitive market’ pricing). The approach directly addresses whether the conventional methodologies, applied to Australia’s National Accounts data, understates significantly the contribution of Australia’s early uptake of ICT to our 1990s productivity growth.

These issues had become amenable to investigation following a recent innovation in productivity measurement by Diewert and Fox (2005). Only one study (Connelly and Fox, 2004) had previously used that technique with Australian data and it assumed constant returns to scale technology and the most simple form of production function (Cobb-Douglas technology). Since that study found an uneven distribution of benefits across sectors from investment in high-technology capital, and little evidence of excess returns to high-technology capital, it may have been expected that the Diewert and Lawrence study would confirm the adequacy of conventional methods for determining the ICT-productivity relationship. However, this proved not to be the case.

The new technique used by Diewert and Lawrence made greater demands on the quantity, quality and internal consistency of National Accounts data than the simpler conventional approaches. These greater demands could not be fully satisfied at the sectoral level. The approach also exposed issues to do with the internal rates of return used to estimate rental prices for capital inputs, and demonstrated that productivity measures were sensitive to alternative ways of addressing these problems. The data limitations were such that the methodology could only be applied to four of the twelve sectors whose aggregate performance is used to proxy the performance of the economy. Diewert and Lawrence state:

Another important conclusion from the study is that the analysis of sectoral productivity presented in section 3 highlights some major shortcomings in the available data. Many of the sectoral productivity results are not credible. This applies particularly to the services sectors where the use of ICT inputs allows 'quality' gains in outputs to be achieved and the range of available outputs to be greatly increased, neither of which is fully captured in the price indexes available for the services. This effect is exacerbated because the price index for ICT inputs does reflect technological drift while the price indexes for services outputs do not, leading to measured MFP growth being diminished. The database indicates that MFP in 7 out of the 12 market sectors was lower in 2003 than it was in 1980 when using a reasonable ex-ante rate of return to calculate user costs—a result that is simply not credible in light of the technological change and microeconomic reform that has occurred over the last two decades.

Issues with productivity data sets are not unique to Australia. Indeed, the ABS is at the forefront of international efforts to improve these statistics. Nevertheless, Diewert and Lawrence recommend greater attention to the hard-to-measure sectors:

While statistical agencies are making advances in measuring the outputs of so-called 'hard to measure' sectors, work in this important area is in its relative infancy and efforts need to be redoubled.

For the four sectors amenable to the analysis, the study found evidence of decreasing returns in some industries¹⁹ and increasing returns in others. Consequently, the constant returns to scale assumption that generates the MFP estimates under conventional methodology used in previous estimates could cause significant errors.

Diewert and Lawrence also examined whether standard user cost formulae reflect the value of ICT to producers. The evidence here is unambiguous and conclusive demonstrating that there are above normal rates of return to ICT capital:

. . . across all industries examined . . . ICT contributes more to output than its cost to producers. This result comes through uniformly despite manifold data limitations in some sectors. This means that the standard growth accounting productivity measures will not adequately capture the 'Information Revolution' characteristics of ICT.

In summary, Diewert and Lawrence have established that the contribution of ICT to the competitive transformation of the economy cannot be identified from the conventional productivity measures. This is a significant finding, with important policy implications. In the words of Diewert and Lawrence,

the fact that ICT consistently contributes more to output than its user cost means that the contribution of ICT to economic growth will be undervalued in the traditional growth accounting methodology. Consequently, failure to find an important role for ICT in explaining economic growth

¹⁹ For manufacturing, this finding is consistent with smaller, more flexible technology-driven facilities.

in these studies does not mean that the rapid uptake of ICT is not a major driver of economic growth. Indeed, the results of this study indicate that greater attention to the uptake of ICT may have an important role in improving economic growth.

1.2.3 Kenneth Carlaw

Under the DCITA consultancy, Dr Carlaw was required to develop a GPT-based model able to explain growth patterns in Australia and competitor economies. Using simulation and econometric techniques, the study considers the likelihood that observed productivity patterns are consistent with those expected of diffusion and evolution of a transforming GPT. This work, reported in chapter 4, explores whether the relationships between ICT investment and conventionally-estimated productivity growth are consistent with GPT theory and whether Australia's experience was consistent with that of other countries.

Like Diewert and Lawrence, Carlaw is seeking to advance the understanding of the role of technology in productivity and economic growth, but from a broader, more theoretic perspective. The Carlaw study builds on wide-ranging empirical and theoretical research undertaken over the past decade by the team of Richard Lipsey, Kenneth Carlaw and Cliff Bekar. Their findings have been drawn together in a monograph *Economic transformations: general purpose technologies and long term economic growth* published in October 2005.

This research focuses on identifying and classifying the major general purpose technologies that have in the past underlain the innovations that have advanced human capability, efficiency and wellbeing. The task-level productivity gains and other characteristics seen in today's information economy have broad similarities to those of previous historic periods of dramatic innovation and change, like the Industrial Revolution. About 20 such technologies have been identified, spread across fields of communication, power, transport, materials, and organisation.²⁰

A sound theoretical framework is required to adequately account for the impact of ICT on productivity growth and underpin aggregate productivity measurement and its interpretation.²¹ The first challenge confronting a formal theory of such change is the development of measures and statistics that can adequately describe the passage and impact of a GPT. Carlaw notes concern expressed by Lipsey Carlaw and Bekar that the meaning of MFPG is used to measure both technological change and the productivity bonus generated by that technological change. But separate measures of technological change and its benefits are needed in a formal theory of technological change. In approaching this issue, Lipsey Carlaw

²⁰ There is wide variation in the properties of GPTs. Some integrate quickly and seamlessly into the economic and social fabric, while others, such as the spread of digital ICTs and intelligent system, have a transformative impact on business, government and society. Today's digital ICTs have similar characteristics to such past transforming GPTs as: network-based technologies, eg factory electrification; communication technologies eg writing and printing; and organisational technologies, eg the invention of the corporation.

²¹ Prescott (1997) calls for a Theory of TFP to account for factors, such as institutional differences.

and Bekar agree that MFPG is ideally a measure of the unexplained residual usually associated with technological change, but argue it is not a measure of technological change: endogenous technological change is brought about by the allocation of resources that have opportunity costs to the activity that generates the new technology. They put forward theoretical and empirical argument to show that available independent measures of technological change are generally negatively correlated with TFPG. In essence they are seeking a theory that can relate the properties of GPT-based change to (correctly measured) productivity bonuses associated with that change.

A priori, Lipsey Carlaw and Bekar expect that the potential productivity bonus from a GPT would not be proportional to the measure of the advance in technological knowledge. They expect correctly measured MFPG to be either uncorrelated or in some cases even negatively related to the contemporaneous measure of the technological change. Carlaw reports the Lipsey Carlaw and Bekar arguments:

... that in order for technological know-how to become productively useful, all technological knowledge must become embodied in some real physical component of the work, whether it is physical or human capital (including all tacit skills), laws and legal institutions, or social and cultural norms. Furthermore, each of these embodiments requires costly investment. So the separation of the contribution of technological change from the contribution measured factors such as physical and human capital to economic growth is difficult. The key to connecting technological change to economic growth lies in identifying specific embodiments of new technology and determining their contribution to economic growth over a long horizon.

Additionally they argue that the introduction of new GPTs can cause large structural adjustment costs and that this is consistent with the initial decline in productivity observed with large-scale technological change:

This pattern is not necessarily inherent in the new GPTs themselves, but it is a possible outcome of the interaction between new GPTs and the existing economic structure into which they are introduced. If there is sufficient friction between the new technologies and the existing economic structure, including necessary redesigns of physical capital, re-skilling of human capital and changes in the organisational technology of firms then a real productivity slowdown can follow the introduction of a transforming GPT for a time. But the introduction of the GPT ultimately rejuvenates growth and there is a long term productivity benefit.

Carlaw undertakes a preliminary test of these expectations using existing MFPG and ISTC estimates available for a number of OECD countries. MFPG imperfectly measures the productivity bonus, while ISTC measures embodied technical advance. The concept of ISTC is widely used in dynamic general equilibrium (DGE) models of technological change (Greenwood et al 1997, 2000; Pakko 2002a, 2002b and 2002c; and Fisher 2004; Violante and Cummins 2002). Carlaw and Kosempel, 2004, had demonstrated that ISTC made important contributions to Canadian output growth during the 1961-96 period, but was negatively

correlated with TFP particularly since 1974. They interpret the ISTC measure to potentially indicate a structural adjustment cost associated with the adoption of the new technology implicit in the high quality capital investments associated with a transforming GPT.

Carlaw applies the process to the OECD data, subtracting ISTC from MFPG to obtain a measure of the productivity bonus net of the adjustment (or quality) cost associated with ISTC. The result is that residual neutral technological change (RNTC) is considered to be a better measure of the productivity bonus than the OECD MFPG measures.²² He reports (in table 2.1 of the study) a negative relationship in most cases, a significant negative relationship in two cases and a significant positive relationship in two other cases. This is taken as ‘weak evidence that there is no general relationship between our independent measure of technological change and TFP growth. There is possibly a negative relationship over the period examined for some economies.’

In the remaining sections of the study, Carlaw builds formal three- and four-sector GPT models to capture the key stylised facts known from the growth literature. The modelling meets some of the challenges that Nelson 1994 identifies for growth theory. In these models, technological change is directly measured, and is independent of economic performance. The TFP calculations generated by the simulations of the theoretical model *inter alia* enables common assumptions of traditional and New Growth theories, such as returns to scale and returns to knowledge in production, to be tested. The key characteristics of the model are summarised:

GPTs arrive at randomly determined times with an impact on the productivity of applied R&D that is determined by the amount of pure research knowledge that has been endogenously generated since the last GPT and elements of randomness. The three sources of randomness outlined above imply that in the short term outcomes are influenced by the particular realizations of the random variables, allowing the average growth rate of output over the lifetime of each successive GPT to differ from that of its predecessor. However, the average growth rate over long periods of time in which several GPTs succeed each other is determined by the accumulated amount of pure knowledge. This is partly endogenous (determined by the allocation of resources to pure research), and partly exogenous (determined by random factors affecting the productivity and timing of those resources). Furthermore, while some GPT driven research programs are richer than others, there is no reason to expect that successive GPTs will always either accelerate or decelerate growth on average over their lifetimes. There is no expectation that each new GPT will produce a productivity bonus in the form of an acceleration to the rate of productivity growth. The model is solved using numerical simulation which requires calibrating parameter values. We choose values in order to achieve long run average growth rates of approximately 2% and GPT arrival rates of on average 30-35 periods. The qualitative results are robust to a wide range of parameter values that meet the restriction specified in the model.

²² The OECD TFP measures are not directly comparable with the market-sector MFPG estimates of the ABS due to various methodological differences.

The properties of the model's solution are:

The model generates a non-stationary equilibrium, such that neither the levels nor the rates of change of the endogenous variables converge to constants. There is a transitional competitive equilibrium in every time period, given the expected marginal productivities of inputs in each sector. But because of technological advance, the nature of the spillovers, and the absence of perfect foresight, the marginal products change from one period to the next in ways that are not anticipated. Although growth never stops, a very productive new GPT can accelerate the average growth rate over its lifetime while a less productive new GPT can slow it. This last characteristic allows us to focus on the historical, path dependent and variable pattern of growth.

The key findings of the simulation modelling are that firstly, the entry of transforming GPTs to the economy cannot be identified by an increase in the correctly measured MFPG bonus, and secondly, that when the introduction of new transforming GPTs requires structural adjustment, TFP growth slows while the technology diffusion rate increases and then increases while the diffusion rate declines.

Australian TFP growth and ICT diffusion rates are calculated and compared to check the robustness of the modelling framework. This empirical exercise yields limited evidence consistent with a 'time to sow, time to reap' prediction of the model. The slow TFP growth when a transforming GPT enters the economy is attributed to the theoretical prediction that there will be resource costs in adopting the new technology and adapting the pre-existing economic structure to it and that these are capitalized in the TFP calculation. As the technology matures, its diffusion slows, and TFP growth increases.

1.2.4 In-house research: extending the Australian research

The second strand of the in-house research (chapter 5) is narrowly focused on the detail of the methodology used in Australia for determining long-run productivity trends. It examines whether findings based on that methodology, for example relied upon in the Review of National Competition Policy Reforms,²³ reflect particular approaches to measurement or interpretation and distinguish adequately between long-run trends and business cycle effects. In particular it asks whether the unusually high acceleration in Australia's MFP index between the early and late 1990s might inappropriately reflect the business cycle effects rather than a change in the long-run relationship and not just a change in the underlying productivity trend. This issue has broader implications for the interpretation to be placed on the ABS cyclical productivity averages.

Distinguishing business cycle from macroeconomic trend in Australia's productivity statistics is complicated by the strong annual volatility in the aggregate MFPG estimates. When graphed, the data exhibit a strong 'sawtooth' pattern with frequent sequences of a local peak

²³ See Productivity Commission Inquiry Report No. 33 of February, 2005.

immediately followed by a local trough and with local troughs immediately followed by local peaks. The extreme values taken by some peaks and troughs greatly strengthen the ‘sawtooth’ pattern of the graphed data, though the extent of such volatility has varied over the periods of interest. Together this makes the determination of a MFPG cycle sensitive to the choice of the averaging methodology, and the cyclic averages dependent on the MFPG pattern.

Nonetheless, the high relative standard error (RSE) of annual MFPG estimates produced by the ABS strongly suggested some standard method for better tracking short-to-medium term changes in the official productivity estimates was needed. The task of developing this standard approach was undertaken in 1989 and 1990 by Charles Aspden, the then head of the ABS National Accounting Section. The method developed by Aspden is now the official ABS approach. The method uses a ‘MFP growth cycle’ to determine a cycle, and makes no use of alternatives such as the ‘MFP classic cycle’. It uses a ‘peak-to-peak’ period of the cycle, rather than other alternatives such as trough-to-trough. Nevertheless, the method allows volatile annual MFPGs to be replaced by their cyclic average, which robustly estimates short-to-medium term change in productivity.

The approach could be described as an ‘an average of MFPGs over a peak-to-peak period of an MFP growth cycle’. Although accurate, this is a rather wordy and cumbersome descriptor for the present official methodology—this study refers to the approach as the ‘Aspden’ approach after its founder.²⁴ Likewise, it is convenient to refer to the resulting estimate of average MFPG as the ‘Aspden’ average, to refer to the MFP-growth-cycle peaks as ‘Aspden’ peaks, and so on.

While the Aspden method has served Australia well, it is only one of several alternative procedures that can be used to distinguish a change in trend productivity in the presence of business cycle effects. Moreover, the Aspden method does not directly capture the productivity impact in capacity utilisation over the business cycle or more generally explain the observed procyclical relationship between output and MFP growth.²⁵

Productivity researchers have felt no need to question an implicit assumption that the Aspden estimates strip out all cyclical effects, and hence measure trend productivity. In effect, previous work assumes the comparison of average MFPG between adjacent cycles would capture the impact of change in average capacity utilisation over the business cycle. This study argues that *averaging* of annual MFPG over any cycle, even the business cycle itself, is not the same as adjusting productivity for variation in capacity utilisation. It questions the

²⁴ Charles Aspden does not object to this naming. In detail, the Aspden method involves determining the difference between the actual and smoothed value of the MFP index as a time series. The years in which this time series suggests a major peak determines ‘MFP growth cycles’. Average MFPG is calculated as the average change in the MFP index between the years where the MFP-growth cycle peaks.

²⁵ see Inklaar (2005)

strong properties attributed to the Aspden averages, and it demonstrates that the Aspden averages are inversely related to the depth of recession between the Aspden peaks.

In brief, chapter 5 finds that the low average MFPG over the 1988–89 to 1993–94 cycle reflects the presence of the strong recession of the early 1990s, while the high average MFPG over the 1993–94 to 1998–99 cycle is largely due to the absence of a recession. The 1.1 percentage point difference between these Aspden averages is thus mostly explained by business cycle variation, and is not a reliable indicator of acceleration in trend productivity growth. Indeed, as described below, the Quiggin (2001) estimate, which took specific account of business cycle effects, gave a much lower estimate that is comparable in magnitude, but not timing, to our preferred Error Correction Model (ECM) estimate.

Productivity researchers had previously rejected a cyclical explanation, claiming that econometric research based on the ECM method supported a acceleration of about 1 percent in MFP in the mid 1990s (Parham, 2004b Appendix). We have tested this view using alternative trend methodologies including X11 smoothing. In theory, the ECM can strip out cyclical from trend, so this is a worthwhile test. An ECM study by Dowrick (2001) found that the change in trend MFPG was 1.4. This high estimate contrasted with a much lower estimate of 0.8 by Quiggin (2001) using non-parametric methods. Quiggin explicitly attempted to take account of the macroeconomic impact of the business cycle. Since then, the ABS data has been revised and updated. Using ECM with the new data, the Productivity Commission (PC, 2003) reported an acceleration in trend MFPG of 0.76%, much lower than the earlier Dowrick estimate.

Chapter 5, in addition to surveying past studies, reports on an alternative estimation procedure that might better take account of the volatility in the data. It estimates an MFPA of 0.7, close to the 0.76 of the PC (2003) and the 0.8 of Quiggin, and considerably less than the 1.1 of the Aspden averages, and the 1.0 used by Parham (2004b).

Chapter 5 shows that the ECM estimates are consistent with Australia experiencing strong *growth* in trend MFP over the 1990s, but not a strong mid-1990s *acceleration* needed for a productivity ‘revival’. Explicitly factoring in the much earlier revival suggested by all the ECM studies indicates the ECM and Aspden estimates of MFPA are not substitute measures of an MFP acceleration. Instead, the finding of chapter 5 is that the Aspden estimates of a mid-1990s MFPA captures a moderation in the 1990s business cycle, while the ECM estimates suggest a high but steady productivity growth over the 1990s with the acceleration preceding the 1990s.

The chapter concludes that these different measures of productivity give a consistent picture of Australia’s productivity growth over the 1990s. It is one of strong steady growth in trend MFP, but with a strong business cycle trough depressing MFPG in the early 1990s Aspden cycle and strong business cycle plateau lifting the MFPG of the following Aspden cycle.

The in-house research leaves the estimation of the relationship between ICT take-up and productivity growth in Australia for subsequent research. Nevertheless, the finding that cyclical factors can explain some of the acceleration between the 1990 Aspden cycles could cause upward revisions of earlier judgements as to the role of ICT in Australia's productivity performance. The evidence in chapter 5 suggests that the 0.2 percentage point contribution from ICT accounted for the bulk of any aggregate MFP acceleration at the time.

1.3 Implications

Despite very different approaches, the studies in this volume share common themes and support particular directions for future productivity research in this, the information age.

First, the studies in very different ways point to likely shortcomings in previous Australian productivity research in appropriately addressing information economy issues. The broad international perspective of the in-house research exposes key issues for research, and indicates the broad range of methodologies that are being applied to investigate the sources of economic growth. The Diewert and Lawrence study (chapter 3) exposes the extent of measurement issues that arise in assessing the impact of ICT. The Carlaw study (chapter 4) raises fundamental issues as to how to interpret conventional MFPG estimates in a period of innovative growth driven by a transforming GPT. The empirical review of the Australian evidence (chapter 5) emphasises the need to fully understand and explore the data being used, and the care needed in separating cyclical and trend productivity change. In all cases, the effect has been to suggest that conventional measures have most likely underestimated the role of ICT in Australia's strong productivity and economic growth.²⁶

Taken together, the studies suggest ICT is central to Australia's productivity performance. Jointness, complementarity, heterogeneity, technology and dynamics are key aspects of innovative growth and have often been excluded from previous analyses as being too difficult to model. Inclusion of these characteristics in economic analysis brings subtle differences to economic policy prescriptions. In particular, it suggests that a sole policy reliance on markets to achieve growth objectives might not be entirely appropriate. Rather today's economic reform calls for a more complex balance of responses and initiatives, with policy being sensitive and responsive to changing context. In this age of transition, responsibility for the transformations needed to realise the potential of ICT extends across all responsible government agencies. There is a common need to promote the new institutions and practices of an information society. This requires support of change in society, encouraging enterprise,

²⁶ Various analyses have shown strong productivity growth to be most responsible for Australia's economic growth. Nevertheless, strong productivity (or efficiency) growth in market sectors need not necessarily be associated with economic growth if internationally competitive market sectors cannot fully employ all available resources in a transitional (or unbalanced growth) phase. While the direct impact of microeconomic reform is limited to increasing market efficiency, appropriate Information Economy policies might enable the fuller use of resources in the transitional phase.

institutional flexibility and resource mobility as appropriate in these times of unusually rapid and uncertain global change.

None of the above suggests that productivity analysis and productivity estimates are unimportant. Just the opposite. The research acknowledges the long and continuing importance of productivity measurement, and on improving its measurement.²⁷

There are other themes common to the studies. Perhaps most importantly is an acceptance of the evidence in support of long-run periods of technologically-driven transitional disequilibrium growth. While the equilibrium assumption normally enables and enlightens economic analysis, it can hinder the investigation of the sources of long-run growth, especially in living standards. Carlaw's research sounds a caution against the unqualified use of MFPG as a productivity bonus or key performance indicator.

The studies reported in this volume each examines a different aspect of the relationship between ICT and productivity growth. The Diewert and Lawrence study emphasises measurement and methodological issues while the Carlaw study examines the role of ICT in generating growth in the longer term. More generally there is a hierarchy of issues that need to be addressed in fully understanding the role of ICT and productivity growth. At the most basic level, there is an overriding imperative for better quality data as emphasised by Diewert and Lawrence. At the next level there are a range of methodological and measurement issues that need to be addressed. These are highlighted by the Diewert and Lawrence and the in-house studies and include the assumptions used in conventional productivity indexes and the way longer-trend growth rates are calculated. Finally there are a number of 'big picture' conceptual issues that look at the role of new general purpose technologies in facilitating long-run growth. The Carlaw study focuses on these higher level issues.

Resolving this hierarchy of issues is a challenge for future research, but in the interim, the productivity research reported here attempts to make advances on both the theoretical and empirical fronts.

A notable aspect of technological change is that it has been labour augmenting. That is, the productivity of workers undertaking clerical, organisational, accounting, and scientific tasks has been enormously augmented through the use of modern ICT. In fact, Tuomi (2004) suggests that estimates of task productivity gains are much greater than those in current macroeconomic productivity indexes.

²⁷ This approach differs from what sometimes appears as an overly defensive denial of 'measurement error' by some mainstream analysts. The additional resources needed to address productivity measurement issues are more likely to flow if the issues are known and accepted. It should be noted that in macroeconomics, 'measurement error' covers a wide range of processes extending well beyond any errors that arise in data collection. Measurement error can arise in, *inter alia*, the measurement of quality change, the choice of index aggregation, the definitions of assets consistent with accounting standards, quality of human capital, estimation of depreciation and capital services, inter-industry flows, etc.

Some dissatisfaction with these current macroeconomic indexes can be seen in the approaches of both Diewert and Lawrence and Carlaw, although their approaches differ. Diewert and Lawrence seek to maintain the basic traditional productivity measures, but to improve measurement by resolving ICT-related issues associated with factors such as depreciation and R&D. On the other hand, Carlaw seeks alternative aggregation of the micro-data underlying the National Accounts, using an approach that takes into account technological complementarities.²⁸

Aggregation based on technologies rather than industries would mark a major change to present practice. How this could be implemented is unclear. Non-parametric methods, for example a form of technological satellite accounts to the SNA, might expose technology issues. Alternatively new techniques with the ABS micro-data, or new forms of productivity practice may be possible.²⁹ Importantly, whatever the approach, it needs the support of more and better data. Some advances have already been made, for example, it is noted that conventional growth accounting findings can be, and already have been analysed/modified for GPT timing and mismeasurement effects (Brynjolfsson and Hitt 2003; Gordon 2003b).

A fundamental difference between the traditional approach (the Diewert and Lawrence study) and the theoretical GPT modelling (the Carlaw study) is the treatment of micro-level technological complementarities. The formation of new technological complementarities is a hallmark of innovative growth, occurring through partitioning and modularising (Milgrom and Roberts 1995), and has its roots in Adam Smith's 1776 'pin factory' example of specialisation as a source of growth and efficiency. Although micro-level technological change occurs side by side with market-based price-driven substitution, aggregate modelling based on price substitutes may be using the wrong methods to determine growth sources.³⁰ As Griliches (2000, p.87) notes the diffusion of best available techniques has received too little attention in the productivity literature.

Particularly in the converging ICT industry, there is evidence that technological complementarity is what drives innovation (Tuomi 2002; Boklin 2004; Fransman 2002; Antonelli 1993, 1999). ICT is the technology that most opens up innovation possibilities

²⁸ Both studies, in different ways, point to the care needed in comparing the capital deepening and MFP elements of the growth accounting decomposition. The new decomposition has hard knowledge, that embodied in new vintage capital as capital deepening, while soft knowledge, that deriving from individual or social learning and embodied in social/professional practice, is included with externalities in the MFPG residual. Embodiment has been and remains contentious in interpreting MFPG (see Hercovitz 1998; Greenwood *et al* 1997,2000; Ho and Stiroh 2001; Bucekkine *et al* 2000, 2002)

²⁹ We note for example that the direction distance functions of Fare and Grosskopf (2004) might ultimately revolutionise aggregation in productivity practice, albeit from small beginnings.

³⁰ Often such assumptions used in mainstream analysis are not tested. A common competitive market assumption is that the price paid for production inputs, such as ICT, must equal the benefit the buyer receives from them. This assumption, not empirically tested, underlays the macroeconomic estimates of the contribution of ICT to the Australia's MFPA in the late 1990s. Yet when tested, in the first study, this assumption was shown to be inappropriate for ICT.

across the economy through micro-level technological complementarities. Unfortunately due to its complexity, the growth process does not generate predictable industry patterns.³¹

Lastly, analysis by Dudley (1999) suggests that the rapid explosion in innovation that marked the industrial revolution was underlain by technological advances that supported the mass transmission of ideas.³² This suggests the importance of internet-networking technology for the high innovative growth of the late 1990s and beyond.³³

³¹ Balk (2001, p.36) survey quotes the comprehensive microstudy by Bartlesman and Doms (2000) as concluding that 'At the micro level, productivity remains very much a measure of our ignorance'.

³² Dudley argues that 'over the millennium prior to 1975, Western Europe's economic institutions underwent fundamental restructuring three times. In each case, innovations in a particular dimension of information processing appear to have accelerated both the generation of ideas and the diffusion of existing ones' (p. 609). For example he demonstrates that 'despite the numerous inventions of the last half of the eighteenth century, it was only with the spread of the new information transmission techniques in the first half of the following century, that the use of mechanised production technology became generalized.' (p.608). The new 'information transmission' technologies were printing and telegraph. He distinguishes three phases in the historic development of information technologies, storage, decoding, and transmission. He develops a simulation model in which the three types of information processing are combined (as per the recombinant growth process of Weitzman 1995 and Olsson 2002) with labour to yield network structures close to those observed in Europe over the past millennium. This is similar to the argument of Tuomi (2002).

³³ Mokyr 2002 also suggests advances in knowledge underlie technological advances.

References (foreword to chapter 1)

- Abramovitz, Moses (1956) 'Resource and Output Trends in the U.S. since 1870,' *American Economic Review*, 46, 5–23.
- Ahn, Sanghoon (2003) 'Technology Upgrading with Learning Cost', *Center for Economic Institutions Working Paper Series*, No. 2003–21. See also 'Technology Upgrading with Learning Cost: A Solution for Two Productivity Puzzles' (1999) OECD Economics Department Working Paper No. 220 at <http://ssrn.com/abstract=193173>. Also conference papers to 'Productivity Growth and the Macroeconomy' NBER 2001 Summer Institute workshop and the DRUID 2003 Summer Conference.
- Antonelli, Cristiano (1993) 'The Dynamics of Technological Interrelatedness: The Case of Information and Communication Technologies. In *Technology and the Wealth of Nations*, eds. D. Foray and C. Freeman (1993) Francis Pinter
- Antonelli, Cristiano (1999) *The Microdynamics of Technological Change*, Routledge
- Arora, Ashish, Andrea Fosfuri and Alfonso Gambardella (2001) *Markets for Technology: The Economics of Innovation and Corporate Strategy*, MIT Press (esp chapter 6: 'Markets for Technology and the Size of the Market: Adam Smith and the Division of Innovative Labour Revisited', pp.143–67)
- APEC (2003) *Drivers of the New Economy in APEC: Innovation and Organisational Practices* APEC Economic Committee at http://www.apec.org/content/apec/apec_groups/other_apec_groups/new_economy_-_e-apec.html
- Bakhshi, Hasan and Jens Larsen (2000), 'Investment-specific technological progress and the UK business cycle', Working Paper no. 129, Bank of England, London
- Balk, Bert M.,(2003) 'The Residual: On Monitoring and Benchmarking Firms, Industries, and Economies with Respect to Productivity'. ERIM Report Series Reference No. EIA-2002-07-MKT. <http://ssrn.com/abstract=678245>
- Bartelsman, Erik J and M. Doms (2000) 'Understanding Productivity: Lessons from Longitudinal Microdata' *Journal of Economic Literature* XXXVIII, p.569–94
- Basu, Susanto, John G. Fernald, Nicholas Oulton and Sylaja Srinivasan 2003 'The Case of the Missing Productivity Growth: Or, Does Information Technology Explain why Productivity Accelerated in the United States but not the United Kingdom?' NBER Working Paper No. 10010, forthcoming in NBER Macroeconomics Annual 2003 edited by Mark Gertler and Kenneth S Rogoff, MIT Press for National Bureau of Economic Research .
- Boklin, Eric, Stanford L. Levin, Nakil Sung and Chang-Ho Yoon (2004) *Global Economy and Digital Society*, Elsevier
- Boucekkine, R., F. del Río and O. Licandro 2002 'Embodied Technological Change, Learning and the Productivity Slowdown', *Scandinavian Journal of Economics*, 105(1), 87–89, 2003
- Boucekkine, Raouf and David de la Croixy 2000 'Information technologies, embodiment and Growth' August at http://www.ires.ucl.ac.be/DP/IRES_DP/2001-6.pdf

- Bresnahan, Timothy F. and Manuel Trajtenberg (1995) 'General Purpose Technologies: 'Engines of Growth'?' *Journal of Econometrics*, 65(1, Special Issue): 83–108
- Breunig, Robert and Marn-Heong Wong (2004) *Australia's Firm-level Productivity— a New Perspective*. <http://ideas.repec.org/p/econ/ausm04/177.html>
- Bruneau, Emile and Michel Lacroix (2001) 'Information sector: towards a 2007 classification' ACN conference, Paris, November 21–22, INSEE (France) at unstats.un.org/unsd/class/intercop/techsubgroup/02-10/TSG0210-14.PDF or http://www.insee.fr/en/nom_def_met/colloques/acn/colloque_9/information_sector_a_cnbis.pdf
- Brynjolfsson, Erik and Lorin Hitt 2003 'Computing Productivity: Firm-Level Evidence' *Review of Economics and Statistics* November at http://s.ssrn.com/sol3/s.cfm?abstract_id=290325
- Carlaw, Kenneth I. (2004) *ICT in Australian Economic Performance: An Investigation of the Assumptions Influencing Productivity Estimates*, Invited Plenary Session #2: Productivity Growth and ICT, Asia Pacific Productivity Conference, Brisbane, 14–16 July
- Carlaw, Kenneth I. and Richard G. Lipsey (2001), 'Externalities versus Technological Complementarities: a model of GPT-driven, sustained growth', A Paper Presented at The Conference in Honour of the 20th Anniversary of Nelson and Winter's book *An Evolutionary Theory Of Economic Change*, Aalborg Denmark, 12–15 June 2001.
- Carlaw, Kenneth I. and Stephen Kosempel (2004) 'The sources of total factor productivity growth: Evidence from Canadian data' *Economics of Innovation and New Technology*, 13(4), 299–309.
- Connolly, E. and K.J. Fox (2004) 'The Impact of High-Tech Capital on Productivity: Evidence from Australia', University of New South Wales, Working Paper, April.
- Daveri, Francesco (2003) Information Technology and Productivity Growth across Countries and Sectors' in Jones Derek C. (2003), Chapter 5, pp 101–120
- David, Paul (1991). 'Computer and Dynamo: The Modern Productivity Paradox in a Not-too-distant Mirror', in *Technology and Productivity* OECD, Paris.
- David, Paul and Gavin Wright (1999) 'General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution', *University of Oxford Discussion s in Economic and Social History*, Number 31.
- DCITA (2005) *Productivity Growth in Service Industries*, Occasional Economic Paper.
- Diewert, Erwin and Denis Lawrence (2004) *ICT in Australian Economic Performance: An Investigation of the Assumptions Influencing Productivity Estimates*, Invited, Plenary Session #2: Productivity Growth and ICT, Asia Pacific Productivity Conference, Brisbane, 14–16 July
- Diewert, W.E. and K.J. Fox (2005), 'On the Estimation of Returns to Scale, Technical Progress and Monopolistic Markups', revised version of Paper 57 presented at the SSHRC International Conference on Index Number Theory and the Measurement of Prices and Productivity, Vancouver, Canada, July and available at <http://www.ipeer.ca/SSHRC.htm>.

- Fare, Rolf and Shawna Grosskopf (2004) *New Directions: Efficiency and Productivity* Kluwer Academic.
- Fischer, Manfred M. (2003) 'The New Economy and Networking' from Jones (2003) *The New Economy Handbook*, Chapter 15, pp.343–367.
- Fisher, Jonas D. M. (1999) 'The New View on Growth and Business Cycles' *Economic Perspectives* (Q1), 35–56.
- Fisher, Jonas D. M. (2003a) *Technology Shocks Matter*, Federal Reserve Bank of Chicago.
- Fisher, Jonas D. M. (2003b) 'Technology shocks and the business cycle', *Chicago Fed Letter*, March.
- Fransman, Martin (2002) *Telecoms in the Internet Age: from boom to bust to ?* Oxford University Press.
- Freeman, Chris and Francisco Louca (2001) *As Time Goes By: From the Industrial Revolution to the Information Revolution*, Oxford University Press, Oxford, UK
- Gelauff, George MM, L Klomp, S Raes, and T Roelandt (eds.), (2004) *Fostering Productivity: Patterns, Determinants and Policy Implications*, Elsevier.
- Gelauff, George MM (2005) 'Economics of knowledge in international perspective: Lecture 5', University of Nijmegen and CPB Netherlands Bureau for Economic Policy Analysis at http://center.uvt.nl/staff/smulders/gtlit/gelauff_5.pdf
- Gera, Surendra and Wulong Gu (2004) 'The Effect of Organisational Innovation and Information Technology on Firm Performance' abridged in *International Productivity Monitor*, No. 9, Fall.
- Gera, Surendra, Wulong Gu and Jenness Cawthray (2003) Innovative Business Strategies and Firm Performance in the New Economy , as Chapter 3 of APEC (2003).
- Gordon, Robert J. (1990) *The measurement of durable goods prices*, University of Chicago.
- Gordon, Robert J. (2003a) *Five Puzzles in the Behaviour of Productivity, Investment and Innovation*, draft chapter for World Economic Forum, Global Competitiveness Report 2003–04, at <http://faculty-web.at.northwestern.edu/economics/gordon/WEFTEXT.pdf>, September and reported in *The Economist* of 13th September 2003.
- Gordon, Robert J 2003b 'Exploding Productivity Growth: Context, Causes and Implications', *Brookings Paper on Economic Activity (BPEA)* 2003:2 pp.207–98
- Greenwood, Jeremy, Zvi Hercowitz and Per Krusell (1997) 'Long-run implications of investment-specific technological change', *American Economic Review*, v 87, pp 342–62.
- Greenwood, Jeremy, Zvi Hercowitz and Per Krusell (2000) 'The role of investment-specific technological change in the business cycle', *European Economic Review*, v 44, pp 91–115.
- Gretton, Paul, Jyothi Gali and Dean Parham (2002) 'Uptake and Impacts of the ICTs in the Australian Economy: Evidence from Aggregate, Sectoral and Firm Levels' Conference Paper, OECD, Paris 9 December 2002. <http://www.pc.gov.au/research/confproc/uiict/index.html>.

- Griliches, Zvi (1996) 'The Discovery of the Residual: An Historical Note', *Journal of Economic Literature*, XXXIV, pp.1324–30.
- Griliches, Zvi (2000) *R&D, Education and Productivity: A Retrospective*, Harvard University Press.
- Hall, Peter (1994) *Innovation & Economics and Evolution: Theoretical Perspectives on Changing Technology in Economic Perspectives*, Harvester Wheatsheaf, Hemel Hempstead.
- Harrod, Roy F. (1948) *Towards a Dynamic Economics* Macmillan, London.
- Helpman, Elhanan, (ed) (1998) *General Purpose Technologies and Economic Growth*, MIT Press, Cambridge.
- Hercowitz, Zvi (1998) 'The 'embodiment' controversy: a review essay', *Journal of Monetary Economics*, v. 41, pages 217–24.
- Ho, Mun S and Stiroh, Kevin J. (2001) 'The embodiment controversy: you can't have two prices in a one-sector model', mimeo.
- IMF (2001) *World Economic Outlook: Chapter 3 The Information Technology Revolution*, October at <http://www.imf.org/external/pubs/ft/weo/2001/02/index.htm>
- Information Society Commission (Ireland) (2005) *Learning to Innovate: Reperceiving the New Economy*, Information Society Commission.
- Inklaar, Robert (2005) 'Cyclical Productivity in Europe and the United States, Evaluating the Evidence on Returns to Scale and Input Utilization' Research Memorandum GD-74 Groningen Growth and Development
- Bertschek, Irene (2003) 'Information Technology and Productivity Gains and Cost Savings in Companies' in Jones Derek C. (2003), Chapter 9, pp 213–228.
- Jones, Derek C. (Ed) (2003) *New Economy Handbook*, Elsevier.
- Lipsey, Richard G., Cliff Bekar and Kenneth I. Carlaw (1998) 'What Requires Explanation,' Chapter 2 in Helpman (1998).
- Lipsey, Richard G., Kenneth I. Carlaw, and Cliff Bekar (2005) *Economic Transformations: General Purpose Technologies and Long Term Economic Growth*, Oxford University Press, Oxford.
- Louçã, Francisco (2003) 'The New Economy and Economic Cycles' in Jones Derek C. (2003), Chapter 33, pp 767–799
- Mann, Catherine (2003) 'Policy Issues and the New Economy for Developing and Transition Economies' from Jones, (2003). *The New Economy Handbook*, Chapter 40, pp.931–84.
- Milgrom, Paul and John Roberts (1995) Complementarities and Fit Strategy: Structure and Organisational Change in Manufacturing, *Journal of Accounting and Economics*, No. 19, pp 179–208.
- Mokyr, Joel (2002) *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton University Press,
- Mulraine, Millan (2005) Investment-Specific Technology Shocks in a Small Open Economy, Draft January at www.chass.utoronto.ca/~mulraine/Draft_Paper.pdf

- Nelson, Richard R. (1994) *An Agenda for Formal Growth Theory*, IIASA Working Paper WP-94-085 International Institute for Applied System Analysis at <http://www.iiasa.ac.at>
- Nelson, Richard R. (1995), 'Recent Evolutionary Theorizing about Economic Change', *Journal of Economic Literature*, 33: 48–90.
- Nelson, Richard and Stanley G Winter (1982) *An Evolutionary Theory of Economic Change*, Cambridge: Harvard University Press
- OECD (2001) *The New Economy: Beyond the Hype, The OECD Growth Project*, OECD, Paris.
- OECD (2004) *The Economic Impact of ICT: Measurement, Evidence and Implications*, OECD, Paris.
- Oliner, Stephen D. and Daniel E. Sichel (2000) 'The resurgence of growth in the late 1990s: is information technology the story?', *Journal of Economic Perspectives*, v 14 (Fall) pp 3–22.
- Olsson, Ola and Frey Bruno S. (2002) 'Entrepreneurship as Recombinant Growth', *Small Business Economics* 19(2) pp.69–80 Springer Science+Business Media B.V
- Oulton, Nicholas (2004) Investment-specific technological change and growth accounting, Working Paper No. 213, Bank of England, London
- Pakko, Michael R. (2002a) 'What Happens When the Technology Growth Trend Changes?: Transition Dynamics, Capital Growth and the 'New Economy'.' *Review of Economic Dynamics*, April 2002, 5(2), pp.376–407.
- Pakko, Michael R. (2002b) 'The High-Tech Investment Boom and Economic Growth in the 1990s: Accounting for Quality' *Federal Reserve Bank of St. Louis Review*, March/April 2002, 84(2), pp. 3–18.
- Pakko, Michael R. (2002c) 'Investment Specific Technology Growth: Concepts and Recent Estimates' *Federal Reserve Bank of St. Louis Review*, November/December 2002, 84(6), pp.37–48.
- Parham, Dean (2004a) 'Productivity taking a breather' *Australian Financial Review*, 26 May 2004 p.63.
- Parham, Dean (2004b) 'Sources of Australia's Productivity Revival', *Economic Record*, 80(249), pp.239–57.
- Parham, Dean, Paul Roberts and H. Sun. (2001) *Information Technology and Australia's Productivity Surge*, Productivity Commission Staff Research Paper, Canberra.
- Perez, Carlota (2002) *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages*, Edward Elgar, Cheltenham.
- Prescott, Edward C. (1997) 'Needed: A Theory of Total Factor Productivity' Research Department Staff Report 242, Federal Reserve Bank of Minneapolis.
- Productivity Commission (2003) *Trends in Australian Manufacturing*, Commission Research Paper, AusInfo, Canberra.
- Quiggin, John (2001) 'The Australian Productivity 'Miracle': A Sceptical View', *Agenda* 8(4), pp. 801–17.

- Schumpeter, Josef A. (1934) *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest and the Business Cycles*, Harvard Business Press: Boston.
- Solow, Robert (1956) 'A Contribution to the Theory of Economic Growth,' *Quarterly Journal of Economics*, 70, 65–94.
- Solow, Robert M. (1957), 'Technical Change and the Aggregate Production Function,' *Review of Economics and Statistics* 39, 312–320.
- Solow, Robert M. (1963) *Capital Theory and the Rate of Return*, North Holland, Amsterdam.
- Tuomi, Ilkka (2002) *Networks of Innovation: Change and Meaning in the Age of the Internet*, Oxford University Press
- Tuomi, Ilkka (2004) 'Knowledge Society and the New Productivity Paradigm: A Critical Review of Productivity Theory and the Impacts of ICT', *IPTS Working Paper*, 11.2.2004.
- Violante, Gianluca and Jason Cummins 2002 Investment-Specific Technical Change in the US (1947–2000): *Measurement and Macroeconomic Consequences* mimeo at [http://ideas.repec.org/a/red/issued/v5y2002i2p243–284.html](http://ideas.repec.org/a/red/issued/v5y2002i2p243-284.html)
- Weitzman, Martin L. (1995) Recombinant Growth *Quarterly Journal of Economics*, 113(2):331–360, May 1998.
- Wilson, Daniel J. (2001) Is Embodied Technology the Result of Upstream R&D? Industry-Level Evidence, Working Paper 01–17, Federal Reserve Bank of San Francisco.

Chapter 2

2 ICT's productivity credentials¹

Investment in new technologies is the third area in which policy can influence growth. ... [It] is special for two reasons. First it appears to not run into the problem of diminishing returns that plague all other productive resources. Secondly the benefits of new technologies spill over to influence all parts of the economy, not just the firms undertaking the investment'²

It [microeconomic reform] is a broadly classified as a form of technological progress.³

... there is a mutually beneficial relationship between organisational change in firms and ICT investments. Information technology is key to facilitating new organisational approaches, from lean production to teamwork to customer relations. OECD (Marian Murphy, 2002)

¹ In-house DCITA research. The study includes material from a paper , 'Paradoxes and Paradigms: Australia's Productivity in an Information Age' presented at the Asia-Pacific Productivity Conference (APPC2004) in July 2004.

² McTaggart, Finlay and Parkin (2003) p 786.

³ McTaggart, Finlay and Parkin (2003) p 735.

2 ICT's productivity credentials

2.1 An analytical framework

In the mid 1990s, after two decades of slowdown, US MFPG showed signs of a dramatic revival. Coincidentally, after four decades of evolution, modern ICT had become integral to the work and leisure activity of most people. The explosion in connectivity, especially apparent in the internet and 'globalisation', prompted an increased awareness of an ICT-productivity relationship. The result was a popularisation of the notion of an information revolution and the New Economy.

The utopian properties attributed by some to an ill-defined New Economy were treated with extreme scepticism by most economists. Five years on, the hype but not the reality, of the underlying transformation had vanished—the unrealistically high expectations associated with over inflated values of technology stocks, had suddenly and dramatically turned. Nevertheless, by year-end 2003, the productivity-raising impact of the 'Information Revolution' had been acknowledged by leading economists the world over.¹ Even the most prominent and longstanding critic, Professor Robert Gordon, changed from an ICT sceptic to an advocate. Gordon's reversal followed statistics that ruled out the business cycle as a source of the high US MFPG, but the persuasion of colleagues, many of whom considered ICT to be a GPT, appears also to have influenced his decision.²

Nevertheless there is still a variety of positions on the extent and measurement of the impact of ICT on productivity growth.³ One such debate centres on whether differences in Australian and US productivity experiences could be explained in terms of the behaviour of the global productivity frontier. The strong steady outward advance of this frontier in the post-WWII 'golden age' had given way to frontier stagnation post 1973, and the MFPG revival in the US in 1995 symbolised the technological lifting of the 'speed limit' on innovative growth. Thus it could be argued that import barriers, government monopolies, the lack of national competition, and other institutional rigidities had caused Australia's productivity to fall

¹ In a recent publication, Maddison (2005a, p.137), drawing on year 2000 research, puts the view that 'there has been a belated but positive payoff in macroeconomic productivity from a couple of decades of high investment in the 'new economy'. 'The fact that there have been no very evident spillovers as yet in computer-using industries may well be due to the costs of absorbing new technologies which have involved a large input of highly trained people, rapid obsolescence of equipment and skills, and some serious blunders.' He suggests that, 'in the longer run, when the new technology has been fully assimilated, significant spillovers to other sectors of the economy may well occur', and 'there are grounds for hoping that progress may be faster than in 1973–95.'

² See Gordon (2003a)

³ See for example Fuss *et al* (2005), Wilson (2004), Fernald (2003), David *et al* (1999), Tuomi (2004), Ahn (2001, 2002), Van Alstyne *et al* (2004), Kaufman *et al* (2005), Daley *et al* (2005), Dai *et al* (2005)

further and further behind the advancing global frontier. Microeconomic reform had removed this drag and Australia was now 'catching up' with the global frontier.

The catch-up story is not consistent with the productivity theory that underlies the growth accounting estimates. That catch up theory assumes a significant departure from efficient markets. This assumption is not consistent with the assumed optimising behaviour that underlies the determination of the productivity frontier. While the practice of aggregate productivity measurement can still be justified on axiomatic grounds, at issue is whether the catch-up hypothesis holds when the assumption of optimising behaviour is dropped.⁴

It suggests ICT as an enabler of productivity growth has not been adequately recognised, although the enabling role of ICT in globalisation is recognised. ICT-enabled transformations have brought Australia closer to the world economic centres. Moreover, ICT reduces the costs associated with distances between Australian population centres, and reduces the scale effects of low population density. Australia may have benefited from cross-country learning spillovers, allowing Australia to 'piggy-back' on US ICT-based learning. Such an explanation would be consistent with a wide range of firm level studies which show strong productivity benefits from investment in ICT.

2.2 Setting the scene

Governments have been highly involved in the development and diffusion of modern ICT. They have overseen, coordinated and encouraged the uptake and use of successive ICT innovations including distributed computing, the Internet, e-mail, and the world wide web and supported the information economy.⁵ Economists seek to explain how modern ICT has contributed to their economies and societies.

While the general importance of ICT is now rarely questioned, economic debate has raged as to just how important ICT is, and why? Here the evidence is limited and mixed, leading to such debates as: Is there a New Economy?⁶ (OECD 2000, 2001) Is there an information revolution?⁷ How much of the growth in total factor productivity (TFP or MFP) is due to ICT? Does the productivity bonus come from production or use and how are any productivity bonuses distributed across firms, industries and countries?

Underlying these debates is a set of deeper questions relating to measurement and interpretation of aggregate productivity. Griliches (2000, p24) describing the underlying sources of productivity growth⁸, claims 'that they are all economic processes subject to

⁴ For differences between axiomatic and economic interpretations, see Coelli *et al* (2005).

⁵ See Bruno Lavin (2003)

⁶ The question was posed by the 1999 OECD growth project, which reported in August 2001.

⁷ Alan Greenspan and other key economists of the US FRB found in the affirmative (eg Greenspan 2000).

⁸ According to Griliches, 'productivity growth represents the reaping of returns generated by knowledge

economic analysis', but that they do not 'fit comfortably within the straight jacket of conventional theory' as '... much of the world is not in continuous, perfectly anticipated equilibrium.'

For Griliches, the issue is finding 'an 'explanation' for the observed changes in the various productivity indexes.' He warns that 'accounting is not explanation ... Explanation must come from comprehending the historical detail, from finding ways of generalising (modelling) the pattern that may be discernable in the welter of it ... if we want to understand better what we are talking about, where technical change is actually coming from, we will need to study history.'(pp. 89–90).

Clearly, addressing the deeper questions is challenging, and might even require departure from comfortable well-known productivity practice. This explains why Griliches concludes 'despite more data, more advanced econometric techniques, and better computer resources, the state of the field has not advanced all that much in the last 25 years.'(2000, p. 24) and why he cautions 'there is no free lunch in economic research either' (2000, p.90).

This chapter attempts to address the deeper questions. It starts by looking at the evidence that suggests technological revolutions influence productivity growth. Against this background, the slow acceptance of the role of ICT in the present 'revolution' seems surprising. The explanation may be the lack of an accepted economic theory of technological change. Here the GPT-based economic-theoretic reasons might explain the emphasis on ICT in government policy worldwide. In making such judgements it might be useful to step back from formal productivity analysis and observe the way in which ICT is enabling change in the world around us.

2.3 Revolutions in the history of economic growth

Macroeconomic research which accepts conventional productivity estimates has the task of explaining the source of long cycles of productivity, based on the statistical reality of the two-decade long US productivity slowdown.

Acceptance of long cycles of productivity change is consistent with economic history. The rapid rise in our living standards over the last two centuries contrasts with little change in subsistence living standards of the immediately preceding centuries. Economic historians attribute this remarkable change to the Industrial Revolution, a change that ultimately

production, and its diffusion within and outside industries. Its essence is the exploitation of new investment opportunities, in the form of new techniques, new products and markets, new methods of communication and the associated increasing returns opportunities that such developments, including the growth of the economy as a whole, opens up. Much of such growth can be thought of as arising endogenously, from the investment of economic resources in the diffusion of new technologies, in their 'embodiment' in physical and human capital, in migration processes, and in R&D investments.'

transformed society. Although often associated with the replacement of water power with location-independent steam power, the range of innovative technologies that occurred in such diverse fields as sanitation, machinery, metal working and printing indicated the complex inter-sectoral growth interdependencies that characterised the industrial revolution.

The next section seeks insight into the validity of 'innovation cycles' and into explanations of the recent productivity cycle from two prominent economists, Jean-Philippe Cotis, chief economist of the OECD, and Zvi Griliches, a distinguished economist who devoted much of his professional life to explaining 'the residual'. Cotis is conversant with the OECD's long and comprehensive investigation into sources of growth, and his views as expressed in the foreword to OECD (2004b) are likely to be of value. Griliches' long career in researching MFP suggests his 'Retrospective' should be insightful. (Griliches 2000).

2.3.1 The OECD on golden ages and productivity slowdowns and revivals

The OECD began its 'New Economy' research in 1999. It became interested because growth divergences across OECD economies ran counter to the expectation of convergence in an age of ICT-based globalisation, with common access to technology. The findings of the OECD growth research were first reported in the OECD ministerial council report *The new economy: beyond the hype* in 2001, with these and later findings summarised in the OECD (2004b) publication 'Understanding Economic Growth'.

Jean-Philippe Cotis, OECD chief economist, in the foreword, contrasts the golden age ('thirty glorious years' of 'exceptionally strong growth' that following World War II) with the productivity slowdown of the following two decades. He asks why 'the very substantial acceleration in productivity seen in the US since 1995 has not yet spread to other countries as widely as might be expected'. He explains that recent divergence in growth across OECD members demonstrates 'that living standards do not converge automatically and technological progress is not 'exogenous' ... but depend on the quality of national institutions and public policy'.

Cotis summarises the key findings of the OECD research. In respect to achieving economic growth, he stresses 'the crucial importance of human capital and R&D'. In respect of 'the recent acceleration of productivity growth in the US and certain OECD countries', he reports that the role of the new information and communication technologies appears 'to be very important, but does seem to depend a great deal on the regulatory and institutional framework in which technological innovation takes place.'

The OECD (2004b) reports findings from a range of different methods that explore different aspects of growth. The report is positive on ICT, detailing various mechanisms through which ICT, as an enabler, contributes to productivity growth.

2.3.2 An alternative view—Zvi Griliches

Griliches is more accepting of the possibility of measurement error as a possible explanation of the slowdown than Cotis.

The most reasonable explanation for the longer run persistence on what started out as a short run response to a real supply (oil price) shock is the character and location of the recovery and the technical changes that followed. The latter were based primarily on developments in information technology, a fact that makes them intrinsically difficult to measure, and were happening in sectors of the economy in which output and productivity are almost impossible to measure in the first place (Griliches 2000 p.90)

The study of growth will require embracing more seriously a view of the economy where decentralised information and incentives in a constantly changing world make all the difference. But progress will lie in merging those general insights with useful theory, careful measurement and serious econometric work. (Griliches 2000 p.90)

2.3.3 What does MFPG really measure

The OECD is well aware that aggregate MFPG is an imperfect measure. The OECD productivity manual (Schreyer 2001) warns that while MFPG is generally taken as a measure of technological change, it can alternatively be a measure of: (i) adjustment costs, (ii) economies of scale, (iii) cyclical effects, (iv) changes in efficiency, or (iv) measurement errors. The manual states: ‘The presence of such factors invalidates the assumptions underlying the simple growth accounting model. It is ‘badly suited’ to non-constant returns to scale, and excludes ‘gains from the elimination of inefficiencies’’. However the need to have some measure of productivity growth has led economists to commonly accept these ambiguities and tensions.

2.4 Slow acceptance of an ‘information revolution’

2.4.1 Macro-effects of macro-innovations

Identification of the drivers and timing of productivity-enhancing revolutions is not without contention. However, most economic historians would agree that the driving invention must mark a radical advance on the prior technology.⁹ It must have widespread impacts on

⁹ Economic historians (eg Maddison, Baumol, Mokyr, North) disagree on when the Western nations took the lead in the productivity stakes, but generally agree it was due to take up of technology, advances in communication and widespread use of knowledge. Eg Maddison attributes the productivity leadership to: (i) The interplay of technical genius and practical application led to advances in navigation, which allowed Europe to explore and trade with the rest of the world. (ii) Although printing was invented by the tenth century A.D. in China, it was used there primarily by the elites and the educated bureaucracy. By contrast, in Europe printed

technological advance across other industry sectors and on social practice. It must have potential for long-run improvement over time as the technology matures. These taken together ensure that there is a long-run transforming impact on society, as experienced during the Industrial Revolution.

It is with the passage of time that one can better identify the innovations that give rise to such 'revolutions'. The widespread recognition of an information revolution at the turn of the century occurred 50 years after the invention of the computer. The early signs came with the amazingly rapid price rises of US technology stocks, increases that lead to unrealistic expectations, and claims the US was a 'New Economy'. Of course, the expectations-related asset price hike drew power from a stimulatory monetary policy. Technology alone is seldom the sole cause of macroeconomic disturbances.

The early hype was rejected by the almost all economists, many quite vigorous in their condemnation. However as the 21st century began, doubts about sustainability of the post-1995 US productivity revival diminished, with the continued strength of ICT innovation and expenditure. Pre-eminent economic organisations ranging from the US Federal Reserve Bank and IMF to the World Bank, the *Economist* magazine and Australian Treasury all recognised the information revolution and its potential to lift productivity.

The speech by FRB chief, Alan Greenspan, on 6th March 2000, was representative of the mainstream economists attributing the resurgence in US productivity growth to the revolution in ICT:

At the end of the day, the benefits of New Technologies can be realised only if they are embodied in capital investment, defined to include any outlay that increases the value of the firm. For these investments to be made, the prospective rate of return must exceed the cost of capital.

Technological synergies have enlarged the set of productive capital investments, while lofty equity values and declining prices of high-tech equipment have reduced the cost of capital. The result has been a veritable explosion of spending on high-tech equipment and software, which has raised the growth of capital stock dramatically over the past five years. The fact that the capital spending boom is still going strong indicates that businesses continue to find a wide array of potential high-rate-of-return, productivity enhancing investments. And I see nothing to suggest that these opportunities will peter out anytime soon.

The speech was made at the peak of equity and ICT markets, a year from the bust. Many economic historians had expected financial market turbulence, seeing similar patterns in past 'revolutions'. (Freeman and Louca 2001, Perez 2002) Such booms assist the financing of ultimately welfare improving change. That has since proved the case here. The productivity growth in the US has continued at sustained high rates not experienced since 1973.

books allowed a much greater proportion of the population to have access to new ideas and new authors. (iii) For many centuries, Oriental cultures showed little interest in superior technologies—even when confronted by them.

Numerous case studies demonstrated how the productivity of particular tasks had been dramatically improved by ICT. Moreover ICT had enabled products, services and processes not previously possible. Professor Robert Gordon was one of very few US economists to question the ICT-led productivity revival on grounds that the productivity resurgence since 1995 might be cyclical and trend labour productivity might not hold up. He reversed his stance when the US productivity statistics of August 2003 effectively strengthened the robustness of trend productivity. His latest estimates factor in the special characteristics associated with technologies like ICT. (Gordon 2003a)

Throughout the 1980s, economists had been expecting to see evidence of recent technological advances, most visible in the rapid advances in ICT, in the form of high MFP growth. So it was a matter of surprise to US economists that the massive computing investments of late 1980s and early 1990s had not delivered TFP growth comparable to the post-war 'golden age' of US science and technology. In 1994, Stephen Oliner and Daniel Sichel of the FRB expressed this surprise as follows:

During the past 15 years, U.S. companies have poured billions of dollars into information technology. Yet, through the 1980s, many observers argue that these companies were not getting their money's worth. As hard as analysts scoured the numbers, they could not show that computing equipment contributed much to productivity growth, leading to Robert Solow's famous quip that 'you can see the computer age everywhere but in the productivity statistics.'

The size and timing of the US productivity revival is no longer contentious. Gordon, an authority on US cycles, has the US Golden Age ending in 1973 and the productivity revival commencing in 1995. The estimates on the productivity impacts of ICT by Oliner and Sichel of the Federal Reserve are widely recognised. The average TFP growth of four tenths of a percentage point over the two decades of productivity slowdown underlay US concern that the US economy may have lost its TFP growth. Since 1995, however, average annual TFP growth of over 1 per cent has given prospect to the productivity 'revival'.

Of the TFP acceleration of 0.74 to 2002, ICT production accounted for 0.4 percentage points with the remainder of 0.34 largely attributed to intensive ICT using industries, such as retail and finance. The US consensus is that the revivals in US TFP growth, and the somewhat larger jump in US labour productivity growth, are due to ICT. Thus for many, the Solow paradox ended with a broad consensus on the importance of ICT to productivity at both macro and micro-levels.¹⁰

¹⁰ Similar findings were made for other countries. For Sweden for example, see Eliasson, Johansson and Taymaz (2002)

2.4.2 Micro-level exploration of ICT and productivity

The OECD recognised the importance of firm-level micro data in 2001, when the macro level analysis was thought to lack sufficient power to adequately explain cross-country MFPG patterns.

However much of the firm-level analysis occurred outside the auspices of the OECD. Perhaps, culminating evidence of the importance of ICT in the US came from Brynjolfsson and Hitt (2003) who reworked their comprehensive data on 527 of the largest US companies over 1987 to 1994 to see whether taking into account the non-contemporaneous nature of the productivity bonus and investment might explain the delayed productivity response in the US. They found it might, concluding:

While the late 1990s saw a surge in productivity and output as well as a corresponding surge in computer investment, it is important to note that our analysis is based on earlier data from the late 1980s and early 1990s. This earlier time period did not enjoy extraordinary growth in the overall economy. If computers indeed require several years to realize their potential growth contribution, the economic performance in the late 1990s may, in part, reflect the massive computer and organisational investments made in the early 1990s.

Similar results came from a range of other countries. By year end 2003, the complementarity between the ICT, management and innovation in driving MFPG had been firmly established not only in the US, but also in many of Australia's competitor economies.

In Canada, research by Surendra Gera and Wulong Gu¹¹ used the GPT concept in explaining the role of ICT. Their research firmly demonstrates that, for Canadian firms, ICT complements organisational change and human capital:

We find that while ICT is productive on its own, it is more productive in firms that combine high levels of ICT with high levels of organisational change. The firms that combine ICT with organisational changes have a high incidence of productivity improvement and have high rates of innovation. These findings seem to suggest that to be successful, firms typically need to adopt ICT as part of a 'system' or 'cluster' of mutually-reinforcing organisational approaches. We also find that ICT and human capital are complements in the service sectors. The firms that combine high levels of ICT and high levels of worker skills have better firm performance. (abstract)

The Canadian study uses a comprehensive establishment-level micro data set—Statistics Canada's 1999 'Workplace and Employee Survey'. The survey is a cross-sectional survey of 6,351 business establishments across the entire spectrum of the Canadian economy in 1999.

¹¹ Respectively are Senior Research and Policy Advisor, Micro-Economic Policy Analysis Branch, Industry Canada and Chief of Research, Micro-economic Analysis Division, Statistics Canada. Their most recent research was published in abridged form in 'The Effect of Organisational Innovation and Information Technology on Firm Performance' is in the *International Productivity Monitor*, No. 9. Fall 2004.

This provides a rich set of measures on organisational changes and firm performance that allows the study to examine the relationship between ICT use, organisational practices and firm performance. In particular, it examines the role of complementarities between ICT use, organisational changes in the areas of production practices, HRM practices and product/service related practices, and human capital as drivers of better firm performance in the knowledge-based economy.

That strong complementarities between ICT and innovation are key to driving firm-level productivity has also been well established in other economies as demonstrated by Marian Murphy of the OECD's economic directorate.¹² Similar findings were made in the comprehensive research by McKinsey Global Institute (Farrell, 2003) and McKinsey (Casserley, 2004). In another study, McKinsey and the London School of Economics (Dorgan et al, 2004) demonstrates that the complementarities between technological and organisational innovation are very strong in Europe. Firms investing in both ICT and management innovation achieved a MFPG of 18% above those just investing in ICT, and 12% greater than those just investing in organisational innovation.

Balk (2001) recommends new firm-level directions for productivity research. In respect to micro studies, he shows that 'much has been learned about the incredible dynamics of firms and the contribution of intra- and inter-firm factors to aggregate productivity change. However, firm-level productivity change as such remained more or less a black box. The logical step forward would therefore be to enhance this analysis by a decomposition of firm-level productivity change, using ... the Malmquist productivity index together with its components technological change and technical efficiency change ... This type of research could lead to a deeper insight into the evolutionary processes that are taking place within modern economies.' Such an approach would be particularly beneficial in exploring ICT effects.

Importantly, Balk claims that the resultant benefit would be 'not only important for its own sake but also for any *government policy that aims at aggregate productivity growth.*' [emphasis added]. The reason is that 'for the fine-tuning of such a policy some understanding of the various factors that alone or together contribute to productivity change is indispensable.' Balk lists the policy issues: Should economic policy be directed at pushing the technological frontiers ahead? Or should economic policy be directed at removing the barriers for (more) efficient behaviour? How to approach the issue of ICT-related scale effects? For this issue, Balk claims a refined form of analysis is called for, stating: 'At this level the role of statistical figures for guiding economic policy must be taken over by carefully designed case studies, whose role it is to stimulate the imagination of all involved.' According to Balk, this is the 'traditional area of interest of business administration.' The

¹² See her quote that introduces this chapter.

recently completed DCITA-funded research consultancy by ANU/Opticon on ICT and management (Grigor *et al*, 2005) is such a study.

Balk's views are worth serious consideration.¹³ The key to understanding and measuring productivity may be to better integrate the traditional economic model of the firm with modern management and organisational theory. Significant advances in understanding have come when the Resource Based View (RBV) of the firm is applied to the study of ICT effects.¹⁴ The findings of such research have been largely ignored by mainstream economics, perhaps because they represent a departure from traditional approaches. How to combine these research areas is an issue when the economic and business studies are merged.¹⁵

2.5 GPT theory and long-run productivity cycles

2.5.1 Background

The increasing understanding and acceptance of the concept of a GPT, with up-front adjustment costs and delayed productivity benefits, was influential in reversing scepticism on the importance of ICT among productivity analysts. The development of the theory was assisted by observations on the evolution and diffusion of modern ICTs.

The likelihood of a very long delay between invention of the computer and the productivity gain was noted early by David (1991). David identified a range of factors that could cause long delays between the introduction of a radical new technology and its contribution to productivity growth. His econometric research established that four decades had elapsed before electrification and dynamo technology delivered its MFP benefits to US manufacturing.

Nevertheless, it was an econometric study of Bresnahan and Trajtenberg (1995) that first described 'revolutionary' technologies such as ICT and electricity as 'General Purpose Technologies'. Bresnahan and Trajtenberg identified other properties of GPTs including the 'innovational complementarities'¹⁶ that their research showed to be characteristic of sustained GPT-driven innovation-based growth.

¹³Successful firm strategy is context sensitive and forward-looking, eg using Kaplan's balanced scorecard to assess health. Such complexity suggests avoidance of fixed assumptions and simple rules. McElroy (2003) sees sustained innovation/productivity growth deriving from complex adaptive systems built on information systems (hard and soft) and knowledge (management).

¹⁴For example see Fahy and Smithee 1999 for an introduction and Melville, Kraemer and Gurbaxani 2004 for its use in ICT. Another departure for economics comes from Ahn (2002) who exposes the importance of 'dynamic technical efficiency' over traditional static 'allocative efficiency'.

¹⁵ See also Legge (1994).

¹⁶ The concept of 'Innovational Complementarity' is more commonly referred to as (broadly defined) 'technological complementarity'.

By 1998, Helpman's book 'General Purpose Technologies and Economic Growth' containing contributions by leading growth economists (Romer; Howitt; Breshanan; Nelson; and, Lipsey, Bekar and Carlaw) had shown the GPT concept was not only conceptually sound, but empirically workable. And there was general acceptance that not only did ICT qualify as a GPT, but that it fell into the special class of 'transforming' GPTs. Realising the potential benefits of transforming GPTs would require 'facilitating adjustment' with government leadership and support of innovation, retraining and entrepreneurship.

2.5.2 ICT as a general-purpose technology—a commonsense appraisal

It is often useful to step back from the practice embodied in professional disciplines to review the 'commonsense' of those propositions in changing environments. Such 'reality checks' can expose the need to drill down and re-examine the assumptions that provide the foundation for professional economic practice. The commonsense explanation behind each economic model is what Nelson and Winter (1982) call appreciative theorising and what they argue should precede the formal modelling.

The early computers had been preceded by other 'general purpose technologies' in the 20th century. The Edison Invention Factory had demonstrated the versatility and breadth of application of electricity as a source of energy. As a general purpose technology, electricity slowly displaced steam and water wheel power, transforming the organization of manufacturing. The internal combustion engine, aircraft and motor vehicles were GPTs that transformed transport and power generation.¹⁷

Technologies have enhanced human capability in key areas such as transport, machinery, power and communications. For example, machine tools have increased the power of manual tools with machinery replacing muscular power for lifting, moving and otherwise working materials. Electricity and internal combustion engines have replaced 'horse' power. Transport equipment have improved our ability to move people and goods. Telephones and telegraphs have improved human communication. Telescopes and microscopes have increased the power of the eye, and so on. Each new (radical) macro-innovation (or GPT) builds on preceding macro-innovations in its field.

The first computer represented a radical break from previous technologies that were used to store, use and transmit information, and had enormous potential to change the future. Enabled by electronics, it required advances in microelectronics to increase its power, decrease its size

¹⁷ Paul David (1999) and Ilkka Tuomi (2002) describe evolutionary transformation in the role of IT, an evolution expected to continue. There is an analogy with John Enos (2003) research into the evolution of steam power where the theoretical thermodynamic limits to power extraction was delayed over centuries awaiting complementary innovation in engineering. The Corliss Steam Engine (Rosenberg and Tratjenberg, 2003) displaced the water wheel in North East USA, then becoming the mobile force that reduced distance through the US railroad system, and now with Paul David's electric dynamo realises much of its theoretical potential in the steam turbines that drive the bulk of Australia's electricity generation.

and price. This required several cycles of invention and investment, from mainframe computers to client server systems to the present day Internet.

Nevertheless the evolution of the computer, from electronic valve to transistor to today's integrated circuit technologies, represented a radical change from past information technologies. This radical change marked this technology as a GPT, even in its infancy. The digital nature of instruction processing and decision rules that give ICT its power pointed to its enormous potential for exploitation in a wide range of fields.¹⁸ The readily programmable characteristic and miniaturisation of digital devices made modern ICT a radical departure from earlier precedents which involved bulky analogue, mechanical or clerical systems for information processing, storage and dissemination.

The potential of ICT stems from its breadth of application, extending beyond traditional informational processing and human communication systems by combining the power of programming with auxiliary peripherals to improve the capability and performance of existing capital. In Australia, this power and versatility of ICT in defence, public administration, statistical, mathematical, and scientific areas was recognised in the 1960s, with federal government one of the early large users. An early initiative of the Australian government was to build a skill base in computer use, encouraging those with the aptitude to study as 'operators' or 'programmers in training' in Canberra.

Even at that early stage the 'general purpose' use of computers could be distinguished from custom applications. The large mainframe computers together with their operating systems and 'language compilers' were clearly 'general purpose'. It was the programmers, writing code in scientific language (Fortran), business language (Cobol), or some other language that determined what the specific purpose was. It is this distinction between general and specific purpose that determines what is a GPT and what is not. The operating system and compiler software that enabled the specific applications were 'general purpose', the user programs were not.¹⁹

Although best known, the language compilers were not the only general-purpose software. Such software is now hidden, as new more specialised user-based platforms are used for a wide range of applications. Here end-users customise ICTs to meet their own special needs. The personal computer of the early 1980s, office friendly software, and local area networks marked a new wave in distributed computing. It took time to learn how to best integrate the

¹⁸ Digital switches and digital information packets have made communication digital, and led to 'ICT' replacing 'IT' as an acronym for the technology in Europe and the OECD.

¹⁹ At that time, users developed their own software to meet a very wide range of specific applications, from security, statistics, business and science, or to suit particular inputs and output peripherals, eg printers for offices, process controllers and sensors for process control and computed assisted design and manufacturing. Thus computers and the strict complements, namely the operating systems and basic input output devices, and the basic programming skills needed to operate them were 'born general purpose'. It was the users, with in-house programs that determined the specific purpose to which they might be put.

PC and mainframe, with the ultimate productivity gains leading in the late 1980s to the huge new investments in ICT that were noted by Solow and others.

For communications, the impact of ICT has and continues to be most remarkable. Like many innovations since, the evolution of the telephone system went far beyond the simple telegraph technology whose network infrastructure led to its rapid diffusion, once its power was accepted as part of the social infrastructure. It differs from other GPTs in that it provided a platform that transformed all aspects of our lives. As Krupa (1992) says:

The telephone system was built to take advantage of a technology that had no clear use at the time of its invention. Its potential has radically expanded recently with the computer networks and fax machines. We could not imagine life without the telephone system and have a hard time understanding why its potential was such a mystery over a century ago.

The telephone is everywhere and nowhere. It is credited for being the first technology to make distances shrink with its instantaneous two-way transmission. Only the phone allowed two people to be in two places at once. Its extraordinary power to alter our concept of space and time is now a common experience for much of the world.

Tuomi (2002) describes how the innovation that is the Internet has parallels in other innovations over time. In particular, continuous evolution of technology requires continuous acceptance of the technology as a blackbox. Thus the high level of science that underlies communication systems is hidden (and appropriately so) from users. This is particularly the case for the communication systems. Underlying such systems is a mathematical theory, first developed by Claude Shannon in 1948 as 'The Mathematical Theory of Communication.' On its 50th anniversary republication, *Scientific American* wrote 'Claude Shannon's major precept, that all communication is essentially digital, is now so commonplace among the modern digitalia that many wonder why Shannon needed to state such an obvious axiom'.

Thus while all technologies evolve, the future of ICT is as yet beyond our vision. And it is hardly surprising that its transformative effects are so hard to capture in the form of productivity statistics. The invention of the car transformed transport in a most obvious way, and as the investment in the complementary infrastructure, roads, oil refineries, motor vehicle plants, etc, was relatively easy to capture. Not so with ICT, where much of the complementary capital is hard-to-measure intangible knowledge and social capital.

This measurement difficulty may be one source of the lack of measured productivity growth associated with the evolution of ICT. Another may be the greater efficiency likely from ICT-assisted market transactions. Again exchange efficiency is generally taken as given in economic analysis, and ICT-related micro-level reductions in transactions costs are not readily identified in aggregate productivity statistics. The productivity gains associated with

increased market efficiency might well be missed as competition and the pervasive general purpose nature of ICT's impact ensures early capture by consumers.

Van Alstyne and Bulkley (2004) claim that explanations that go to the nature of ICT may be better at explaining why ICT might improve welfare than productivity decompositions based on growth accounting. They show how insight into the productivity paradoxes comes from asking: 'Why information should influence productivity?' They go behind the measurement issues to demonstrate the mechanisms by which information sharing and the development of the knowledge base improves productivity, albeit in ways that are difficult to capture in growth accounting.

2.6 Market failure with sustained GPT-based growth

2.6.1 Conventional analysis

The work of GPT theorists, in particular Bresnahan and Trajtenberg (1995) and Carlaw and Lipsey (2002) demonstrate dynamic market failure is associated with the evolution and diffusion of a transforming GPT. The economics is somewhat technical, revolving around the difference between price/value-driven complementarities and technological complementarity. The former, termed Hicksian (gross) complementarities, require that demand for technology 'y' rises when the price of technology 'x' falls. The latter requires that cooperating technology 'x' be redesigned for advance in technology 'y'. The former applies in an atemporal setting, where producers can select from the universe of all technologies, the latter to a world in which major new technologies emerge in particular (path dependent) processes.

For ICT, technological complementarities generate new-to-the-world technological platforms through linking the activities of the semiconductor sector (GPT-producing) and the ICT application (GPT-using) sectors. For transforming GPTs, sustained growth requires mutual dependency between the innovation in the GPT-producing and GPT-using sector. Innovation in one stimulates innovation in the other. For ICT, this creates vertical externalities, ignored in the perfect market pricing model. Moreover, horizontal externalities arise because the more application sectors pay for and use ICT, the lower the price of the GPT — the consequence being a free-rider incentive for application sectors to delay purchase, and a socially sub-optimal level of innovation. The analysis can be extended to show the likelihood of coordination failure and the serious consequences for economic growth if such coordination issues are not addressed. The existence of such market failures may explain why policies to realise the potential of ICT are critical elements in the growth policies of most nations.

The separability of producer and user contributions to TFP growth is central to both US and Australian growth accounting estimates. Such separability allows the relative importance of

ICT use and ICT production to be estimated. Such estimation is assumed when aggregate TFP growth is estimated as the (weighted) sum of the TFP growths in the statistically separate industries that produce and use ICT. The resulting estimates depend on the accurate separation of the ICT producing and using activities by industry of output, a process more easily achieved in theory than practice.

However, it is not just the industrial classification that can distort the distribution of TFP growth between production and use. Prices can also be a source of bias. Movement in prices are important because they distinguish between:

- the return to ICT producers from the new technological and scale advances that are embodied in successive vintages of ICT capital; and
- the true value of such embedded advances to the users, upgrading their ICT capability in response to lower ICT prices, increased capability and external opportunity.

The large sustained declines in real prices of 15–30 per cent per year found for ICT by the OECD (2004) suggests the role that prices are assumed to play in conventional economic analysis may fail. Moreover it suggests that dynamic optimisation is more critical than the static resource allocation of general equilibrium theory. What principally drives innovative growth may not be a-temporal optimisation between ICT and other inputs, but the timing of the upgrades. Ahn (2003) uses dynamic optimisation techniques to identify the optimum upgrade path. His model fits many of the observed characteristics of ICT. It demonstrates, for example, that realising the potential of general purpose technology through investment is neither instantaneous nor costless for most users.²⁰

Another important issue that affects the economic assumption of independence between GPT-based ICT-innovation and the 'specific-purpose' user innovation is uncertainty, especially as it relates to further evolution. The market, in conjunction with government as user, standard setter and regulator, sets forward technological projections to reduce risk, assist efficiency and avoid unnecessary duplication. Other issues relate to the possibility of market power by ICT producers or users, interdependence between research investments of ICT producers and their ICT customers, and risk aversion among producers and users. Observers see technological rivalry for temporary IP protection over standards in a winner-take-all race as what drives competition. Price competition is not the primary driver.

The traditional assumption that price separates independent producers and users doesn't apply in the Kline Rosenberg (1986) chained link model of innovation. Neither does it exist in the Lipsey structuralist-evolutionary model for government technology policy. The

²⁰ Ahn's (2003) model, verified empirically, uses a measure of ISTC and shows this is inversely correlated with the true TFPG bonus. This provides support for a similar finding by Carlaw (2004).

reliance of innovation on interaction between buyer and seller is well recognised in the empirical literature, by David Teece and others.

The use of the producer/user separation through equilibrium market prices is a necessary first construct when looking at National Accounts data. But this assumption should be tested empirically. In particular, for ICT, the bipolar separation of 'enabling technology' from 'innovative business' misses the middle ground where the most crucial innovation occurs and where innovation research should be focused. It is here that technological competition drives change, as ICT service firms work with businesses to convert tacit business practice to codified routines that, in turn, become 'general purpose' business systems that are built around information systems (IS). The assumption of a price divide between supplier of user application software and user may therefore be problematic. The IT service companies supplying the software typically interact closely with user firms in developing IS solutions.

Firm level studies show that success comes from focussing on innovation and the dynamic creation of new products rather than the static reallocating of existing resources. The marginal trade-off between increasing the quantity of one existing input at the expense of another is less critical to growth than the creation of a new product or service. In other words, the static optimisation associated with price substitution between existing inputs is much less critical than combining existing technologies to produce new ones. For example, minimising the average cost at fixed prices of a mix of communication and the IT services, will not deliver the sustained growth that is expected from their convergence to form new products, such as 'web services'.²¹

2.6.2 Evolutionary considerations

Baumol (2004), Griliches (1997) and Schreyer (2001) all warn of the shortcomings of neoclassical analysis for the study of innovation. All suggest an evolutionary perspective is needed to provide balance. The OECD Productivity Manual quotes Griliches, 2000:

We can take productivity growth calculation and allocate it in great detail to the various missed components, reducing thereby the role of the 'unallocated' residual. But this, while very instructive and valuable, only shifts the problem to a new set of questions: why was there all this investment in human capital? Will it continue? Where did the improvements in capital equipment come from? [...] Real explanations will come from understanding the sources of scientific and technological advances and from identifying the incentives and circumstances that brought them about and that facilitated their implementation and diffusion.

The manual then continues:

In a quite fundamental sense, innovations and information asymmetries are one and the same phenomenon. Indeed, such asymmetries can scarcely be termed market

²¹ This is somewhat different to bundling, where the bundle may be cheaper than individual components if separably available, and to clustering of inputs.

imperfections when they are necessary conditions for any technical change to occur in a market economy ... equilibrium concepts may be the wrong tools to approach the measurement of productivity change, because if there truly was equilibrium, there would be no incentive to search, research and to innovate, and there would be no productivity growth. ... productivity measurement allows one to quantify—in a systematic and consistent way—the proximate sources of growth. It has explanatory power in that it captures the workings of supply of, demand for and substitution between categories of measurable inputs. At the same time, growth accounting has to be complemented by institutional, historical and case studies if one wants to explore some of the underlying causes of growth, innovation and productivity change. (Schreyer, 2001, para 204–6)

The evolutionary school assesses importance in a very different way to growth accounting.²² Its conceptualisation of a GPT draws on the ideas of Basu, Fernald, Oulton and Srinivasan (2003). This research describes the unexpected cross linkages associated with transforming GPTs, linkages often described as ‘technological complementarities.’²³

Christensen (1997) documents the difficulty in appreciating the competitive potential of an emerging technology, raising awareness of what may be misleadingly called ‘disruptive technologies.’ Christensen (2004) cites Andy Groves of Intel suggesting that ‘You shouldn't call them disruptive technologies, you should call them straight, boring technologies.’ The remark demonstrates that the search for emerging technologies with long-run strategic potential is ‘business as usual’ for many firms.

The unexpected action at a distance described by Basu, Fernald, Oulton and Srinivasan clearly distinguishes this evolutionary ICT concept from the neoclassical one. And it certainly can give different answers to the question of importance. Neoclassical growth theory does not recognise the long-run potential importance arising from small inconspicuous beginnings. Size is important. It is only when a technology begins to mature that it will make an observable contribution to growth. Assessing the importance of a GPT by the size of its contribution in its early state may mislead growth-oriented policy.²⁴

²² For example, Metcalfe (1997) finds that the difference between the neoclassical growth theory and evolutionary growth theory matters, ‘not least because it influences deeply our interpretation of the historical record, and our understanding of the channels through which policy initiatives shape economic growth.’ In respect to knowledge-productivity relationship, Metcalfe (2001) argues ‘From the perspective of the growth-knowledge relation, markets take on a new light. We see them not as devices to optimally allocate given resources to given ends, but as institutions to facilitate change, to permit entrepreneurship, to encourage challenges to the established order. Thus they are devices for keeping the economy ordered, but out of equilibrium, they are frameworks that shape ongoing structural change. Nor are market institutions given. They have to be established, and their establishment, growth, stabilization and decline involve the investment of real resources in market making activity.’

²³ Technological Complementarities are described in Lipsey and Carlaw 2002.

²⁴ As pointed out by Nelson (2005), growth theories that focus on an aggregate measure of growth, such as GNP per capita, are blind to what is going on beneath the aggregate, where differing rates of advance in different sectors, and the birth and death of industries are an essential part of the growth process. The broad theory of economic growth that Nelson presents sees the process as involving the co-evolution of technologies, institutions, and industry structure.

2.7 Conclusion

This chapter sought to present a broad perspective on the role of ICT in productivity growth, economic growth and prosperity.

A key performance indicator of economic progress is productivity growth. However, there are grounds for believing that this indicator, as usually measured, is flawed especially in application to ICT, in part because of unresolved issues in the measurement of intangible capital particularly important in service industries. Some see measurement as a possible explanation of the long-run cycles and golden ages of the MFP time series. Moreover, the importance of transforming agents like ICT only become apparent when they become proportionately significant, yet technical complementarity suggests that ICT has played a catalytic role in the assisting growth even when a small proportion of the capital stock.

Explanations for growth phenomena are to be found in evolutionary economics and complexity theory rather than atemporal mainstream economics. The evolutionary school includes deep studies on innovation including those associated with fundamental transformations.

History suggests that a very important source of the high growth in living standards over the last two hundred years is the new knowledge capital embedded in work practices and social norms, not simply the accumulation of capital as conventionally measured. Discoveries such as the water wheel, steam power and electricity represented fundamental and irreversible improvements and were associated with a massive restructuring of production and social systems. Perhaps the most fundamental of all general purpose technologies are those associated with ICT. This may be why research is increasingly focussing on ICT as a transforming GPT marking the transition to an information economy. We conclude, therefore, that there are strong grounds to encourage the continued evolution and diffusion of ICT, and to support the development of new comprehensive frameworks to analyse the impacts.

References (chapter 2)

- Aghion, Philippe and Peter Howitt (1998), 'On the Macroeconomic Effects of Major Technological Change', in Helpman, E. (1998) (ed), pp121–144.
- Ahn, Sanghoon (2001) Firm Dynamics and Productivity Growth: A Review of Micro Evidence from OECD Countries, Working Paper No. 297 (Economics Department, OECD, Paris)
- Ahn, Sanghoon (2002) Competition, Innovation and Productivity Growth: A Review of Theory and Evidence., *OECD Working Paper*, ECO/WKP(2002)3.
- Ahn, Sanghoon (2003) 'Technology Upgrading with Learning Cost', *Center for Economic Institutions Working Paper Series*, No. 2003–21. See also 'Technology Upgrading with Learning Cost: A Solution for Two Productivity Puzzles' (1999) OECD Economics Department Working Paper No. 220 at <http://ssrn.com/abstract=193173>. Also conference papers to 'Productivity Growth and the Macroeconomy' NBER 2001 Summer Institute workshop and the DRUID 2003 Summer Conference.
- APEC (2003) *Drivers of the New Economy in APEC: Innovation and Organisational Practices* APEC Economic Committee at http://www.apec.org/content/apec/apec_groups/other_apec_groups/new_economy_-_e-apec.html
- Arora, Ashish, Andrea Fosfuri and Alfonso Gambardella (2001) *Markets for Technology: The Economics of Innovation and Corporate Strategy*, MIT Press (esp chapter 6: 'Markets for Technology and the Size of the Market: Adam Smith and the Division of Innovative Labour Revisited', pp.143–67)
- Australian Treasury (2001) 'A More Productive Australia: Technology and Policy', *Round Up of Winter* p.37 (extract from Budget Paper 1 of 2000–2001) at <http://www.treasury.gov.au/documents/103/PDF/roundup.pdf>.
- Balk, Bert M. (2001) 'The Residual: On Monitoring and Benchmarking Firms, Industries, and Economies with respect to productivity' Inaugural address on accepting the appointment of professor of business administration, in particular the measurement of price, quantity and productivity changes and economic statistical research, supported by Statistics Netherlands, at the Rotterdam School of Management, 9th November, 2001. <http://www2.eur.nl/WebDOC/doc/iarm/erimia20020909150511.pdf>
- Balk, Bert M. (2003) 'The Residual: On Monitoring and Benchmarking Firms, Industries, and Economies with Respect to Productivity'. *ERIM Report Series* Reference No. EIA-2002–07–MKT, 31 March at <http://ssrn.com/abstract=678245>
- Bartelsman, Erik J and M. Doms (2000) 'Understanding Productivity: Lessons from Longitudinal Microdata' *Journal of Economic Literature* XXXVIII, p.569–94
- Basu, Susanto, John G. Fernald, Nicholas Oulton and Sylaja Srinivasan 2003 'The Case of the Missing Productivity Growth: Or, Does Information Technology Explain why Productivity Accelerated in the United States but not the United Kingdom?' NBER Working Paper No. 10010, forthcoming in NBER Macroeconomics Annual 2003 edited by Mark Gertler and Kenneth S Rogoff, MIT Press for National Bureau of Economic Research .
- Bernanke, B and Refet Gurkaynak. 2001. 'Is Growth Exogenous? Taking Mankiw, Romer, and Weil Seriously.' *National Bureau of Economic Research Working Paper: 8365*

- Bresnahan, Timothy F. and Manuel Trajtenberg (1995) 'General Purpose Technologies: 'Engines of Growth'?' *Journal of Econometrics*, 65(1, Special Issue): 83–108 First published as Bresnahan, T. and E. Trajtenberg, (1992) 'General Purpose Technologies: Engines of Economic Growth?' *NBER Working Paper* No. 4148.
- Breunig, Robert and Marn-Heong Wong (2004) *Australia's Firm-level Productivity—a New Perspective*. <http://ideas.repec.org/p/ecm/ausm04/177.html>
- Brynjolfsson, Erik and Lorin Hitt (2003) 'Computing Productivity: Firm-Level Evidence' *Review of Economics and Statistics* November at http://s.ssrn.com/sol3/s.cfm?abstract_id=290325
- Casserley, Dominic (2004) 'Helping Britons work smarter' *The McKinsey Quarterly*, No. 3, pp. 112–6 adapted from Casserley, Dominic (2004) 'How to achieve Wal-Mart productivity in the UK, *The Times* of London, 22nd March, and based on research undertaken with the Centre for Economic Performance of the London School of Economics.
- Coelli, Timothy J, DS Prasado Rao, Christopher J O'Donnell and George E Battese (2005) *An Introduction to Efficiency and Productivity Analysis*, 2nd ed, Springer, at <http://www.springer.com/sgw/cda/frontpage/0,11855,4-40545-22-60399000-0,00.html>
- Cotis, Jean-Philippe (2004) 'Foreword', prefacing OECD (2004b), pp.3–4.
- Dai, Qizhi, Robert J. Kauffman, Salvatore T. March (2005) Valuing Information Technology Infrastructures: A Growth Options Approach, Forthcoming in *Information Technology and Management*, April at http://misrc.umn.edu/workingpapers/fullpapers/2005/0510_040405.pdf
- Daly, Mary and Fred Furlong (2005) 'Gains in U.S. Productivity: Stopgap Measures or Lasting Change?' *FRBSF Economic Letter*, No. 2005–05, March 11, 2005, Center for the Study of Innovation and Productivity at FRBSF's Economic Research Department. <http://www.frbsf.org/publications/economics/letter/2005/el2005-05.pdf>
- David, Paul (1991). 'Computer and Dynamo: The Modern Productivity Paradox in a Not-too-distant Mirror', in *Technology and Productivity* OECD, Paris.
- David, Paul and Gavin Wright (1999) 'General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution', *University of Oxford Discussion s in Economic and Social History*, Number 31.
- Davis, Graeme and Robert Ewing (2005) 'Why has Australia done better than new zealand? Good luck or good management?' Treasury Working Paper2005 — 01, based on a paper to *Productivity: Performance, Prospects and Policy* workshop, Wellington, New Zealand, 29 July 2004 at <http://www.treasury.gov.au/documents/949/RTF/Treasury%20Working%20Paper%202005-01.rt>
- Dimmick, John and Tao Wang (2005) 'Towards an economic theory of media diffusion based on the parameters of the logistic growth equation' (2005) *Journal of Media Economics*, 18 (4) pp.233–246

- Dorgan, Stephen J, and John Dowdy (2004) 'When IT lifts Productivity' *McKinsey Research Brief*, pp14–6 draws also on Dorgan, Stephen J, and John Dowdy (2002) 'How good management raises productivity' *The McKinsey Quarterly*, No. 4, pp9–11. and based on research undertaken with Nick Bloom and John van Reenan of the London School of Economics.
- Dosi, Giovanni (1988), 'Sources, Procedures, and Microeconomic Effects of Innovation', *Journal of Economic Literature*, 26 (3): pp. 1120–1171.
- Eliasson, Gunnar, Dan Johansson and Erol Taymaz (2002) '*Industrial Dynamics of the New and Old Economy—who is embracing whom?*' to DRUID conference, Copenhagen, 6–8 June, 2002, a revision of '*Simulating the New Economy*' published by KTH, Stockholm. This is part of a larger project on *The Macroeconomic Effects of Computer and Communications (C&C) Technology* financed by the Swedish Transport & Communications Research Board (Kfb).
- Enos, John L. (2003) 'Sporadic Innovation and Historical Continuity', *Prometheus* 21 (2) June pp.161–75.
- Fahy, John and Alan Smithee (1999) 'Strategic Marketing and the Resource Based View of the Firm' *Academy of Marketing Science Review* [Online] 1999 (10) at: <http://www.amsreview.org/articles/fahy10-1999.pdf>
- Farrell, Diana, Heino Fassbender, Thomas Kneip, Stephan Kriesel and Eric Labaye (2003) 'Reviving French and German Productivity' *The McKinsey Quarterly*, No. 1 McKinsey and Company. This McKinsey Global Institute study contains three industry comparisons with the US, viz. (i) Bouvard, Francois and Stephan Kriesel 'French and German Trucking: IT for the long haul' (pp 53–5): and (ii) Kriesel, Stephen, Peter Leukert and Tidjame Thiam (2003) 'French and German Banking: Showing IT Strengths' (pp 50–2) and (iii) Telecom: Advantage France and Germany at <http://www.euractiv.com/Article?tcmuri=tcm:29-117644-16&type=Analysis>. The findings were published in Australia as Farrell, Diana (2004) : 'The real new economy' *Australian Financial Review* at <http://afr.com/articles/2004/01/27/1075088013804.html> drawn from the Harvard Business Review
- Fernald, John and Shanthi Ramnath (2003) 'Information Technology and the U.S. Productivity Acceleration', *Chicago Fed Letter*, The Federal Reserve Bank of Chicago September 2003 Number 193. http://www.chicagofed.org/publications/fedletter/2003/cflsept2003_193.pdf
- Freeman, Chris and Francisco Louca (2001) *As Time Goes By: From the Industrial Revolution to the Information Revolution*, Oxford University Press, Oxford, UK
- Fuss, Melvyn and Leonard Waverman (2005) *The Networked Computer: The Contribution of Computing and Telecommunications to Economic Growth and Productivity*, A Digital Transformations Working Paper at http://www.london.edu/assets/documents/NetworkedComputer_WavFuss.pdf
- Gelauff, George MM (2003) *Social capital: an indispensable asset in the knowledge-based economy*, Workshop on Social Capital and Economic Development, University of Tilburg, March 27 at <http://spitswww.uvt.nl/web/fsw/lustrum/papers/gelauff.pdf>
- Gera, Surendra and Wulong Gu (2004) 'The Effect of Organisational Innovation and Information Technology on Firm Performance' *International Productivity Monitor*, No. 9, Fall.

- Gera, Surendra, Wulong Gu and Jenness Cawthray (2003) *Innovative Business Strategies and Firm Performance in the New Economy*, as chapter 3 of APEC (2003).
- Gordon, Robert J. (1990) *The measurement of durable goods prices*, University of Chicago.
- Gordon, Robert J. (2003a) *Five Puzzles in the Behaviour of Productivity, Investment and Innovation*, draft chapter for World Economic Forum, Global Competitiveness Report 2003–04, at <http://faculty-web.at.northwestern.edu/economics/gordon/WEFTEXT.pdf>, September and reported in *The Economist* of 13th September 2003.
- Greenspan (2000) Remarks by Chairman Alan Greenspan on *The revolution in information technology* before the Boston College Conference on the New Economy, March 6, 2000 at www.federalreserve.gov/boarddocs/speeches/2000/20000306.htm
- Greenwood, Jeremy, Zvi Hercowitz and Per Krusell (1997) 'Long-run implications of investment-specific technological change', *American Economic Review*, v 87, pp 342–62.
- Greenwood, Jeremy, Zvi Hercowitz and Per Krusell (2000) 'The role of investment-specific technological change in the business cycle', *European Economic Review*, v 44, pp 91–115.
- Gregor, Shirley, W. Fernandez, D. Holtham, M Martin, S. Stern, M. Vitale and G. Pratt (2005) *Achieving value from ICT: key management strategies*, Opticon Australia/ANU, DCITA Occasional Paper, DCITA at <http://www.dcita.gov.au/ie/environment/transformation>
- Gretton, Paul, Jyothi Gali and Dean Parham (2002) 'Uptake and Impacts of the ICTs in the Australian Economy: Evidence from Aggregate, Sectoral and Firm Levels' Conference Paper, OECD, Paris 9 December 2002. <http://www.pc.gov.au/research/confproc/uiict/index.html>.
- Griliches, Zvi (1996) 'The Discovery of the Residual: An Historical Note', *Journal of Economic Literature*, XXXIV, pp.1324–30.
- Griliches, Zvi (2000) *R&D, Education and Productivity: A Retrospective*, Harvard University Press.
- Hall, Peter (1994) *Innovation Economics and Evolution: Theoretical Perspectives on Changing Technology in Economic Perspectives*, Harvester Wheatsheaf, Hemel Hempstead.
- Harrod, Roy F. (1948) *Towards a Dynamic Economics* Macmillan, London.
- Helpman, Elhanan (2004) *The Mystery of Economic Growth*, Harvard University Press
- Helpman, Elhanan, (ed) (1998) *General Purpose Technologies and Economic Growth*, MIT Press, Cambridge.
- IMF (2001) *World Economic Outlook: Chapter 3 The Information Technology Revolution*, October at <http://www.imf.org/external/pubs/ft/weo/2001/02/index.htm>
- Inklaar, Robert (2005) 'Cyclical Productivity in Europe and the United States, Evaluating the Evidence on Returns to Scale and Input Utilization' Research Memorandum GD–74 Groningen Growth and Development
- Jones, Derek C. (Ed) (2003) *New Economy Handbook*, Elsevier.

- Jorgenson, Dale W and Stiroh, K J (2000b) 'Raising the speed limit: U.S. economic growth in the information age', *Brookings Papers on Economic Activity*, 1, pp 125–211.
- Jorgenson, Dale W., Mun S. Ho, and Kevin J. Stiroh (2002) 'Projecting Productivity Growth: Lessons from the U.S. Growth Resurgence.' *Federal Reserve Bank of Atlanta Economic Review* 87(3): 1–13.
- Jovanovic, Boyan and Peter L. Rousseau (2003) 'General Purpose Technologies' in forthcoming in Aghion, Philippe and Steven Durlauf eds. 2005 *The Handbook of Growth*, Elsevier.
- Kauffman, Robert J. and Ajay Kumar (2005) 'A critical assessment of the capabilities of five measures for ICT development' Working Paper No. 05/06. MISRC Working Papers Series. University of Minnesota. <http://misrc.umn.edu/workingpapers>
- King, Robert G., C. Plosser and S. Rebelo (1988) Production, growth and business cycles, I: The Basic Neoclassical Model. *Journal of Monetary Economics* 21, 196–232.
- Krupa, Frederique (1992) *The Evolution of the Telephone System: From Bell's Electric Toy to the Internet*, April 22, at <http://www.translucency.com/frede/desindex.html>
- Lavin, Bruno (2003) *Leaders and Facilitators: The New Roles of Governments in Digital Economies*, in World Economic Forum (2003) *The Global Information Technology Report 2002–3*
- Legge, John M. (1994) *The disconnect between economics and business studies: some implications for public policy formation*, Economic Society of Australia, ISSN 08120439.
- Lipsey, Richard G., Cliff Bekar and Kenneth I. Carlaw (1998) 'What Requires Explanation,' Chapter 2 in Helpman (1998).
- Lipsey, Richard G., Kenneth I. Carlaw, and Cliff Bekar (2005) *Economic Transformations: General Purpose Technologies and Long Term Economic Growth*, Oxford University Press, Oxford.
- Maddison, Angus (2005a) *The World Economy: A Millennial Perspective*, Development Centre of the Organisation for Economic Co-Operation And Development, OECD
- Maddison, Angus (2005b) *Growth and Interaction in the World Economy: The Roots of Modernity*, AEI Press, Washington. see http://www.aei.org/publications/pubID.22680.filter.all/pub_detail.asp
- McElroy, Mark W (2003) *The New Knowledge Management: Complexity Learning and Sustainable Innovation*, Butterworth Heinemann/Knowledge Management Consortium International (KMCI Press)
- McTaggart Douglas, Christopher Findlay and Michael Parkin (2004) *Economics: fourth edition*, Addison Wesley
- Melville, Nigel, Kenneth L. Kraemer and Vijay Gurbaxani (2004) 'Information Technology and Organisational Performance: An Integrative Model of IT Business Value' in *MIS Quarterly*, 28(2) at www.misq.org/archivist/vol/no28/Issue2/Melville.html
- Metcalfe, J. S. (1997) 'The evolutionary explanation of total factor productivity growth: Macro measurement and micro process' CRIC Discussion Paper No 1, June p.10

- Metcalfe, J. S. (2001) 'Knowledge of Growth and the Growth of Knowledge' Presidential Address to the 8th International J. A. Schumpeter Society Conference, Centre for Innovation and Competitiveness (CRIC) University of Manchester. p.10
- Milgrom Paul and John Roberts 1990 'The Economics of Modern Manufacturing: Technology, Strategy and Organisation' *American Economic Review*, v80 pp511–28, June.
- Milgrom Paul, Yingyi Qian and John Roberts 1991 'Complementarities, Momentum and the Evolution of Modern Manufacturing' *American Economic Review*, v81(2) pp.84–88, May
- Milgrom, Paul and John Roberts (1995) Complementarities and Fit Strategy: Structure and Organisational Change in Manufacturing, *Journal of Accounting and Economics*, No. 19, pp 179–208.
- Mokyr, Joel (2002) *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton University Press,
- Mukoyama, Toshihiko (2004) *Endogenous Depreciation, Mismeasurement of Aggregate Capital, and the Productivity Slowdown* mimeo, Concordia University August.
- Murphy, Kevin, Craig Riddell and Paul Romer (1988) 'Wages and Technology in the United States and Canada' in Helpman E. (ed.) (1988)
- Murphy, Marian (2002) *Industry Issues: Organisational Change And Firm Performance*, STI Working Paper 2002/14, OECD, Paris at [http://www.oalis.oecd.org/oalis/2002doc.nsf/linkto/dsti-doc\(2002\)14](http://www.oalis.oecd.org/oalis/2002doc.nsf/linkto/dsti-doc(2002)14)
- Nahuis, Richard and Henry van der Wiel (2005) *How Should Europe's ICT Ambitions look like? An Interpretative Review of the Facts*, Discussion Paper 2, Tjalling C. Koopmans Research Institute, Utrecht School of Economics, April, at <http://www.uu.nl/content/05-22.pdf>
- Nelson, Richard and Stanley G Winter (1982) *An Evolutionary Theory of Economic Change*, Cambridge: Harvard University Press
- Nelson, Richard R (2005 forthcoming December) *Technology, Institutions, and Economic Growth*, Harvard University Press,.
- Nelson, Richard R. (1990) 'Capitalism as an engine of progress', *Research Policy*, v.19.
- Nelson, Richard R. (1994) *An Agenda for Formal Growth Theory*, IIASA Working Paper WP-94-085 International Institute for Applied System Analysis at <http://www.iiasa.ac.at>
- Nelson, Richard R. (1995), 'Recent Evolutionary Theorizing about Economic Change', *Journal of Economic Literature*, 33: 48–90.
- Nelson, Richard R. (1996) *The Evolution of Competitive or Comparative Advantage: A Preliminary Report on a Study*, IIASA Working Paper WP-96-21 International Institute for Applied System Analysis, February at <http://www.iiasa.ac.at>
- Nelson, Richard R. (1996) *The Sources of Economic Growth*, Harvard. University Press, Cambridge, MA
- North, Douglass C. (2005) *Understanding the Process of Economic Change (Princeton Economic History of the Western World)*, Princeton University Press

- OECD (2000) *Productivity Growth in ICT Producing and ICT-using Industries – a Source of Growth Differentials in the OECD?*, OECD Directorate for Science, Technology and Industry, Paris.
- OECD (2001) *The New Economy: Beyond the Hype, The OECD Growth Project*, OECD, Paris.
- OECD (2002) 'Chapter VI. Product Market Competition and Economic Performance' at <http://www.oecd.org/dataoecd/55/34/2487682.pdf> and Chapter VI VI. Intra-Industry and Intra-Firm Trade and The Internationalisation of Production at <http://www.oecd.org/dataoecd/6/18/2752923.pdf> in *OECD Economic Outlook 71*
- OECD (2003a) *ICT and Economic Growth: Evidence from OECD Countries, Industries and Firms*, OECD, Paris.
- OECD (2003b) *The Sources of Economic Growth in OECD Countries*, OECD, Paris.
- OECD (2004a) *The Economic Impact of ICT: Measurement, Evidence and Implications*, OECD, Paris.
- OECD (2004b) *Understanding Economic Growth: Macro-level, Industry-level, Firm-level*, OECD Paris.
- Oliner, Stephen D. and Daniel E. Sichel (1994) 'Computers and Output Growth Revisited: How Big Is the Puzzle?' *Brookings Papers on Economic Activity*, 2: 1994, 273-334.
- Oliner, Stephen D. and Daniel E. Sichel (2000) 'The resurgence of growth in the late 1990s: is information technology the story?', *Journal of Economic Perspectives*, v 14 (Fall) pp 3–22.
- Oliner, Stephen D. and Daniel E. Sichel (2000b) 'The resurgence of growth in the late 1990s: is information technology the story?', *Journal of Economic Perspectives*, v 14 (Fall) pp 3–22.
- Oliner, Stephen D. and Daniel E. Sichel (2002a), 'Information Technology: Where are we now and where are we going?' *Federal Reserve Bank of Atlanta Economic Review*, 87(3), pp. 15–44.
- Oulton, Nicholas (2004) Investment-specific technological change and growth accounting, Working Paper No. 213, Bank of England, London
- Parham, Dean (1999) 'The New Economy? A Look at Australia's Productivity Performance' Productivity Commission Staff Research Paper, AusInfo, Canberra.
- Parham, Dean (2004a) 'Productivity taking a breather' *Australian Financial Review*, 26 May 2004 p.63.
- Parham, Dean (2004b) 'Sources of Australia's Productivity Revival', *Economic Record*, 80(249), pp.239–57.
- Parham, Dean, Paul Roberts and H. Sun. (2001) *Information Technology and Australia's Productivity Surge*, Productivity Commission Staff Research Paper, Canberra.
- Perez, Carlota (2002) *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages*, Edward Elgar, Cheltenham.
- Productivity Commission (2003) *Trends in Australian Manufacturing*, Commission Research Paper, AusInfo, Canberra.
- Quiggin, John (2001) 'The Australian Productivity 'Miracle': A Sceptical View', *Agenda* 8(4), pp. 801–17.

- Rosenberg, Nathan and Manual Trajtenberg (2003) 'A General Purpose Technology at Work: The Corliss Steam Engine in the late 19th Century US'. forthcoming, *Journal of Economic History* at http://www.tau.ac.il/~manuel/R&D_course/
- Sato, R. and M. Beckman (1968) 'Neutral Inventions and Production Functions' *Review of Economic Studies*, 35, pp. 57–66.
- Schmidt, Gordon (2004) *Dynamics of Endogenous Growth: A Case Study of the Romer Model*, Elsevier.
- Schreyer, Paul (2001), *OECD Productivity Manual: A Guide to the Measurement of Industry-Level and Aggregate Productivity Growth*, OECD, Paris at http://www.oecd.org/catch_404/?404;http://www.oecd.org/subject/growth/production-manual.pdf .
- Schumpeter, Josef A. (1934) *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest and the Business Cycles*, Harvard Business Press: Boston.
- Shannon, Claude, introduced by Warren Weaver (1948, 1998), *Mathematical Theory of Communication (Paperback)*, Board of Trustees, University of Illinois, also reprinted with corrections from *The Bell System Technical Journal*, Vol. 27, pp. 379–423, 623–656, July, October, 1948 at <http://cm.bell-labs.com/cm/ms/what/shannonday/shannon1948.pdf>
- Silva, Sandra Tavares (2004), 'On evolutionary technological change and economic growth: Lakatos as a starting point for appraisal' at http://www.fep.up.pt/investigacao/workingpapers/04.03.12_WP139_SandraSilva.pdf.
- Solow, Robert M. (1963) *Capital Theory and the Rate of Return*, North Holland, Amsterdam.
- Tuomi, Ilkka (2002) *Networks of Innovation: Change and Meaning in the Age of the Internet*, Oxford University Press
- Tuomi, Ilkka (2004) 'Knowledge Society and the New Productivity Paradigm: A Critical Review of Productivity Theory and the Impacts of ICT', *IPTS Working Paper*, 11.2.2004.
- Van Alstyne, Marshal and Nathaniel Bulkley (2004) 'Why Information Should Influence Productivity', chapter 6 0 of Castells, Manuel (2004) (ed.) *The Network Society: A Cross-Cultural Perspective*; Edward Elgar Publishing.
- UN Dept of Economic and Social Affairs (2005) *Understanding knowledge societies* Division of Public Administration and Development Management, United Nations.
- Wilson, Daniel J. (2004) 'IT and beyond: The contribution of heterogeneous Capital to Productivity' Working Paper 2004–13 Federal Reserve Bank of San Francisco.

Chapter 3

3 Erwin Diewert and Denis Lawrence¹

The role of ICT in Australia's economic performance

An investigation of assumptions influencing the productivity estimates²

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An early version of the research was presented as an Invited Paper, to Plenary Session #2: 'Productivity Growth and ICT' at the Asia Pacific Productivity Conference, Brisbane, 14 –16 July 2004.
Estimates from this research are available in tabular form from the Information Economy Division of DCITA.

3 Diewert and Lawrence

3.1 Introduction

The then National Office for the Information Economy (NOIE)¹ ... posed two central questions regarding the role of information and communications technology (ICT) in productivity growth:

- Do the assumptions underlying the index-based productivity measures adequately capture the ‘Information Revolution’ characteristics of ICT?

and

- Can the contribution of ICT to the competitive transformation of the economy be identified from these productivity measures?

On the first question, recent work by Lipsey and Carlaw (2004) and Lipsey (2005) has criticised the Jorgenson and Griliches (1967) traditional growth accounting methodology for assuming that firm, industry and economy wide technology sets are subject to constant returns to scale and that markets are perfectly competitive. Lipsey (2005) writes:

Non convexities are a key part of the desirable growth process. Scale effects, rather than being imperfections to be offset, are some of the most desirable results of new technologies. Entry costs for new products and new firms that cause non-convexities are the costs of innovation and the sources of some of the rents that drive innovating behaviour.

In fact, the assumptions of constant returns to scale and perfectly competitive markets that are embedded in the foundations of much of the modern productivity literature have long been recognised as unsatisfactory. For instance, in the forthcoming Heckman-Leamer Handbook of Econometrics, Diewert and Nakamura (2005) write:

It is true that in a world where all factor inputs are paid their marginal products and there is no potential for reaping increasing returns to scale, then the only way in which growth in output could occur would be through increased input use or through changes in external circumstances. This is the world assumed by Solow (1957) and many others....However, this definition of productivity growth seems unlikely to satisfy Harberger’s (1998, p.1) recommendation that we should approach the measurement of productivity by trying to ‘think like ... a CEO.’ The perspective of the CEO could be better accommodated by allowing for a fuller range of market imperfections, common goods ..., increasing returns to scale, and the information investments that aid businesses in taking advantage of these other factors that are assumed away in many empirical studies. ...The challenge for index number theorists is to develop models that incorporate rather

¹ The community and business aspects of NOIE were incorporated into DCITA in April 2004

than assume away what economic practitioners view as some of the main means by which total factor productivity improvement is accomplished.

The problem has been to find theoretically and empirically feasible ways of allowing for departures from these assumptions.²

If one takes a pragmatic approach to productivity measurement and simply defines productivity growth as an index of output growth divided by an index of input growth, as recommended by Diewert (1992) and others including Balk (2003, section 4) and Schreyer (2001, section 2.3), then this measure includes the effects of both increasing returns to scale and technical progress. However, for many policy purposes, it is of interest to separate the contributions of returns to scale and technical progress on productivity growth.

Generally speaking, either an engineering approach or an econometric approach must be used in order to separately estimate the effects of returns to scale and technical progress. However, traditional econometric approaches are plagued by multicollinearity; ie usually the index of technical progress and output both grow over time and it is difficult to disentangle the effects of technical progress (a shift in the production function) and returns to scale.

In this report we develop a new econometric approach using a multi-equation monopolistic markup model which provides a better basis for separately identifying the effects of technical change and returns to scale. This approach builds on and extends important advances by Diewert and Fox (2005a) in the treatment of monopolistic market conditions and returns to scale.³ It provides a practical test of one of the major criticisms of traditional productivity measurement and, hence, provides an empirical basis for testing whether the growth accounting method is understating the likely contribution of ICT to economic growth.

On the second central question posed by NOIE, index number methods for estimating the contribution of ICT to productivity growth rely on a number of other assumptions that may not be satisfied for this dynamic input. In particular, as ICT is a durable input, its price is some form of user cost. User costs rely on a large number of assumptions, which are probably not satisfied for this particular input.⁴ Hence, in this report we allow for a divergence between the user cost of ICT

² Others who have questioned and pushed for ways of relaxing the assumptions of constant returns to scale and perfect markets include Griliches (1963) (1964) (1967), Diewert (1974) (1976) (1978), Caves, Christensen and Swanson (1980) (1981), Caves, Christensen and Diewert (1982a) (1982b), Panzar (1989), Hall (1988) (1990), Klette (1999), Morrison and Siegel (1997), Yoshioka, Nakajima and Nakamura (1994), Bartelsman (1995), Nakajima, Nakamura and Yoshioka (1998) (2001), Diewert and Fox (2005a) (2005b), Fox (2005), and Diewert et al. (2005).

³ Diewert and Fox (2005a) correct and extend the treatment of markups and returns to scale in the work of Hall (1988) (1990) and of Basu and Fernald (1997) (2002). Our approach builds as well on advances in the estimation of returns to scale due to Yoshioka, Nakajima and Nakamura (1994), Nakajima, Nakamura and Yoshioka (1998) (2001) and Diewert et al. (2005).

⁴ For material on constructing capital aggregates and user costs for productivity measurement purposes, see Jorgenson (1963) (1986) (1989) (1990) (2001), Hall and Jorgenson (1967) and Diewert (1992; 191-195) (2004a) (2004b) and Diewert and Lawrence (2000).

and the value of ICT in production for each major Australian industry. This divergence is mathematically equivalent to a monopolistic markup on ICT inputs; ie in both cases, there is a divergence between selling or purchase price and the marginal cost (in the monopoly case) or the contribution to profits (in the ICT input case). Taking advantage of this insight, we modify the monopolistic markup model by taking the ICT input out of the list of competitive inputs in the cost function and treat ICT as a negative monopolistic net output. If the markup parameter for ICT turns out to be 0, then the usual user cost assumptions are justified and no disequilibrium in the ICT market is found. However, a more likely hypothesis is that ICT inputs are worth more than their price. That is, they contribute more to the value of output at the margin than their marginal cost. The model we develop can be adapted to test this hypothesis for Australian industries, provided the required data are available. This provides a quantitative framework for testing whether conventional estimates of the contribution of ICT significantly understate its importance.

In the following section of the report we develop the theoretical model used to examine the extent of returns to scale and whether there is disequilibrium in the market for ICT inputs. In section 3 we review the data used and key characteristics of each sector's productivity performance. We then present our econometric results in section 4 before drawing some broad conclusions and identifying priorities for future research in section 5.

3.2 Methodology

3.2.1 The basic production function methodology

Our goal in this is to attempt to accomplish two things:

- to decompose Australian industry total factor productivity growth (TFPG) into a part that is due to technical change (a shift in the production function) and a part that is due to non-constant returns to scale (a movement along the production function); and
- to determine whether ICT inputs contribute more or less to output growth than their cost.

Our approach relies on the econometric estimation of a system of non-linear equations and is, thus, more complex than some of the single equation approaches that have recently been developed to examine markup and returns to scale factors such as Diewert and Fox (2005a) (2005b), Basu and Fernald (1997) (2002), and Hall (1988) (1990).

In order to minimise the number of parameters that must be estimated, we have imposed some simplifications on the Australian sectoral data. We have aggregated into one all non-ICT inputs (denoted by x_1). Likewise, we have aggregated into one all ICT inputs (denoted by x_2). We assume that there is an aggregate industry production function f in each sector of the form $y = f(x_1, x_2, t)$ for period t . We treat each industry as having only one output (call it y). This simplification also allows

us to adopt a production function framework for our analysis, yielding productivity results that are more transparent than for dual representations⁵. We also assume that the industry faces an aggregate inverse demand function for its output in period t of the form $p = P(y, t)$, where p is the selling price in period t if y units are placed on the market during that period and $P(y, t)$ is the industry inverse demand function.

If there are increasing returns to scale in the industry, we cannot assume competitive profit maximising behaviour, since it is well known that competitive behaviour is not consistent with this situation. Hence, we consider the following *period t monopolistic profit maximisation problem*:

$$(1) \max_x P[f(x, t)]f(x, t) - w_1^t x_1 - w_2^t x_2$$

where $x \equiv [x_1, x_2]$. The first order necessary conditions for the period t input vector $x^t \equiv [x_1^t, x_2^t]$ to solve (1) are:

$$(2) p^t \nabla_x f(x^t, t) + \{\partial P[y^t, t]/\partial y\} y^t \nabla_x f(x^t, t) = w^t; \quad t = 0, 1, \dots, T$$

where $p^t \equiv P[y^t, t]$ is the period t output price, $y^t \equiv f(x^t, t)$ is the period t output produced, $x^t \equiv [x_1^t, x_2^t]$ is the period t input vector, $w^t \equiv [w_1^t, w_2^t]$ is the period t input price vector and $\nabla_x f(x^t, t) \equiv [\partial f(x^t, t)/\partial x_1, \partial f(x^t, t)/\partial x_2]$ is the vector of first order partial derivatives of the period t production function with respect to the components of the input vector.

It should be the case that the inverse demand curve is downward sloping so that

$$(3) \partial P(y^t, t)/\partial y \leq 0; \quad t = 0, 1, \dots, T.$$

If this is the case, then we can define the period t non-negative *markup* m^t as follows:

$$(4) m^t \equiv - [\partial P(y^t, t)/\partial y] y^t / P(y^t, t) \geq 0; \quad t = 0, 1, \dots, T.$$

Note that m^t is an elasticity (it gives minus the percentage change in selling price due to a one percent change in the output quantity supplied to the market) and so it is a pure number. We use the markup m^t to define the *markup factor* M^t as follows:

$$(5) M^t \equiv 1 - m^t; \quad t = 0, 1, \dots, T.$$

We assume that M^t is greater than 0 for each t and it should be equal to or less than 1.⁶

If we make use of (4) and (5), we can rewrite equations (2) as follows:

$$(6) w^t = p^t M^t \nabla_x f(x^t, t); \quad t = 0, 1, \dots, T.$$

⁵ On the tradeoffs from using a production function versus other possible frameworks, see Diewert et al. (2005).

⁶ M^t will equal 1 if m^t equals 0 so that we have competitive behaviour in this case.

Now divide both sides of (6) by the period t output price p^t , assume for the time being that the elasticity of demand is constant over time, and then the resulting two equations become the following two estimating equations (once an appropriate functional form for f is specified):

$$(7) \quad w_1^t/p^t = M \partial f(x_1^t, x_2^t, t)/\partial x_1; \quad t = 0, 1, \dots, T;$$

$$w_2^t/p^t = M \partial f(x_1^t, x_2^t, t)/\partial x_2.$$

However, we also want to allow for a *systematic over or under-valuation* of the two inputs. In particular, we would like to determine whether there is any evidence that producers systematically under-value ICT inputs. To allow for this possibility, we generalise equations (7) to the following two equations:

$$(8) \quad w_1^t/p^t = M\phi_1 \partial f(x_1^t, x_2^t, t)/\partial x_1; \quad t = 0, 1, \dots, T;$$

$$w_2^t/p^t = M\phi_2 \partial f(x_1^t, x_2^t, t)/\partial x_2.$$

If producers consistently undervalue the contribution of ICT, then ϕ_2 will be a positive constant that is less than one. If producers consistently overvalue the contribution of non-ICT inputs to production, then ϕ_1 will be a positive constant that is greater than one.

Unfortunately, it is not possible to separately identify the three parameters M , ϕ_1 and ϕ_2 . Thus, we reparameterise our model as follows:

$$(9) \quad M_1 \equiv M\phi_1;$$

$$M_2 \equiv M\phi_2.$$

Substituting (9) into (8), we obtain the following estimating equations:

$$(10) \quad w_1^t/p^t = M_1 \partial f(x_1^t, x_2^t, t)/\partial x_1; \quad t = 0, 1, \dots, T;$$

$$w_2^t/p^t = M_2 \partial f(x_1^t, x_2^t, t)/\partial x_2.$$

In this study we estimate the parameters M_1 and M_2 for selected Australian industries. If M_2 is less than 1, then this is evidence that ICT is undervalued relative to its cost.

Note that equations (10) have a simple interpretation that is independent of our previous assumptions. The partial derivative $\partial f(x_1^t, x_2^t, t)/\partial x_n$ is the extra amount of output that the addition of one more unit of x_n could produce in period t and $p^t \partial f(x_1^t, x_2^t, t)/\partial x_n$ is the value created by employing this extra unit of x_n in period t . If this value is greater than its period t cost, w_n^t , then the period t markup factor, M_n^t , will be less than one; i.e., under these conditions, we will have:

$$(11) \quad M_n^t \equiv w_n^t/p^t \partial f(x_1^t, x_2^t, t)/\partial x_n < 1.$$

Equations (10) simply smooth over the individual markup factors⁷ defined by (11) by setting $M_n = M_n^t$ for $n = 1, 2$ and $t = 0, 1, \dots, T$. Thus, if our estimated M_n turns out to be less than one, then this is direct evidence that over the sample period, a marginal unit of input n contributed more to the creation of output than its cost, w_n^t .⁸ Of course, all of this is contingent on the accurate estimation of the production function, a topic we now turn to.

3.2.2 Choosing a functional form for the production function

The basic functional form for the production function that we use is the following variant of the normalised quadratic functional form originally developed by McFadden (1978; 279) and Diewert and Wales (1987; 51):

$$(12) f(x_1, x_2, t) \equiv a + b_1x_1 + b_2x_2 + c_1x_1t + c_2x_2t + dt - (1/2) e^2 [\alpha x_1 - x_2]^2/x_1$$

where a, b_1, b_2, c_1, c_2, d and e are parameters to be estimated.⁹ Note that e is squared in (12); this squaring ensures that f will be concave in x_1 and x_2 and hence that satisfaction of the first order conditions (2) will imply that we have a global maximum for the profit maximisation problems, provided that the elasticity of demand that the producer faces is constant in each period. If the parameter d is positive, then we have output augmenting technical change that occurs independently of input usage. If the parameter c_n is positive, then we have input n augmenting technical change. The bigger in magnitude e is, the less substitutable are the two inputs.¹⁰ This functional form is reasonably flexible.

Partially differentiate the $f(x_1, x_2, t)$ defined by (12) with respect to x_1 and x_2 and substitute these derivatives into the estimating equations (10). The resulting estimating equations become:

$$(13) w_1^t/p^t = M_1[b_1 + c_1t + (1/2)e^2(v^t)^2 - e^2\alpha v^t]; \quad t = 0, 1, \dots, T;$$

$$(14) w_2^t/p^t = M_2[b_2 + c_2t + e^2v^t]$$

where v^t is an exogenous variable defined as follows:

$$(15) v^t \equiv [\alpha x_1^t - x_2^t]/x_1^t; \quad t = 0, 1, \dots, T.$$

We may add the production function equation itself to equations (13) and (14) as a third estimating equation (and indeed this is necessary to identify the parameters in (13) and (14)):

$$(16) y^t = a + b_1x_1^t + b_2x_2^t + c_1x_1^t t + c_2x_2^t t + dt - (1/2) e^2 [v^t]^2 x_1^t; \quad t = 0, 1, \dots, T.$$

⁷ If we take this simple productivity interpretation of the M_n , then it would perhaps be appropriate to call these factors *productivity factors* rather than markup factors.

⁸ Thus $1/M_n$ is 1 plus the percentage undervaluation of input n over the sample period.

⁹ The parameter α is not estimated; we choose α so that $\alpha x_1 - x_2$ equals 0 in period 1.

¹⁰ If $e = 0$, then the two inputs are perfect substitutes.

The endogenous variables in (13), (14) and (16) are w_1^t/p^t (the price of input 1 divided by the price of output), w_2^t/p^t (the price of input 2 divided by the price of output) and y^t (output in period t). The variables that we condition on are: input 1, x_1 , input 2, x_2 , and time t .¹¹

However, there is a heteroskedasticity problem with equation (16): as time progresses, usually output y^t will grow considerably and hence the residuals will usually not have a constant variance.¹² In order to deal with this heteroskedasticity problem, we divide both sides of equation (16) through by x_1 . This leads to the following estimating equation in place of (16):

$$(17) y^t/x_1^t = a(1/x_1^t) + b_1 + b_2(x_2^t/x_1^t) + c_1t + c_2(x_2^t/x_1^t)t + d(1/x_1^t)t - (1/2)e^2[v^t]^2; \quad t = 0, 1, \dots, T.$$

The production function defined by (12) proved to be not quite flexible enough to adequately model the Australian industry data. Hence, in the following section, we generalise (12) by adding some extra parameters. We also allow the markup factors M_1 and M_2 in equations (13) and (14) to trend over time.

3.2.3 The addition of spline variables

We now generalise the production function defined by (12) above to the splined normalised quadratic production function:

$$(18) f(x_1, x_2, t) \equiv a + b_1x_1 + b_2x_2 + c_{11}x_1t_1(t) + c_{12}x_1t_2(t) + c_{13}x_1t_3(t) + c_{21}x_2t_1(t) \\ + c_{22}x_2t_2(t) + c_{23}x_2t_3(t) + d_1t_1(t) + d_2t_2(t) + d_3t_3(t) - (1/2) e^2 [\alpha x_1 - x_2]^2/x_1$$

where the exogenous time trend variables t_1 , t_2 and t_3 are defined as follows for $t = 0, 1, \dots, T$:

$$(19) t_1(t) \equiv t \quad \text{for } t = 0, 1, 2, \dots, t_1^*; \\ \equiv t_1^* \quad \text{for } t = t_1^* + 1, t_1^* + 2, \dots, T;$$

$$(20) t_2(t) \equiv 0 \quad \text{for } t = 0, 1, 2, \dots, t_1^*; \\ \equiv t - t_1^* \quad \text{for } t = t_1^* + 1, t_1^* + 2, \dots, t_1^* + t_2^*; \\ \equiv t_2^* \quad \text{for } t = t_1^* + t_2^* + 1, t_1^* + t_2^* + 2, \dots, T;$$

$$(21) t_3(t) \equiv 0 \quad \text{for } t = 0, 1, 2, \dots, t_1^* + t_2^*;$$

¹¹ The variable v equals $[\alpha x_1 - x_2]/x_1$ and hence is determined by x_1 and x_2 .

¹² This is not such a big problem with equations (13) and (14), since we normalise all prices to equal one in the base period. Since we divide the input prices by the output prices, the dependent variables in these two equations are invariant to the degree of general inflation. However, because ICT prices drop considerably over the sample period while the price of other inputs generally rose, there was also a heteroskedasticity problem in equation (14) in our empirical work.

$$\equiv t - (t_1^* + t_2^*) \text{ for } t = t_1^* + t_2^* + 1, t_1^* + t_2^* + 2, \dots, T.$$

Note that if we add together the $t_n(t)$, we get $t-1$; ie for $t = 0, 1, 2, \dots, T$:

$$(22) \quad t_1(t) + t_2(t) + t_3(t) = t.$$

Thus the $t_n(t)$ functions simply decompose the time trend t over the entire sample period into the sum of three partial time trends. The first partial time trend increases linearly until period t_1^* is reached and then it remains constant over the rest of the sample time periods. Then the second partial time trend takes over at the first break point t_1^* and increases linearly from an initial value of 0 at t_1^* to a final value of t_2^* at the second break point t_2^* . This second spline function then remains constant for the remainder of the sample period. Finally, for $t \geq t_1^* + t_2^*$, the final partial time trend takes over and increases linearly from an initial value of 0 at $t_1^* + t_2^*$ to a final value of t_2^* at the final observation in the sample.

Essentially the production function defined by (18) allows for differential rates of output and input augmenting technical progress over the three time periods 0 to t_1^* , t_1^* to t_2^* and t_2^* to T . This increases the flexibility of the functional form but at a cost – we now have to estimate 9 technical change parameters, c_{11} , c_{12} , c_{13} , c_{21} , c_{22} , c_{23} , d_1 , d_2 and d_3 instead of the previous 3 technical change parameters, c_1 , c_2 and d .¹³

Using the functional form defined by (18), we now obtain the following counterpart to our earlier scaled production function estimating equation (17):

$$(23) \quad y^t/x_1^t = a(1/x_1^t) + b_1 + b_2(x_2^t/x_1^t) + c_{11}t_1(t) + c_{12}t_2(t) + c_{13}t_3(t) + c_{21}(x_2^t/x_1^t)t_1(t) \\ + c_{22}(x_2^t/x_1^t)t_2(t) + c_{23}(x_2^t/x_1^t)t_3(t) + d_1(1/x_1^t)t_1(t) + d_2(1/x_1^t)t_2(t) + d_3(1/x_1^t)t_3(t) \\ - (1/2)e^2[v^t]^2; \quad t = 0, 1, \dots, T.$$

We can differentiate the production function defined by (23) and obtain counterparts to our earlier estimating equations (13) and (14). However, we also generalise (13) and (14) to allow for linear spline trends in the markups. Thus, our system of estimating equations that are the counterparts to (13) and (14) are the following two equations:

$$(24) \quad w_1^t/p^t = [M_1 + m_{11}t_1(t) + m_{12}t_2(t) + m_{13}t_3(t)][b_1 + c_{11}t_1(t) + c_{12}t_2(t) + c_{13}t_3(t) + (1/2)e^2(v^t)^2 - e^2\alpha v^t]; \\ t = 0, 1, \dots, T;$$

$$(25) \quad w_2^t/p^t = [M_2 + m_{21}t_1(t) + m_{22}t_2(t) + m_{23}t_3(t)][b_2 + c_{21}t_1(t) + c_{22}t_2(t) + c_{23}t_3(t) + e^2v^t].$$

¹³ In three of our industries, we required only two spline segments instead of 3 and so there were only 6 technical change parameters to estimate instead of 9.

There are 21 unknown parameters in the 3 estimating equations (23)–(25). Since our sample size is 24, we have 72 degrees of freedom available to estimate these 21 parameters. In order to reduce the number of parameters to be estimated, we decided to set the base period markup factors M_1 and M_2 equal to each other. This seemed to be a sensible strategy since at the beginning of the sample period, ICT inputs were very small in most cases and perhaps not as well measured as they were at the end of the sample period. This leaves 20 parameters to be estimated. For 3 industries, we further reduced the number of parameters by having only one break point t_1^* instead of two break points, t_1^* and t_2^* . This restriction reduced the number of parameters by 5.¹⁴ For the remaining two industries, we started with the one break model, adding extra parameters for the two break model until statistically satisfactory results were obtained.

Once the parameters in (23)–(25) have been estimated, we can construct the markup factors for each input n for each year t , $M_n(t)$ say, using the following formulae:

$$(26) M_1(t) \equiv M + m_{11}t_1(t) + m_{12}t_2(t) + m_{13}t_3(t); \quad t = 0, 1, \dots, T;$$

$$M_2(t) \equiv M + m_{11}t_1(t) + m_{12}t_2(t) + m_{13}t_3(t).$$

We measured returns to scale ρ^t at each observation t , using the following traditional production function definition of returns to scale:

$$(27) \rho^t \equiv \partial \ln f(\lambda x_1^t, \lambda x_2^t, t) / \partial \lambda |_{\lambda=1} = [f_1(x_1^t, x_2^t, t)x_1^t + f_2(x_1^t, x_2^t, t)x_2^t] / f(x_1^t, x_2^t, t); \quad t = 0, 1, \dots, T.$$

We also measure technical progress τ^t in each period t as the percentage increase in output due to the passage of one year:

$$(28) \tau^t \equiv \partial \ln f(x_1^t, x_2^t, t) / \partial t = [\partial f(x_1^t, x_2^t, t) / \partial t] / f(x_1^t, x_2^t, t); \quad t = 0, 1, \dots, T.$$

We turn now to a description of the data.

3.3 Data used

The database used in this study is based on detailed sectoral productivity data supplied by the Australian Bureau of Statistics (ABS). The database covers 12 market sectors for the 24 years 1979–80 to 2002–03. The time period was started in 1979–80 because nearly all relevant series were available from that year onwards and the major developments in ICT have occurred in the ensuing period. The 12 market sectors included in the database and the corresponding abbreviations used subsequently are:

Accommodation, cafes and restaurants (ACC);

¹⁴ The one break point model is a special case of the two break model: we need only impose the following restrictions on the parameters in equations (23)–(25): $c_{12} = c_{13}$; $c_{22} = c_{23}$; $d_2 = d_3$; $m_{12} = m_{13}$; $m_{22} = m_{23}$.

Agriculture, forestry and fishing (AFF);

Communication (COM);

Construction (CON);

Cultural and recreational services (CRS);

Electricity, gas and water (EGW);

Finance and insurance (FIN);

Manufacturing (MAN);

Mining (MIN);

Retail trade (RET);

Transport and storage (TRN); and,

Wholesale trade (WHO).

The ABS assembles its industry-level multifactor productivity (MFP) estimates using a two stage process. It first aggregates between 10 and 12 capital components into an index of 'capital services'. This is an index of the quantity of total capital inputs where constant price productive capital stock estimates are aggregated using rental prices as weights. Having derived the capital services index, this is then aggregated with an index of labour hours to form an overall index of labour and capital inputs using labour and capital income shares as weights. Income is taken to be the sum of compensation of employees, gross operating surplus, gross mixed income (of proprietors) and net taxes on production. The output measure is taken to be an index of gross value added (ie gross outputs produced less intermediate inputs consumed in production).

Most sectors' capital services indexes are built up from the following 11 capital components.

- Computers
- Electronic equipment
- Industrial machinery and equipment
- Inventories
- Land
- Non-dwelling construction
- Other plant and equipment
- Other transport equipment

- Ownership transfer costs
- Road vehicles
- Software

Three sectors—Cultural and recreational services, Communications and Finance and insurance—do not have an inventories capital component while three sectors have an additional specialised capital component. These are: livestock for Agriculture, forestry and fishing; exploration for Mining; and, artistic originals for Cultural and recreational services.

Because we undertake econometric modelling in this study, we use a modified version of the ABS MFP data so that our database balances in broad terms. This requires that price times quantity equals value and the sum of labour and capital input component values equals the total annual cost of labour and capital. To achieve this we use constant price series as quantity measures rather than the corresponding quantity indexes used by ABS.

ABS supplied constant price series for gross value added for the entire period and current price gross value added for the shorter period 1989–90 to 2002–03 using the 1993 System of National Accounts (SNA93) definitions. ABS was unable to supply consistent current price gross value added series for earlier years so we have spliced the earlier ANZSIC gross value added series for the period 1982–83 to 1989–90 onto the ABS' SNA93 estimate for 1989–90. The gap prior to 1982–83 was filled by splicing the nearest corresponding ASIC current price gross value added series.

Annualised quarterly hours worked by industry were supplied by ABS for each of the 12 sectors for the period from 1985–86 onwards and used as the labour quantity measure. Hours worked estimates for earlier years were obtained by splicing the nearest corresponding series from the Industry Commission (1997). The cost of labour inputs was taken to be the product of the ABS' labour income share and gross value added.

Measuring and valuing capital inputs generally presents the greatest challenge in productivity studies. This is well recognised by the ABS (2000, para 27.23) who note:

Of all the constituents of the MFP measures, capital input poses the most problems. A major weakness of the estimates of capital services stems from the uncertain quality of the data used in their construction, such as mean asset lives and asset life distributions.

The ABS uses age-efficiency profiles to derive productive capital stock quantity estimates in constant prices which are used in this study.

The more problematic aspect of measuring capital inputs in this instance relates to calculating rental prices. ABS (2000, para 27.55) indicates that rental prices are formed as follows:

$$(29) \quad r_{ijt} = T_{ijt} p_{ijt} (i_{it} + d_{ijt} - g_{ijt}) + p_{ijt} x_{it}$$

where the subscript i refers to the sector, j to the asset type, and t to the time period and r is the rental price, T is the income tax parameter, i is the nominal internal rate of return, p is the price deflator for new capital goods, g is the rate of capital gains or losses, d is the depreciation rate, and x is the effective average non-income tax rate on production.

In this study we do not include the non-income tax rate on production as we use gross value added as the measure of income and this is expressed in basic values (ie indirect taxes are excluded). The internal rate of return was initially solved for as a residual to ensure the value of labour and capital equal the value of gross value added. Using the ABS data we have been able to reproduce the ABS' internal rate of return and, hence, rental prices for the manufacturing sector. However, most other sectors have low or in some cases negative internal rates of return. This creates problems for productivity measurement as the capital components cannot then be readily aggregated. Even in those cases where the internal rate of return is low but non-negative, the rental price typically becomes highly volatile, particularly for land and inventory asset types where there is zero depreciation. This then reduces the scope to undertake econometric analysis using the data. The ABS appears to have addressed this problem by imposing a rate of return across most sectors similar to that obtained for the manufacturing sector. While this produces rates of return of a larger magnitude, the resulting rental prices remain volatile.

In this study we have formed rental prices by assuming that producers expect to earn a 4 per cent real rate of return ex-ante. This rate is consistent with a wide range of international evidence reviewed in Robbins and Robbins (1992) and with the findings of previous Australasian studies (eg Lawrence and Diewert 1999). The rental price is formed by substituting 4 per cent for the value of i in equation (57) and setting the capital gains/losses terms to zero. The capital components are then aggregated into four capital groups as follows.

- ICT comprising computers, software and electronic equipment
- Machinery and equipment comprising industrial machinery and equipment, other plant and equipment, other transport equipment and road vehicles
- Land and buildings comprising land, non-dwelling construction and ownership transfer costs
- Inventories

The three sectors which do not have inventories reported (Communications, Cultural and recreational services and Finance and insurance) have only the first three capital groups. For the three sectors that have an additional specialised capital component, this component is included in the Land and buildings group. Electronic equipment is included in the ICT capital group as it captures the use of computerised equipment and associated technology. This also makes econometric estimation more tractable as the computers and software components are quite small in the first half of the period.

While the use of a 4 per cent real rate of return is consistent with evidence available for a wide range of countries and is consistent with rational producer behaviour, it is at odds with the ABS data for several of the 12 sectors. Indeed, the real rates of return required to balance the value of value added and the sum of labour and capital costs vary from a low of -0.7 on average for Transport and storage to a high of 12 per cent on average for Cultural and recreational services. This raises significant concerns about the quality of the data for some sectors and the weight that

can be put on productivity estimates derived from this data at both the sectoral and aggregate levels. The impact of using a 4 per cent real rate of return on the overall value of inputs relative to the value of outputs depends on the capital intensity of each sector as well as the magnitude of the gap between 4 per cent and the real rate required to balance the database.

Table 1: **Balancing the sectoral databases, 1980–2003 average results**

<i>Year</i>	<i>Outputs \$m</i>	<i>Inputs \$m</i>	<i>Outputs/Inputs Ratio</i>	<i>Balancing Real RoR</i>	<i>Labour share</i>
Accommodation, cafes etc	7,800	9,194	85%	0.42%	77%
Agriculture, forestry & fishing	15,171	32,882	46%	1.84%	33%
Communication	10,904	12,179	88%	1.47%	57%
Construction	23,603	21,619	107%	8.92%	77%
Cultural & recreational	6,616	5,919	115%	12.03%	58%
Electricity, gas & water	11,322	16,179	69%	0.27%	37%
Finance & insurance	23,751	26,104	85%	0.70%	60%
Manufacturing	51,225	50,098	101%	4.20%	63%
Mining	19,517	16,516	125%	10.65%	28%
Retail trade	21,048	23,961	88%	-0.34%	82%
Transport & storage	21,542	26,595	80%	-0.70%	66%
Wholesale trade	21,080	21,619	97%	3.34%	70%

Source: Meyrick and Associates sectoral productivity database

In table 1, we present the average values of outputs and inputs for each sector over the 24 years studied using a 4 per cent real rate of return, the average ratio of the value of outputs to the value of inputs, the average real rate of return that would be required to balance the database for that sector and the average labour income share for the sector. For two sectors—Manufacturing and Wholesale trade—the values of outputs and inputs match closely using a real rate of return of 4 per cent and we can have relative confidence in the data for these sectors. For another three sectors—Communications, Construction and Retail trade—the ratio of the value of outputs to the value of inputs is within 12 per cent in absolute value of 100 per cent. While this range is higher than ideal, the data for these sectors are thought to be reasonable. However, the data for the remaining 7 sectors are not considered reasonable—the ratios of the value of outputs to the value of inputs deviate from 100 per cent by between 15 and 46 per cent in absolute value and they have unreasonably high or low balancing real rates of return. These sectors include the three most capital intensive sectors—Agriculture, forestry and fishing; Electricity, gas and water; and, Mining. Measurement errors in these sectors make econometric estimation difficult and the results that would be obtained unreliable. Consequently, we concentrate on econometric estimation for the first five sectors mentioned above—Manufacturing, Wholesale trade, Communications, Construction and Retail trade—where the ABS data is consistent with a reasonable average real rate of return. The measurement problems evident in the remaining sectors have important implications for reported productivity growth both in those sectors and at the aggregate level.

To facilitate subsequent econometric estimation the four capital group rental prices are smoothed using the Lowess algorithm in Shazam (While 1997). In most cases an f parameter of 0.4 is used in

the Lowess algorithm.

3.3.1 Sectoral productivity performance

Chained Fisher MFP indexes for the six sectors with the highest MFP growth rates are presented in figure 1. MFP and partial productivity index values and trend annual growth rates for all sectors are presented in appendix B. Communications and Agriculture both have the highest MFP trend growth rates of 2.75 per cent per annum. Manufacturing has the next highest annual trend growth rate at 1.59 per cent. Based on this data, manufacturing is the only sector whose MFP has increased steadily over the period. The other three sectors in the top half of MFP performance—Transport with an annual trend growth rate of 0.76 per cent, Construction with 0.12 per cent and Retail trade with -0.78 per cent—all suffered MFP reversals over the first half of the period before recovering somewhat in the second half. The performance of Transport, Construction and Retail trade, in particular appears somewhat implausible with very modest productivity advances for the first two over the two and a half decade period and Retail trade failing to reattain its 1980 performance level by 2003.

These concerns are further confirmed by the productivity performance of the lower performing MFP sectors presented in figure 2. None of these sectors reattain their 1980 MFP levels by 2003. While some such as Wholesale trade and Finance and insurance show some MFP growth from around 1991 onwards, others such as Cultural and recreational services and Accommodation, cafes and restaurants show MFP declines over the whole period. Measurement problems in these sectors appear to be endemic.

Figure 1: MFP indexes for better performing sectors, 1980–2003

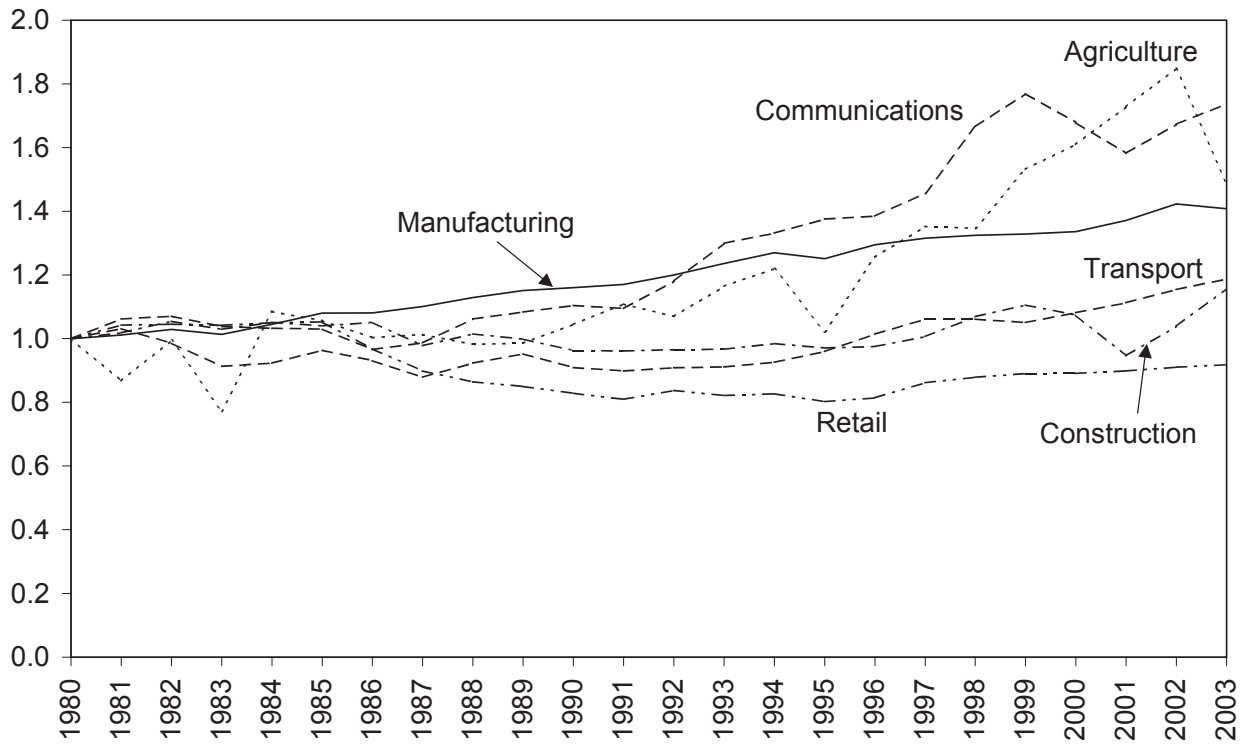
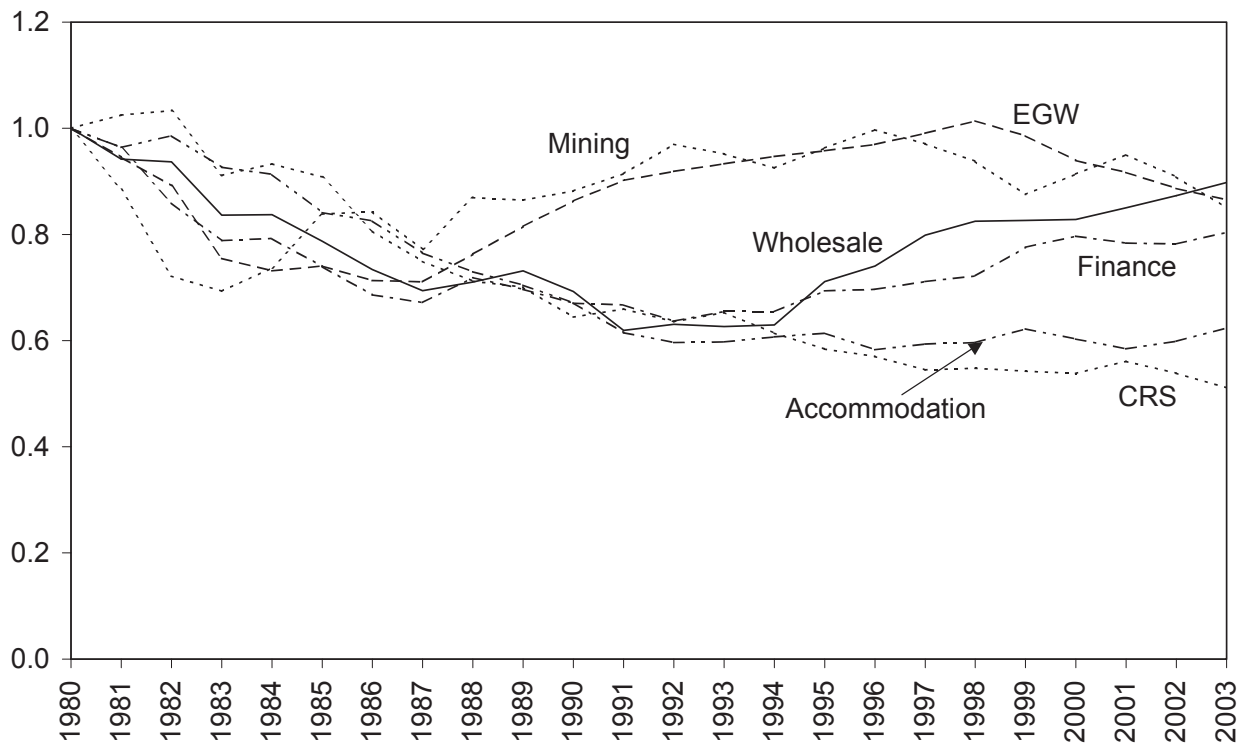


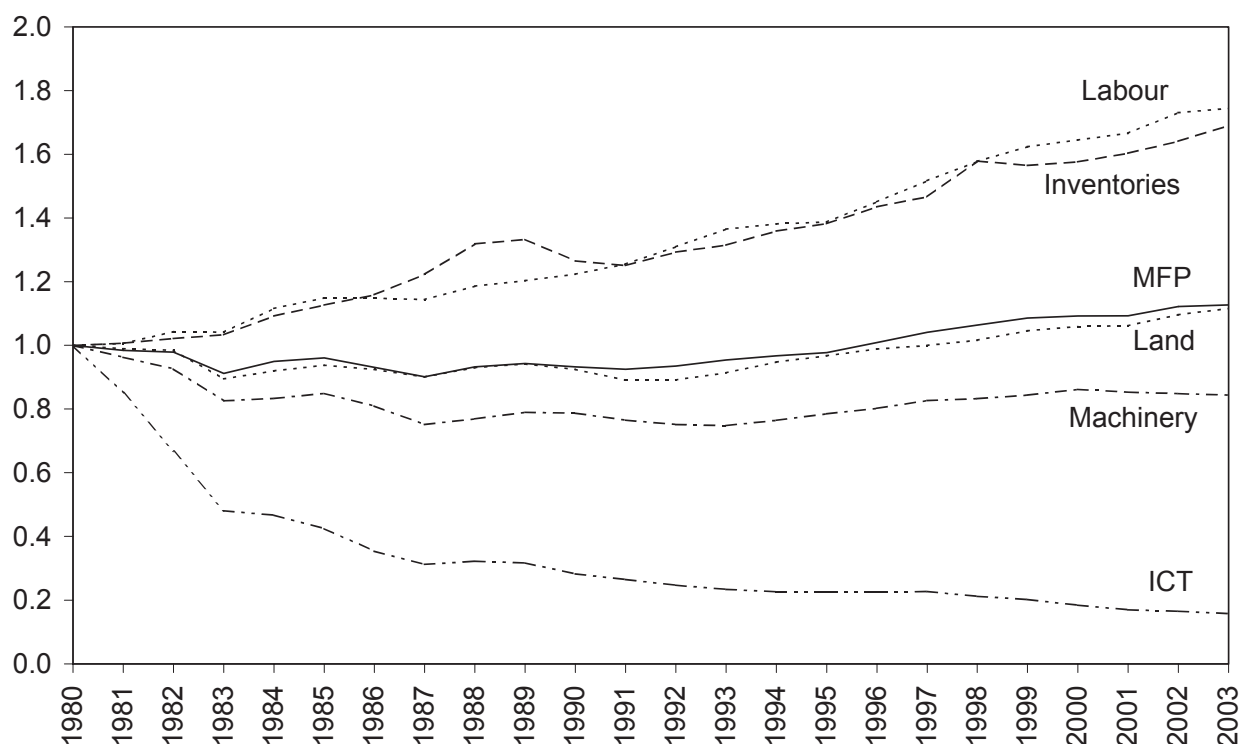
Figure 2: MFP indexes for lesser performing sectors, 1980–2003



Other sectors such as Electricity, gas and water that have undergone major microeconomic reforms over the last two decades show trend annual growth of only a modest 0.75 per cent and with 2003 MFP levels being 14 per cent below those in 1980. This result is at odds with detailed industry level studies which show much higher and more consistent productivity growth—see, for example, Lawrence (2002) and Meyrick and Associates (2003) for detailed electricity industry studies. Another sector that has been the subject of major reforms, rationalisation and increased availability of a wide range of new products—Finance and insurance—shows a trend MFP decline of 0.5 per cent per cent per annum.

These results highlight shortcomings in the data. Measurement problems in the increasingly important services sectors of the economy have long been recognised—see, for example, Lawrence and Diewert (1999) and Diewert and Fox (1999) for reviews of the issues. In particular, despite advances in the methods used by statistical agencies, changes in the quality and range of outputs are not adequately captured in National Accounts output measures. This leads to productivity performance in these sectors being seriously understated. As a result, the usefulness of the available data will be compromised when it comes to trying to determine the role ICT has played in MFP growth.

Figure 3: MFP and partial productivity indexes for aggregate market sector, 1980–2003



The productivity results for the aggregate market sector presented in figure 3 show modest trend annual MFP growth of 0.7 per cent. The partial productivity of labour increased the most rapidly with a trend annual increase of 2.5 per cent. The partial productivity of inventories also increased

rapidly at a trend 2.3 per cent reflecting greater use of ‘just-in-time’ inventory management—something that has been greatly facilitated by improved ICT over the period. The partial productivity of land increased only slightly less than MFP over the period while the partial productivities of machinery and ICT fell with annual trends 0.3 and 6.7 per cent, respectively, as greater use was made of these inputs.

The productivity results presented in figure 4 for the manufacturing sector—the sector where we believe the available data are the most robust—reflect a broadly similar pattern to the aggregate market sector results but MFP in this sector increases by a higher trend annual rate of 1.6 per cent. Labour productivity increases by a trend rate of 3.1 per cent while the trend rate of increase for land and inventories partial productivities are around half that for MFP in the sector. Increasing use of ICT and machinery again led to trend falls in the partial productivity of these inputs.

A broadly similar pattern is reflected in the other sectoral productivity results presented in figures 5 to 15. In all cases labour partial productivity has increased relative to MFP and in most cases the partial productivities of ICT and machinery have decreased relative to MFP. In some sectors such as Electricity, gas and water the behaviour of inventories partial productivity is erratic reflecting a combination of measurement problems and the fact that inventories start from a small base in some of these sectors. In the Mining sector the partial productivity of ICT broadly follows MFP reflecting the relative importance of electronic equipment in that sector.

Figure 4: MFP and partial productivity indexes for Manufacturing, 1980–2003

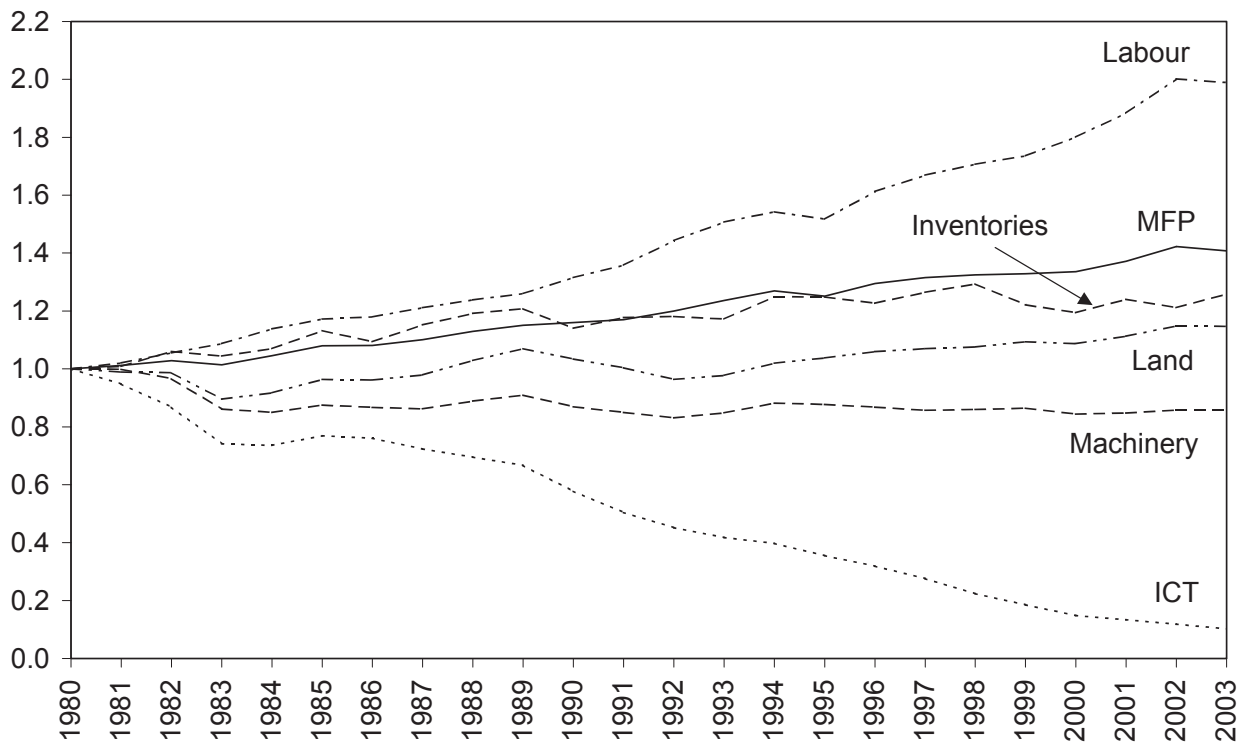


Figure 5: MFP and partial productivity indexes for Agriculture, forestry & fishing, 1980–2003

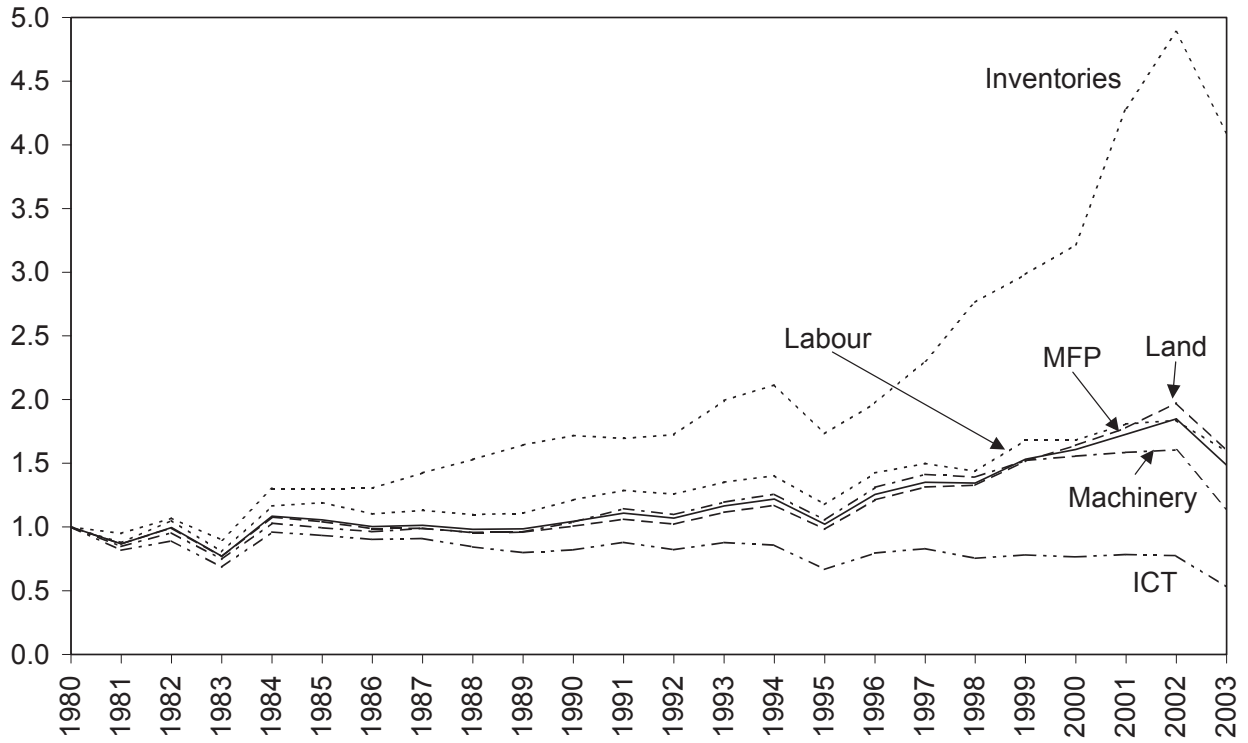


Figure 6: MFP and partial productivity indexes for Mining, 1980–2003

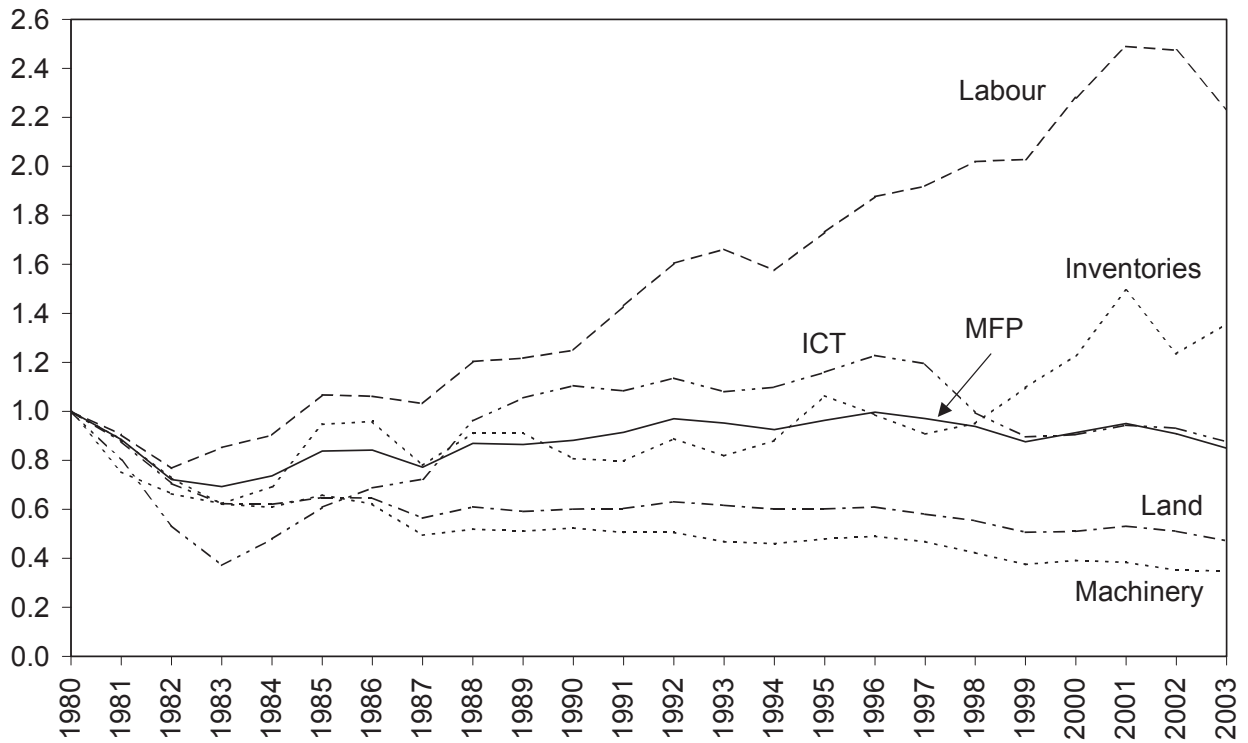


Figure 7: MFP and partial productivity indexes for Construction, 1980–2003

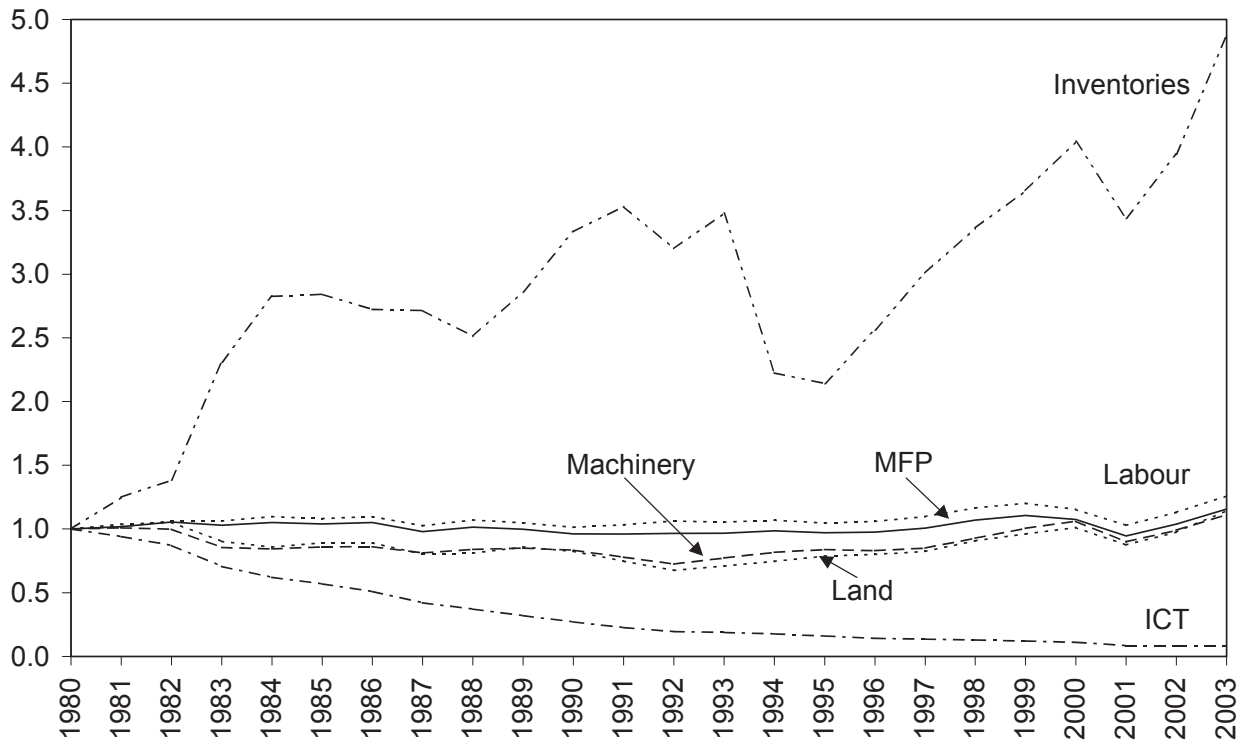


Figure 8: MFP and partial productivity indexes for Accommodation, 1980–2003

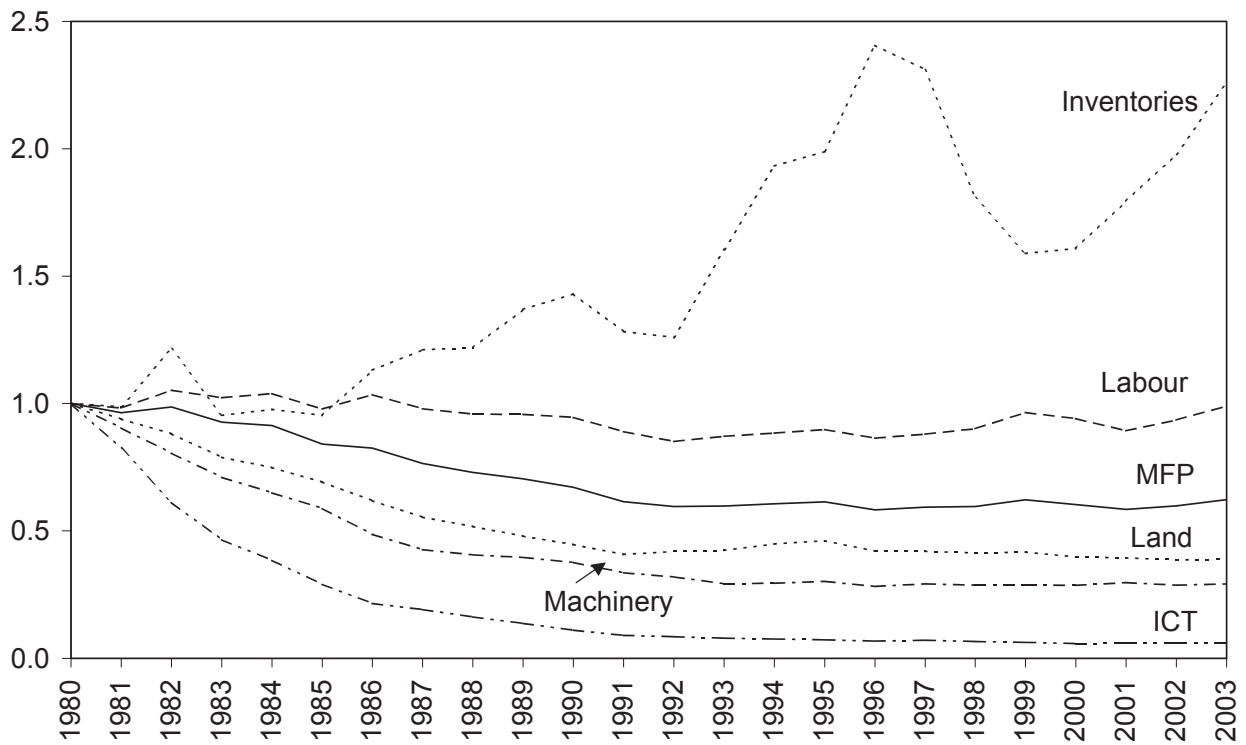


Figure 9: MFP and partial productivity indexes for Electricity, gas & water, 1980–2003

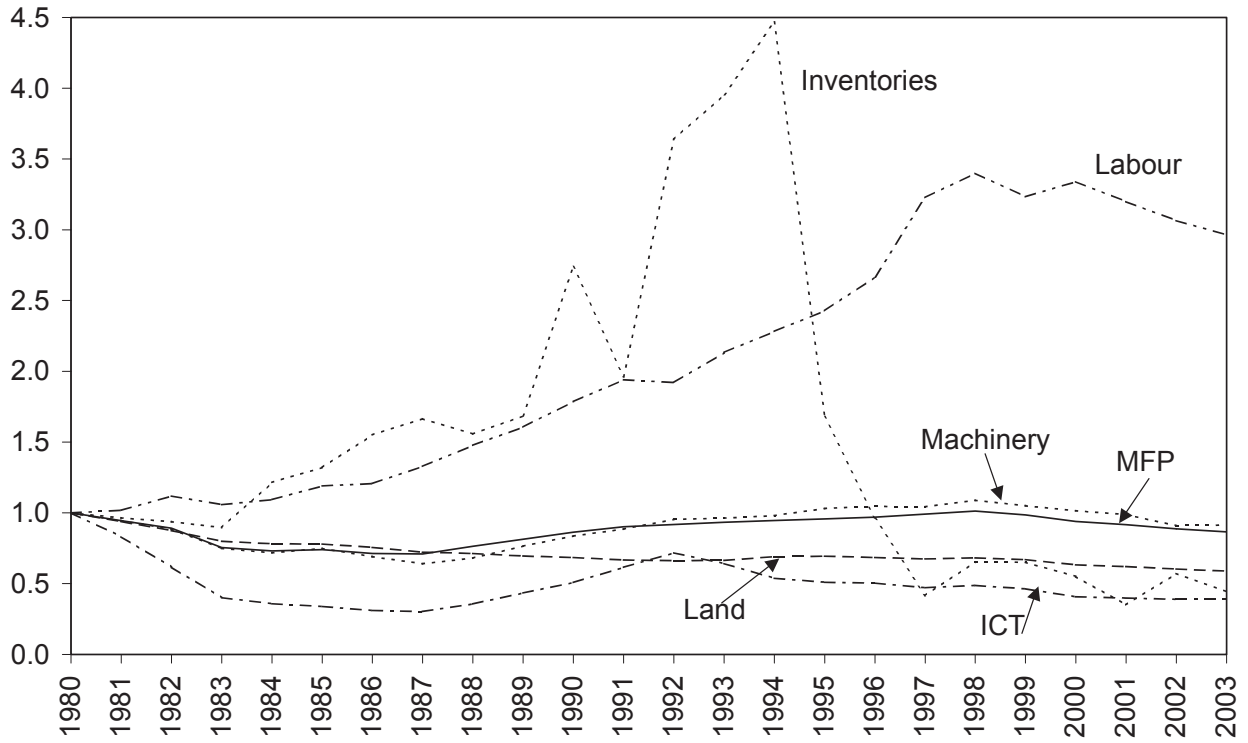


Figure 10: MFP and partial productivity indexes for Retail trade, 1980–2003

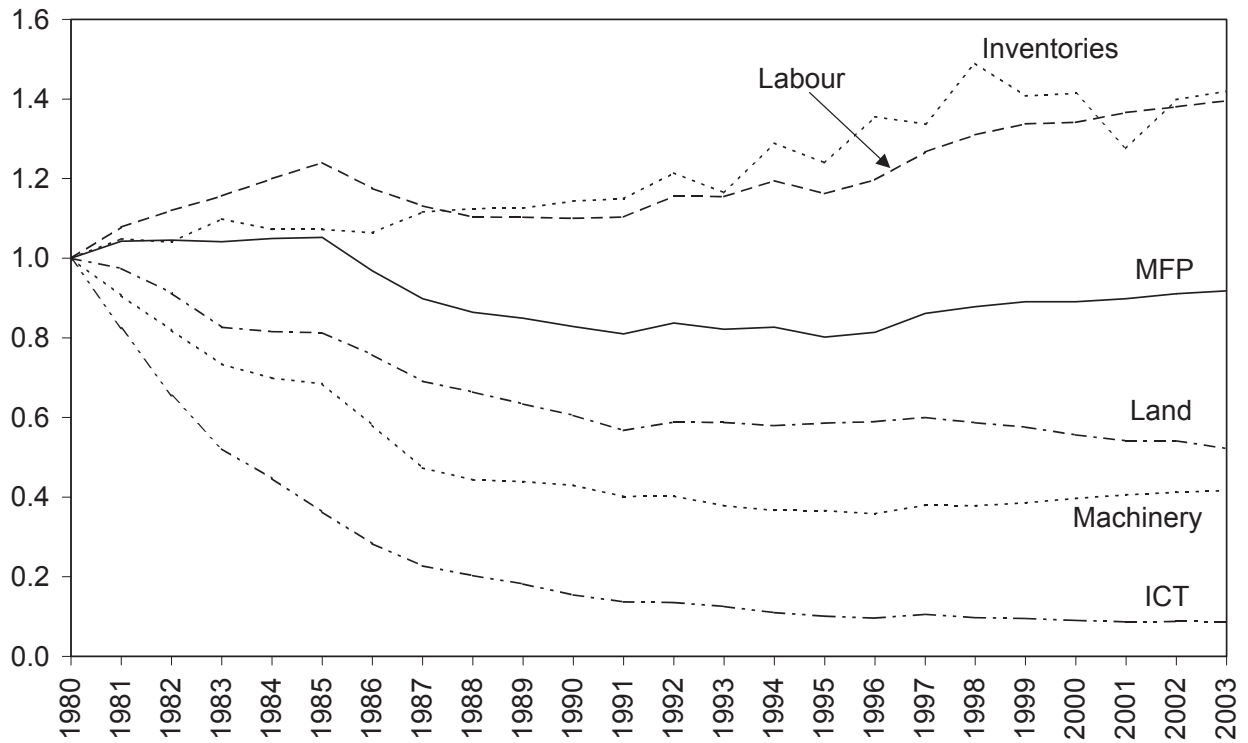


Figure 11: MFP and partial productivity indexes for Wholesale trade, 1980–2003

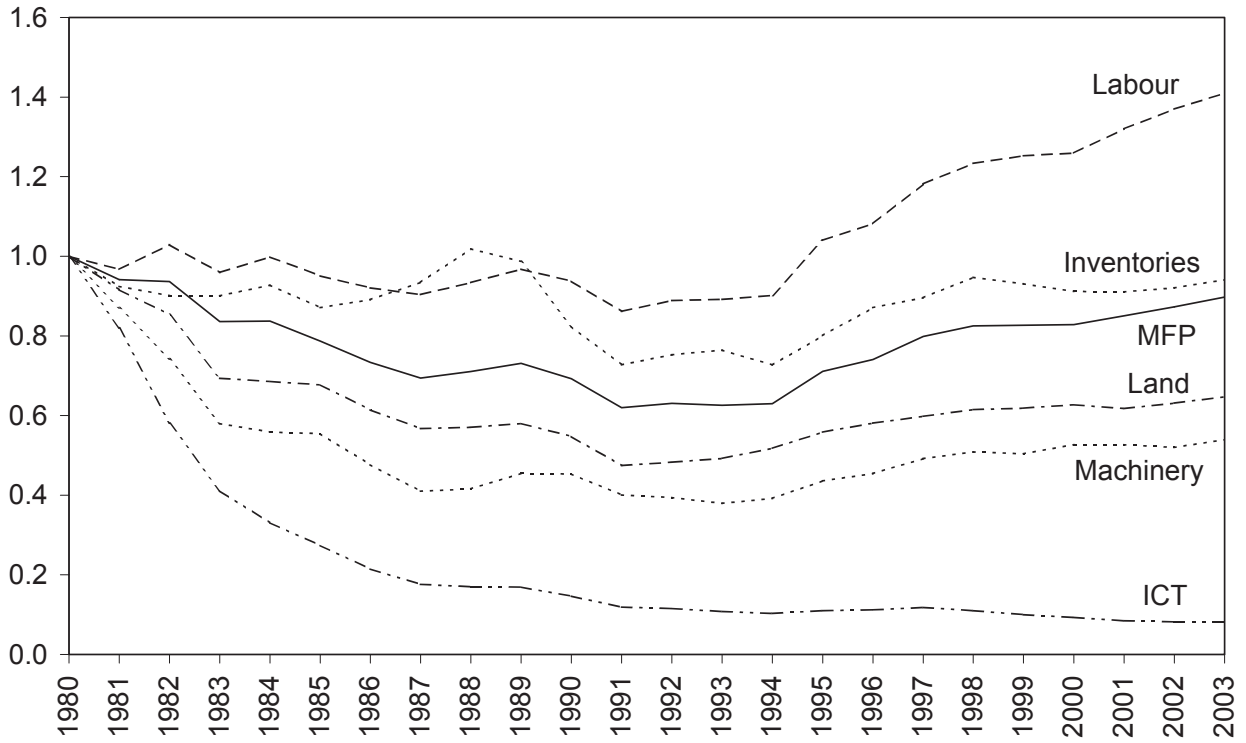


Figure 12: MFP and partial productivity indexes for Transport and storage, 1980–2003

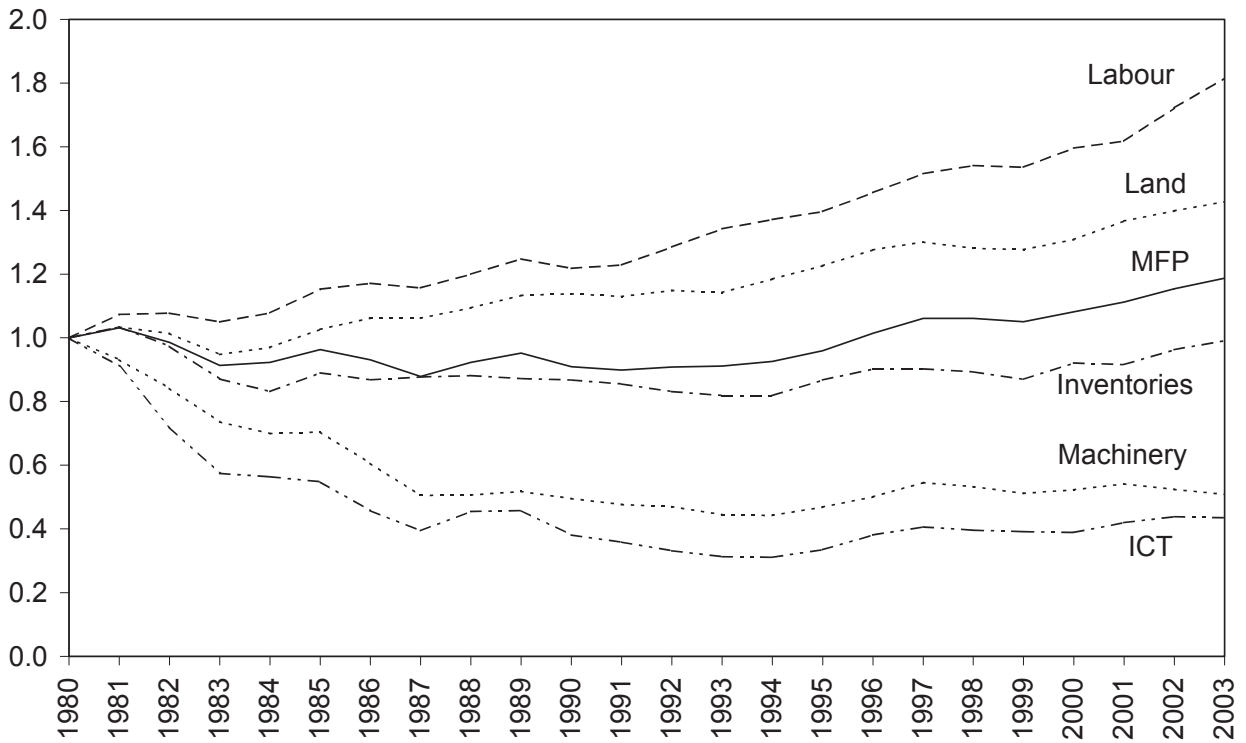


Figure 13: MFP and partial productivity indexes for Communications, 1980–2003

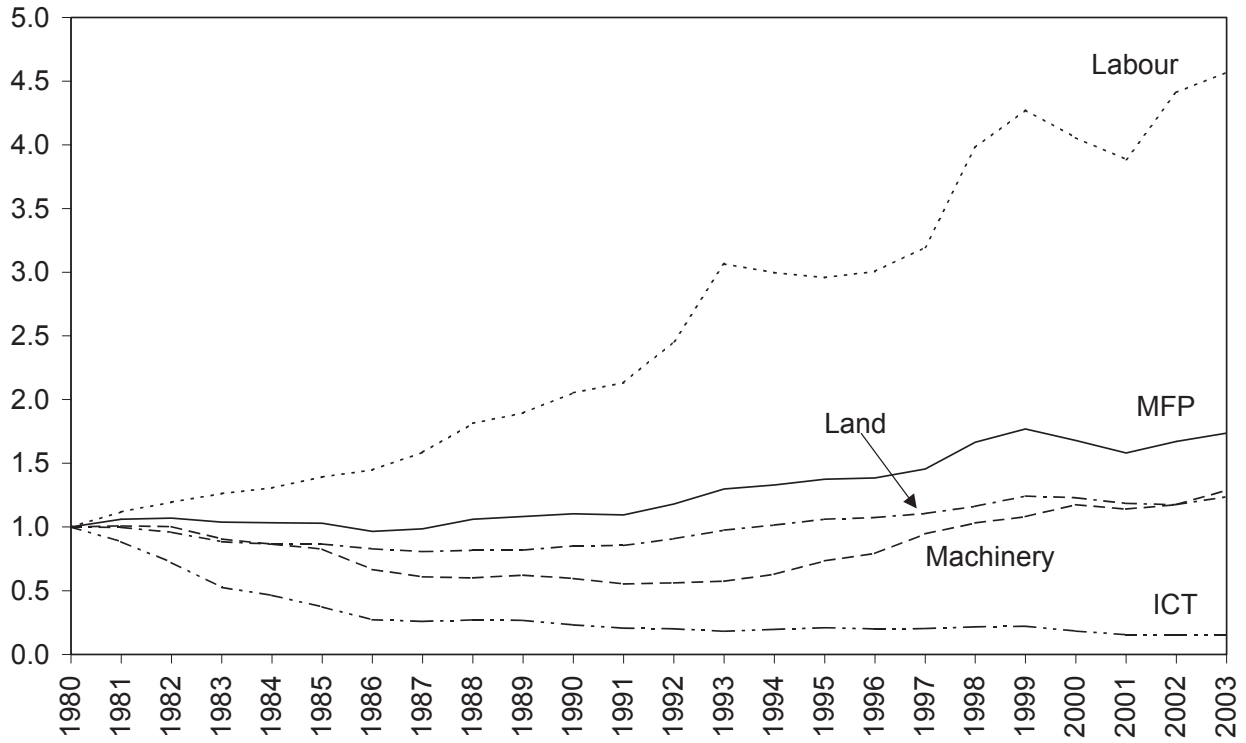


Figure 14: MFP and partial productivity indexes for Finance and insurance, 1980–2003

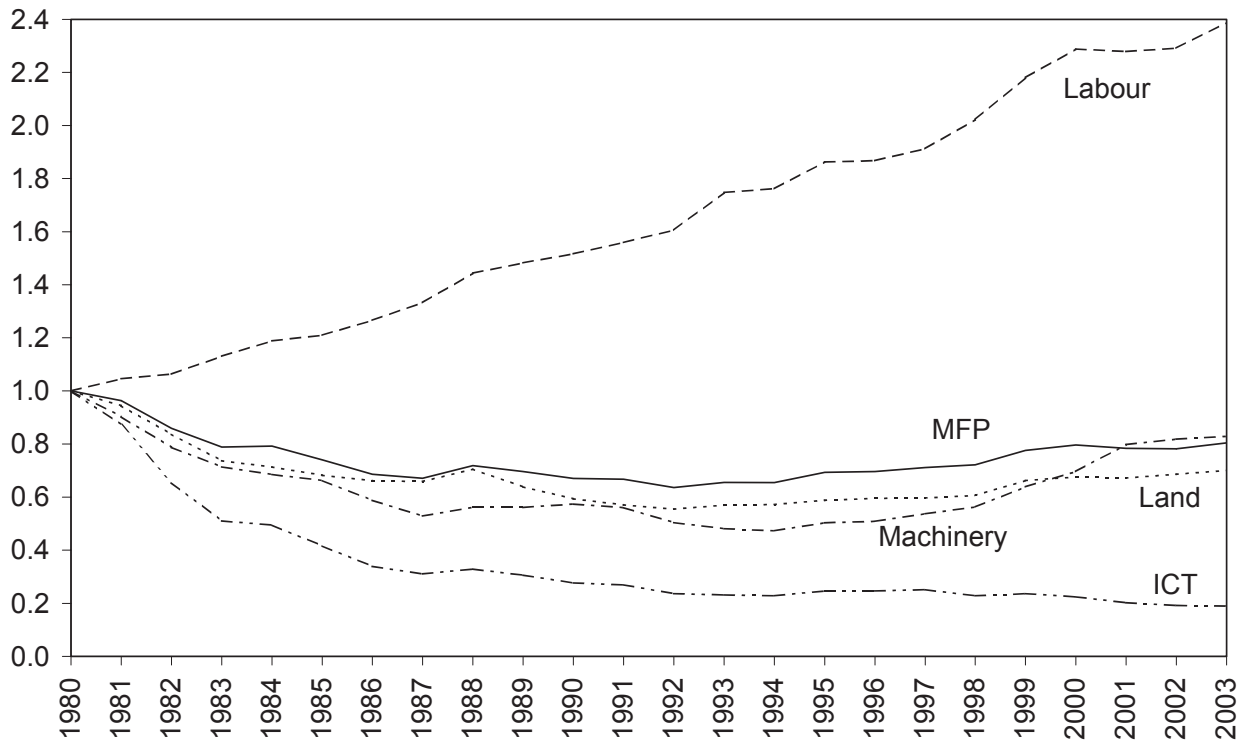
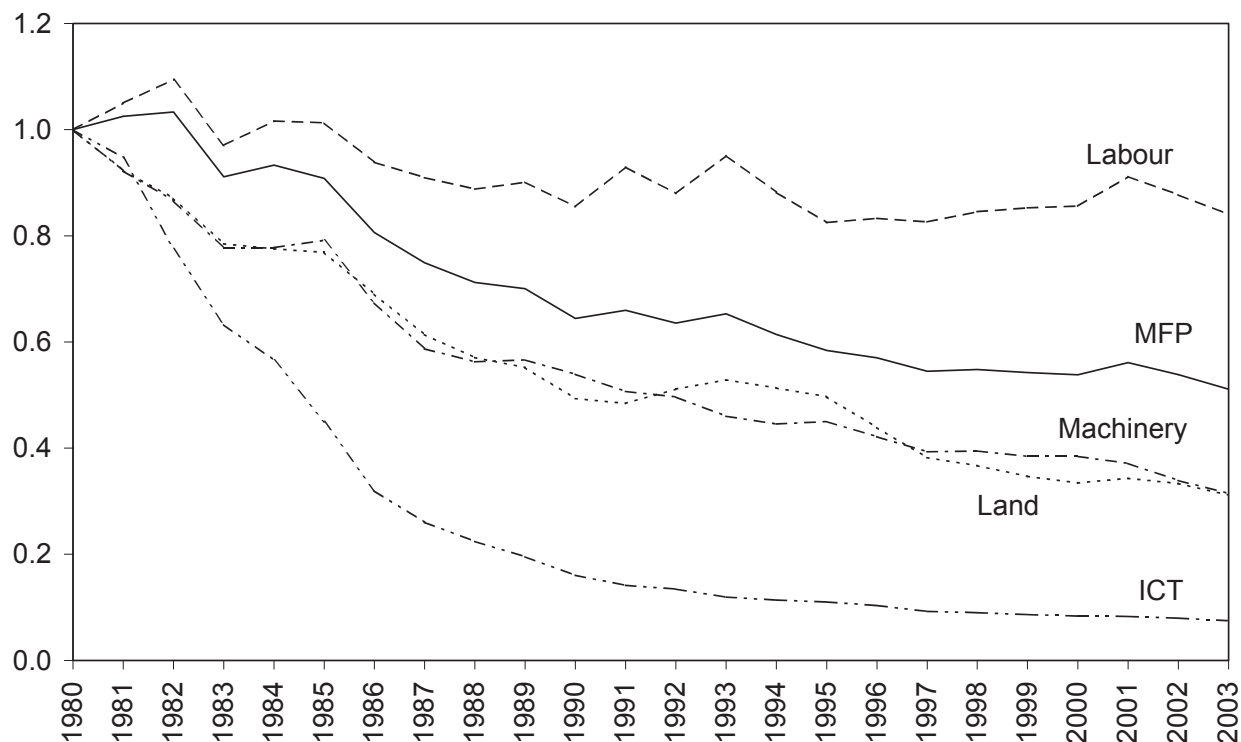


Figure 15: MFP and partial productivity indexes for Cultural and recreational, 1980–2003



3.3.2 Comparison with ABS and PC productivity estimates

In table 2 we present a comparison of the annual trend MFP and labour productivity growth rates obtained in this study using a 4 per cent real rate of return and those obtained at the aggregate level by the ABS (2003) and at the sectoral level by the Productivity Commission (PC 2004).

The MFP trend annual growth rates obtained in this study are lower at the aggregate market sector level than those obtained by the ABS. Our trend annual MFP growth rates, in particular, are markedly lower in the Mining, Electricity, gas and water, Wholesale trade, Retail trade, Accommodation, cafes and restaurants, Transport and storage, Communications and Finance and insurance sectors than those obtained by the PC. On the other hand, there is much less difference in the trend annual growth rates obtained for labour productivity. This highlights the importance of alternative assumptions that can be made regarding the formation of capital user costs and the relative weights applied to labour and capital in aggregating to a total inputs index.

The ABS and PC use a ‘hybrid’ two stage method to form total inputs indexes. Firstly, an exogenous nominal rate of return is applied for most sectors in forming capital user costs which are then used to aggregate the various capital components into a capital services index. The capital services index is then aggregated with the labour hours index using income shares as weights. The

ABS and PC indexes are hybrid in the sense that unbalanced rates of return are used for most sectors to aggregate to a total capital services index but then the value of total capital inputs is chosen to balance the sum of labour and capital costs with gross income in the second stage aggregation.

This hybrid approach has advantages and disadvantages. Firstly, the value of total labour and capital inputs is set to equal total gross income. However, the weights used in the second stage aggregation are not consistent, in most cases, with those used to form the capital services index. This has the scope to introduce bias to the total inputs index and makes the fact that unrealistic rates of return are being used in the second stage aggregation less transparent.

Table 2: Comparison of trend annual productivity growth rates, 1980–2003

<i>Year</i>	<i>MFP</i>		<i>Labour Productivity</i>	
	<i>ABS/PC</i>	<i>This study</i>	<i>ABS/PC</i>	<i>This study</i>
Aggregate Market Sector	0.96%	0.73%	2.06%	2.52%
Agriculture, etc	2.61%	2.75%	2.85%	2.80%
Mining	1.89%	0.69%	4.90%	5.04%
Manufacturing	1.46%	1.59%	3.04%	3.05%
Electricity, gas & water	2.91%	0.75%	6.15%	6.10%
Construction	0.14%	0.12%	0.69%	0.48%
Wholesale trade	1.18%	-0.22%	1.92%	1.57%
Retail trade	0.41%	-0.78%	1.14%	1.03%
Accommodation, cafes etc	-1.14%	-2.47%	-0.43%	-0.52%
Transport & storage	1.53%	0.76%	2.34%	2.36%
Communications	4.13%	2.75%	6.61%	6.91%
Finance & insurance	0.38%	-0.50%	2.93%	3.89%
Cultural & recreational	-3.00%	-3.18%	-0.93%	-0.91%

The approach used in this study also has advantages and disadvantages. Firstly, we consistently use the same exogenous real rate of return in the single stage aggregation process. However, in all but two sectors—Manufacturing and Wholesale trade—we have a database that is not balanced in the sense that the sum of capital and labour costs is not equal, on average, to gross value added. While neither approach is entirely satisfactory, we feel the use of the exogenous real rate of return adopted in this study is consistent with rationale ex-ante producer behaviour while also serving to highlight the non-robustness of the data in most sectors and the true importance of measurement problems in most sectors.

3.4 Econometric results

As noted in the preceding section, we have concentrated our econometric estimation on the five sectors where the available data appear consistent with a reasonable average real rate of return and, thus, appear most robust. These are the Manufacturing, Wholesale trade, Communications, Construction and Retail trade sectors. Statistically satisfactory results could not be obtained for the Communications sector and, thus, results are presented for the other four sectors below.

3.4.1 Manufacturing

Equations (23)–(25) were run for the Australian manufacturing industry using the data described in section 3 above. We set the base period markup factors $M_1 = M_2 \equiv M$ and chose only one break point, t_1^* equal to observation 12, based on a plot of residuals. This left 15 parameters to be estimated. We used the non-linear regression algorithm in SHAZAM (White 1997) to do the estimation. The estimated parameters and corresponding t-statistics are listed below in table 3.

Table 3: **Estimated parameters for manufacturing**

<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>	<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>
a	-2.8889	-1.04	d ₂	0.4427	2.29
b ₁	1.0765	8.48	e	0.3904	2.35
b ₂	1.0665	8.08	M	0.9241	8.09
c ₁₁	-0.0089	-0.77	m ₁₁	0.0211	1.92
c ₁₂	-0.0006	-0.06	m ₁₂	0.0206	1.53
c ₂₁	-0.0287	-3.59	m ₂₁	-0.0003	-0.04
c ₂₂	-0.0316	-3.26	m ₂₂	-0.0304	-3.05
d ₁	0.5742	2.34			

Source: Meyrick and Associates estimates

The R^2 for the three equations (23)–(25) were 0.9953, 0.9391 and 0.9981, respectively, indicating that the model fits the data very well.

We then use the definitions (26) to recover the markup factors for non-ICT inputs, $M_1(t)$, and for ICT inputs, $M_2(t)$, for each year t in our sample. We also use definition (27) to construct the measure of returns to scale, ρ^t , and definition (28) to construct the measure of technical progress, τ^t , for year t . These annual variables for manufacturing are presented in table 4.

Table 4: Scale, technical change and markup factor results for manufacturing

<i>Year</i>	<i>Returns to Scale</i> ρ^t	<i>Technical Change</i> τ^t	<i>Non-ICT Markup Factor</i> $M_1(t)$	<i>ICT Markup Factor</i> $M_2(t)$
1980	1.1374	0.0174	0.9240	0.9240
1981	1.1071	0.0168	0.9452	0.9237
1982	1.0786	0.0163	0.9663	0.9234
1983	1.0558	0.0178	0.9875	0.9231
1984	1.0283	0.0179	1.0086	0.9228
1985	1.0008	0.0172	1.0297	0.9225
1986	0.9749	0.0167	1.0509	0.9222
1987	0.9502	0.0162	1.0720	0.9218
1988	0.9288	0.0150	1.0932	0.9215
1989	0.9094	0.0139	1.1143	0.9212
1990	0.8862	0.0139	1.1354	0.9209
1991	0.8617	0.0142	1.1566	0.9206
1992	0.8391	0.0160	1.1772	0.8902
1993	0.8225	0.0157	1.1978	0.8598
1994	0.8101	0.0150	1.2184	0.8294
1995	0.8015	0.0140	1.2391	0.7990
1996	0.7860	0.0136	1.2597	0.7686
1997	0.7739	0.0129	1.2803	0.7382
1998	0.7663	0.0116	1.3009	0.7078
1999	0.7577	0.0104	1.3215	0.6774
2000	0.7475	0.0090	1.3422	0.6470
2001	0.7360	0.0081	1.3628	0.6166
2002	0.7230	0.0070	1.3834	0.5862
2003	0.7201	0.0054	1.4040	0.5558
Average	0.8835	0.0014	1.1655	0.8227

Source: Meyrick and Associates estimates

The results indicate that most of the productivity improvements in manufacturing over the last two and a half decades have been due to technical progress rather than increasing returns to scale. In fact, our regressions indicate that returns to scale in Australian manufacturing have averaged around 0.88, which is a situation of decreasing returns to scale. One explanation for this could be the increasing move from large scale, specialised plants of the past to smaller, flexible manufacturing plants where the plant can be more easily adapted to produce a wide range of products. The model produces an average estimate of technical change of 1.4 per cent per annum,

close to the trend index number productivity estimate from section 3.

With respect to the efficiency of ICT inputs, we find evidence that marginal units of ICT add more output than their cost and that this efficiency factor has been growing over time. On the other hand, our results show that non-ICT inputs add more output than their cost at the beginning of the sample period but over time, this has changed so that at the end of the sample period, non-ICT inputs were producing less output than their cost. Over the entire 24 year sample period, a marginal unit of ICT added to production that cost one dollar produce on average approximately $1/0.8227 \approx 1.2$ dollars worth of output according to our estimates. By 2003 an extra dollar of ICT inputs increased the value of manufacturing output by around 1.8 dollars.

For manufacturing the results show that both the assumptions of the traditional growth accounting models we are examining—constant returns to scale and the assumption that user costs reflect ICT's value in production—have to be seriously questioned. Based on our findings, the contribution of ICT to economic growth in manufacturing would be substantially undervalued using the traditional growth accounting methodology.

3.4.2 Wholesale trade

Equations (23)–(25) were run for the Australian wholesale trade industry using the data described in section 3 above. We set base period markup factors $M_1 = M_2 \equiv M$ and again chose only one break point, t_1^* equal to observation 12, based on the plot of residuals leaving 15 parameters to estimate. The estimated parameters are listed below in table 5. The R^2 for the three equations were 0.9035, 0.9165 and 0.9894, respectively.

Table 5: **Estimated parameters for wholesale trade**

<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>	<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>
a	-1.1139	-0.89	d ₂	0.1113	1.29
b ₁	1.1645	5.67	e	0.0000	0.00
b ₂	1.1013	5.25	M	0.8625	5.24
c ₁₁	-0.0477	-2.44	m ₁₁	0.0244	1.22
c ₁₂	0.0427	3.57	m ₁₂	-0.0070	-0.53
c ₂₁	-0.0621	-4.51	m ₂₁	-0.0395	-3.91
c ₂₂	-0.0318	-4.50	m ₂₂	0.0392	2.68
d ₁	0.0415	0.40			

Source: Meyrick and Associates estimates

The descriptive variables for scale, technical change and input markup factors in wholesale trade are listed in table 6. The results indicate there is evidence of increasing returns to scale for the years 1980–1996 and decreasing returns after 1996. Technical progress was strongly negative for the

years 1980–1991 and then turned positive. The markup factors for both non-ICT and ICT inputs started off at 0.8625, so that both inputs were producing more than their marginal costs. However, over time the efficiency of non-ICT inputs declined and while the efficiency of ICT inputs increased. Over the entire 24 year sample period, a marginal unit of ICT added to production that cost one dollar would produce on average approximately $1/0.6641 \approx 1.5$ dollars worth of output according to our estimates. Again, the contribution of ICT to economic growth in the wholesale trade would be substantially undervalued using the traditional growth accounting methodology.

Table 6: Scale, technical change and markup factor results for wholesale trade

<i>Year</i>	<i>Returns to Scale</i> ρ^t	<i>Technical Change</i> τ^t	<i>Non-ICT Markup Factor</i> $M_1(t)$	<i>ICT Markup Factor</i> $M_2(t)$
1980	1.1999	-0.0430	0.8625	0.8625
1981	1.1859	-0.0451	0.8869	0.8230
1982	1.1775	-0.0479	0.9113	0.7835
1983	1.1744	-0.0509	0.9357	0.7440
1984	1.1663	-0.0544	0.9601	0.7045
1985	1.1460	-0.0580	0.9846	0.6650
1986	1.1358	-0.0625	1.0090	0.6254
1987	1.1291	-0.0677	1.0334	0.5859
1988	1.1232	-0.0730	1.0578	0.5464
1989	1.1155	-0.0790	1.0822	0.5069
1990	1.1076	-0.0867	1.1066	0.4674
1991	1.1068	-0.0965	1.1310	0.4279
1992	1.0867	0.0483	1.1240	0.4671
1993	1.0644	0.0439	1.1169	0.5063
1994	1.0425	0.0393	1.1099	0.5456
1995	1.0272	0.0363	1.1029	0.5848
1996	1.0122	0.0342	1.0959	0.6241
1997	0.9988	0.0327	1.0889	0.6633
1998	0.9864	0.0286	1.0819	0.7026
1999	0.9755	0.0248	1.0749	0.7418
2000	0.9663	0.0216	1.0678	0.7811
2001	0.9552	0.0178	1.0608	0.8203
2002	0.9452	0.0157	1.0538	0.8596
2003	0.9368	0.0145	1.0468	0.8988
Average	1.0736	-0.0169	1.0411	0.6641

Source: Meyrick and Associates estimates

3.4.3 Construction

Equations (23)–(25) were run for the Australian construction industry using the data described in section 3 above. We set base period markup factors $M_1 = M_2 \equiv M$ and again chose only one break point, t_1^* equal to observation 11, based on the plot of residuals leaving 15 parameters to estimate. The estimated parameters are listed below in Table 7. The R^2 for the three equations were 0.5261, 0.4473 and 0.9949, respectively.

The descriptive variables for scale, technical change and input markup factors in construction are listed in table 8. Construction exhibited increasing returns to scale throughout the sample period with the average returns to scale being 1.27. This result seems consistent with the construction industry having relatively large fixed capital inputs with complementary labour and so returns to scale can be quite a bit greater than one until the capital equipment is fully utilised. Technical progress was strongly negative for the years 1985–1993 but turned positive in 1999.

Table 7: **Estimated parameters for construction**

<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>	<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>
a	-4.1040	-3.24	d ₂	-0.4258	-5.02
b ₁	1.5791	9.89	e	2.3137	5.39
b ₂	1.5281	9.35	M	0.6523	8.95
c ₁₁	-0.0546	-2.93	m ₁₁	0.0262	2.16
c ₁₂	0.0351	4.82	m ₁₂	-0.0250	-3.40
c ₂₁	-0.0393	-1.42	m ₂₁	-0.0069	-0.55
c ₂₂	0.0317	1.61	m ₂₂	-0.0268	-3.18
d ₁	0.3667	2.21			

Source: Meyrick and Associates estimates

The markup factor for both non-ICT and ICT inputs was below 1 for all observations, indicating that the addition of a marginal non-ICT input or the addition of a marginal ICT input produced more revenue than its respective cost. Over the entire sample period, a marginal unit of ICT added to production that cost one dollar would produce on average approximately $1/0.4975 \approx 2$ dollars worth of output according to our estimates.

3.4.4 Retail trade

Equations (23)–(25) were run for the Australian retailing industry using the data described in section 3 above. We set base period markup factors $M_1 = M_2 \equiv M$. For the technology index we chose two break points, t_1^* and t_2^* equal to observations 6 and 10. However, for the non-ICT input markup factor splines, we used only one break point at observation 10 and for the ICT markup factor, we had only a single time trend leaving us with a total of 17 parameters to estimate. The

estimated parameters are listed below in Table 17. The R^2 for the three equations were 0.4115, 0.4636 and 0.9987, respectively.

Table 8: Scale, technical change and markup factor results for construction

<i>Year</i>	<i>Returns to Scale</i> ρ^t	<i>Technical Change</i> τ^t	<i>Non-ICT Markup Factor</i> $M_1(t)$	<i>ICT Markup Factor</i> $M_2(t)$
1980	1.4987	-0.0071	0.6523	0.6523
1981	1.4241	-0.0092	0.6785	0.6454
1982	1.3820	-0.0096	0.7048	0.6384
1983	1.3920	-0.0056	0.7310	0.6315
1984	1.3543	-0.0047	0.7573	0.6246
1985	1.2717	-0.0089	0.7835	0.6177
1986	1.2177	-0.0108	0.8098	0.6107
1987	1.1689	-0.0125	0.8360	0.6038
1988	1.1244	-0.0142	0.8622	0.5969
1989	1.0765	-0.0184	0.8885	0.5900
1990	1.0398	-0.0208	0.9147	0.5830
1991	1.0844	-0.0062	0.8898	0.5563
1992	1.1403	-0.0103	0.8648	0.5295
1993	1.1769	-0.0078	0.8399	0.5028
1994	1.2106	-0.0058	0.8149	0.4760
1995	1.2339	-0.0031	0.7899	0.4493
1996	1.2690	-0.0025	0.7650	0.4225
1997	1.3098	-0.0026	0.7400	0.3957
1998	1.3315	-0.0010	0.7151	0.3690
1999	1.3422	0.0010	0.6901	0.3422
2000	1.3327	0.0039	0.6652	0.3155
2001	1.3699	0.0037	0.6402	0.2887
2002	1.3866	0.0045	0.6152	0.2620
2003	1.3882	0.0060	0.5903	0.2352
<i>Average</i>	1.2719	-0.0059	0.7600	0.4975

Source: Meyrick and Associates estimates

The descriptive variables for scale, technical change and input markup factors in retail trade are listed in table 10. The industry exhibited decreasing returns to scale throughout the sample period with the average returns to scale being 0.8924. However, near the end of the sample period, returns to scale approached one. Technical progress was strongly negative for the years 1986–89 (although

this most likely indicates data problems for these years) but positive in other years. The markup factor for non-ICT inputs was well above one for all years, averaging 1.45. This indicates a lack of profit maximising behaviour on the part of retailers because they are hiring marginal units of non-ICT inputs at prices higher than the marginal output that they produce. On the other hand, the markup factors for ICT inputs were less than 1 for all years after 1984 with an average ICT markup factor of 0.6982. Thus over the entire 24 year sample period, a marginal unit of ICT added to production that cost one dollar would produce on average approximately $1/0.6982 \approx 1.4$ dollars worth of output according to our estimates. The contribution of ICT to economic growth in retail trade would be substantially undervalued using the traditional growth accounting methodology.

Table 9: Estimated parameters for retail trade

<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>	<i>Parameter</i>	<i>Estimate</i>	<i>t-statistic</i>
a	0.8443	0.40	d ₁	0.0678	0.22
b ₁	0.8488	2.74	d ₂	0.0817	0.43
b ₂	0.8219	2.68	d ₃	-0.1049	-1.70
c ₁₁	-0.0003	0.00	e	-0.7049	-4.72
c ₁₂	-0.0690	-2.12	M	1.2015	2.69
c ₁₃	0.0085	0.97	m ₁₁	0.0446	0.58
c ₂₁	-0.0250	-1.90	m ₁₃	-0.0158	-1.09
c ₂₂	-0.0220	-1.52	m ₂₁	-0.0438	-2.71
c ₂₃	0.0090	0.95			

Source: Meyrick and Associates estimates

3.5 Conclusions

In this study we have set out to address two key questions:

- Do the assumptions underlying the index-based productivity measures adequately capture the ‘Information Revolution’ characteristics of ICT? and,
- Can the contribution of ICT to the competitive transformation of the economy be identified from these productivity measures?

To address the first question, we have concentrated our efforts on examining whether there is evidence of non-constant returns to scale in Australian industry and whether standard user cost formulae reflect the value of ICT to producers. We have found varying evidence with respect to returns to scale with one of the four industries examined exhibiting increasing returns for all of the 24 year period, two for part of the period and decreasing returns for the balance of the period and the fourth exhibiting decreasing returns for the whole period. However, we have found consistent evidence across all industries examined that ICT contributes more to output than its cost to producers. This result comes through uniformly despite manifold data limitations in some sectors.

This means that the standard growth accounting productivity measures will not adequately capture the ‘Information Revolution’ characteristics of ICT.

Table 10: **Scale, technical change and markup factor results for retail trade**

<i>Year</i>	<i>Returns to Scale</i> ρ^t	<i>Technical Change</i> τ^t	<i>Non-ICT Markup Factor</i> $M_1(t)$	<i>ICT Markup Factor</i> $M_2(t)$
1980	0.8732	0.0083	1.2015	1.2015
1981	0.8666	0.0076	1.2461	1.1577
1982	0.8623	0.0067	1.2907	1.1140
1983	0.8556	0.0059	1.3353	1.0702
1984	0.8514	0.0050	1.3799	1.0264
1985	0.8513	0.0036	1.4245	0.9827
1986	0.8467	-0.0570	1.4691	0.9389
1987	0.8354	-0.0606	1.5137	0.8951
1988	0.8247	-0.0654	1.5583	0.8514
1989	0.8115	-0.0706	1.6029	0.8076
1990	0.8349	0.0004	1.5871	0.7638
1991	0.8495	0.0007	1.5713	0.7201
1992	0.8627	0.0009	1.5556	0.6763
1993	0.8791	0.0014	1.5398	0.6325
1994	0.8951	0.0022	1.5240	0.5888
1995	0.9137	0.0033	1.5083	0.5450
1996	0.9265	0.0038	1.4925	0.5013
1997	0.9359	0.0036	1.4767	0.4575
1998	0.9478	0.0042	1.4609	0.4137
1999	0.9594	0.0047	1.4452	0.3700
2000	0.9703	0.0053	1.4294	0.3262
2001	0.9796	0.0057	1.4136	0.2824
2002	0.9886	0.0060	1.3979	0.2387
2003	0.9969	0.0063	1.3821	0.1949
Average	0.8924	-0.0070	1.4503	0.6982

Source: Meyrick and Associates estimates

In answer to the second question, the fact that ICT consistently contributes more to output than its user cost means that the contribution of ICT to economic growth will be undervalued in the traditional growth accounting methodology. Consequently, failure to find an important role for ICT in explaining economic growth in these studies does not mean that the rapid uptake of ICT is not a

major driver of economic growth. Indeed, the results of this study indicate that greater attention to the uptake of ICT may have an important role in improving economic growth.

Our results differ from those of Connolly and Fox (2004) who found an uneven distribution of benefits from investing in high-tech capital across sectors and little evidence of excess returns to high-tech capital using Cobb–Douglas based regressions. The methodology developed in this represents a further advance in the modelling of the relationship between ICT and productivity.

Another important conclusion from the study is that the analysis of sectoral productivity presented in section 3 highlights some major shortcomings in the available data. Many of the sectoral productivity results are not credible. This applies particularly to the services sectors where the use of ICT inputs allows ‘quality’ gains in outputs to be achieved and the range of available outputs to be greatly increased, neither of which is fully captured in the price indexes available for the services. This effect is exacerbated because the price index for ICT inputs does reflect technological drift while the price indexes for services outputs do not, leading to measured MFP growth being diminished. The database indicates that MFP in 7 out of the 12 market sectors was lower in 2003 than it was in 1980 when using a reasonable ex-ante rate of return to calculate user costs—a result that is simply not credible in light of the technological change and microeconomic reform that has occurred over the last two decades.

A major emphasis going forward has to be on improving the quality of available data and making sure that it better reflects changes in quality in the services sectors in particular. While statistical agencies are making advances in measuring the outputs of so-called ‘hard to measure’ sectors, work in this important area is in its relative infancy and efforts need to be redoubled. At a more basic level, this study has highlighted significant problems with the internal rates of return used to form rental prices for capital inputs and the potential sensitivity of productivity measures to alternative ways of addressing these problems.

References (chapter 3)

- Australian Bureau of Statistics (ABS) (2000), *Australian National Accounts: Concepts, Sources and Methods*, Catalogue 5216.0, Canberra.
- Australian Bureau of Statistics (ABS) (2003), *Australian System of National Accounts*, Catalogue 5204.0, Canberra, November.
- Balk, B.M. (2003), 'The Residual: On Monitoring and Benchmarking Firms, Industries, and Economies with Respect to Productivity,' *Journal of Productivity Analysis* 20, 5–47.
- Bartelsman, E.J. (1995), 'Of Empty Boxes: Returns to Scale Revisited,' *Economics Letters* 49, 59–67.
- Basu, S. and J.G. Fernald (1997), 'Returns to Scale in U.S. Production: Estimates and Implications,' *Journal of Political Economy* 105, 249–283.
- Basu, S. and J.G. Fernald (2002), 'Aggregate Productivity and Aggregate Technology,' *European Economic Review* 46, 963–991.
- Caves, D.W., L. Christensen, and W.E. Diewert (1982a), 'Multilateral Comparisons of Output, Input, and Productivity Using Superlative Index Numbers,' *Economic Journal* 92(365), 73–86.
- Caves, D.W., L. Christensen, and W.E. Diewert (1982b), 'The Economic Theory of Index Numbers and the Measurement of Input, Output, and Productivity,' *Econometrica* 50(6), 1393–1414.
- Caves, D.W., L. Christensen and J.A. Swanson (1980), 'Productivity in U.S. Railroads, 1951–1974,' *Bell Journal of Economics* 11, 166–181.
- Caves, D.W., L. Christensen, and J.A. Swanson (1981), 'Productivity Growth, Scale Economics and Capacity Utilization in U.S. Railroads, 1955–1974,' *American Economic Review* 71, 994–1002.
- Connolly, E. and K.J. Fox (2004), 'The Impact of High-Tech Capital on Productivity: Evidence from Australia', University of New South Wales, Working Paper, April.
- Diewert, W.E. (1974), 'Applications of Duality Theory', in M.D. Intriligator and D.A. Kendrick (eds), *Frontiers of Quantitative Economics, Volume 2*, Amsterdam: North-Holland, pp. 106–171.
- Diewert, W.E. (1976), 'Exact and Superlative Index Numbers', *Journal of Econometrics* 4, 114–145.
- Diewert, W.E. (1978), 'Superlative index numbers and consistency in aggregation,' *Econometrica* 46(4), 883–900; and Ch. 9 in Diewert and Nakamura (1993), 253–74
- Diewert, W.E. (1992), 'The Measurement of Productivity', *Bulletin of Economic Research* 44(3), 163–198.
- Diewert, W.E. (2004a), 'Measuring Capital,' Department of Economics, University of British Columbia, Discussion Paper 04–10, <http://www.econ.ubc.ca/discpapers/dp0410.pdf>.
- Diewert, W.E. (2004b), 'Issues in the Measurement of Capital Services, Depreciation, Asset Price Changes and Interest Rates,' Department of Economics, University of British Columbia, Discussion Paper 04–11, <http://www.econ.ubc.ca/discpapers/dp0411.pdf>.

- Diewert, W.E. and K.J. Fox (1999), 'Can Measurement Error Explain the Productivity Paradox?', *Canadian Journal of Economics* 32(2), 251–280.
- Diewert, W.E. and K.J. Fox (2005a), 'On the Estimation of Returns to Scale, Technical Progress and Monopolistic Markups', revised version of Paper 57 presented at the SSHRC International Conference on Index Number Theory and the Measurement of Prices and Productivity, Vancouver, Canada, July and available at <http://www.ipeer.ca/SSHRC.htm>.
- Diewert, W.E. and K.J. Fox (2005b), 'Malmquist and Törnqvist Productivity Indexes: Returns to scale and technical progress with imperfect competition,' unpublished manuscript.
- Diewert, W.E. and D.A. Lawrence (2000); 'Progress in Measuring the Price and Quantity of Capital'; in L. Lau (ed), *Econometrics Volume 2: Econometrics and the Cost of Capital: Essays in Honour of Dale W. Jorgenson*, pp. 273–326.
- Diewert, W.E., T. Nakajima, A. Nakamura, E. Nakamura, and M. Nakamura (2005), 'The Definition and Estimation of Returns to Scale with an Application to Japanese Industries,' working paper.
- Diewert, W.E. and A.O. Nakamura (2005), 'The Measurement of Aggregate Total Factor Productivity Growth,' in J.J. Heckman and E.E. Leamer (eds), *Handbook of Econometrics*, Volume 6, North Holland.
- Diewert, W.E. and T.J. Wales (1987), 'Flexible Functional Forms and Global Curvature Conditions', *Econometrica* 55, 43–68.
- Fox, K.J. (2005), 'Returns to Scale, Technical Progress and Total Factor Productivity Growth in New Zealand Industries,' in W.E. Diewert, B.M. Balk, D. Fixler, K.J. Fox and A.O. Nakamura (eds), *Price and Productivity Measurement*, Trafford Press, forthcoming.
- Griliches, Z. (1963), 'Estimates of the Aggregate Agricultural Production Function from Cross-Sectional Data', *Journal of Farm Economics*, May 1963, 45(2), 419–428.
- Griliches, Z. (1964), 'Research Expenditures, Education, and the Aggregate Agricultural Production Function', *American Economic Review* 54(6), 961–974.
- Griliches, Z. (1967), 'Production Functions in Manufacturing: Some Preliminary Results', in M. Brown (ed), *The Theory and Empirical Analysis of Production*, NBER, Studies in Income and Wealth, New York: Columbia University Press, Vol 31, 275–340.
- Hall, R.E. (1988), 'The Relationship between Price and Marginal Cost in U.S. Industry', *Journal of Political Economy* 96, 921–947.
- Hall, R.E. (1990), 'Invariance Properties of Solow's Productivity Residual', in P. Diamond (ed), *Growth, Productivity, Employment*, Cambridge MA: MIT Press.
- Hall, R.E. and D.W. Jorgenson (1967), 'Tax Policy and Investment Behavior', *American Economic Review* 57, 391–414.
- Harberger, A. (1998), 'A Vision of the Growth Process,' *American Economic Review* 88(1): 1–32.
- Industry Commission (1997), *Productivity Growth and Australian Manufacturing Industry*, Staff Research Paper, Canberra.
- Jorgenson, D.W. (1963), 'Capital Theory and Investment Behaviour', *American Economic Review* 53, 247–259.

- Jorgenson, D.W. (1986), 'Econometric Methods for Modeling Producer Behaviour', in Z. Griliches and M.D. Intriligator (eds), *Handbook of Econometrics*, Vol III, New York: Elsevier Science Publishers BV, pp. 1842–1915.
- Jorgenson, D.W. (1989), 'Capital as a Factor of Production', in D.W. Jorgenson and R. Landau (eds), *Technology and Capital Formation*, Cambridge Mass.: MIT Press, pp. 1–35.
- Jorgenson, D.W. (1990). 'Productivity and Economic Growth', in E. Berndt and J. Triplett (eds), *Fifty Years of Economic Measurement*, University of Chicago Press, Chicago.
- Jorgenson, D.W. (2001), 'Information Technology and the U.S. Economy,' *American Economic Review* 91 (1), 1-32.
- Jorgenson, D.W. and Z. Griliches (1967). 'The Explanation of Productivity Change', *Review of Economic Studies* 34, 249–283.
- Klette, T.J. (1999), 'Market Power, Scale Economies and Productivity: Estimates from a Panel of Establishment Data,' *Journal of Industrial Economics* 47(4), 451–476.
- Lawrence, D. (2002), 'The Australian Electricity Supply Industry's Productivity Performance', Appendix 2 in *COAG Energy Market Reforms*, Report prepared by ACIL Tasman for the COAG Energy Market Review Panel (Parer Review), Canberra.
- Lawrence, D. and W.E. Diewert (1999), *Measuring New Zealand's Productivity*, The Treasury Working Paper 99/5, Wellington.
- Lipsey, R.G. (2005), 'Policy Challenges in the New Economy,' in R. Lipsey and A.O. Nakamura (eds), *Services Industries and the Knowledge Based Economy*, Calgary: University of Calgary Press.
- Lipsey, R.G. and K. Carlaw (2004), 'Total Factor Productivity and the Measurement of Technological Change,' *Canadian Journal of Economics* 37(4), 1118–50.
- McFadden, D. (1978), 'The General Linear Profit Function', in M. Fuss and D. McFadden (eds), *Production Economics: A Dual Approach*, Volume 1, , Amsterdam: North Holland, pp. 269-28.
- Meyrick and Associates (2003), *Regulation of Electricity Lines Businesses, Analysis of Lines Business Performance—1996–2003*, Report prepared for the New Zealand Commerce Commission, Canberra.
- Morrison, C.J. and D. Siegel (1997), 'External Capital Factors and Increasing Returns in U.S. Manufacturing,' *Review of Economics and Statistics*, 647–654.
- Nakajima, T., M. Nakamura and K. Yoshioka (1998), 'An Index Number Method for Estimating Scale Economies and Technical Progress Using Time-Series of Cross-Section Data: Sources of Total Factor Productivity Growth for Japanese Manufacturing, 1964-1988', *Japanese Economic Review* 49, 310–334.
- Nakajima, T., M. Nakamura and K. Yoshioka (2001), 'Economic growth: past and present,' in M. Nakamura (ed), *The Japanese Business and Economic System: History and Prospects for the 21st Century*, New York: Palgrave/MacMillan/St.Martin's Press, 13–40.
- Panzar, J.C. (1989), 'Technological Determinants of Firm and Industry Structure,' in R. Schmalensee and R.D. Willig (eds), *Handbook of Industrial Organization*, Volume I, Elsevier Science Publisher, 3–59.

- Productivity Commission (PC) (2004), *Productivity Estimates to 2002-03*, March, Canberra, (<http://www.pc.gov.au/>).
- Robbins, G. and A. Robbins (1992), *Capital, Taxes and Growth*, Policy Report No.169, National Centre for Policy Analysis, Dallas, Texas.
- Solow, R.M. (1957), 'Technical Change and the Aggregate Production Function,' *Review of Economics and Statistics* 39, 312–320.
- Schreyer, P. (2001), *OECD Productivity Manual: A Guide to the Measurement of Industry–Level and Aggregate Productivity Growth*. Available for download in unabridged form at http://www.oecd.org/catch_404/?404;http://www.oecd.org/subject/growth/prod-manual.pdf.
- White, K.J. (1997), *SHAZAM User's Reference Manual Version 8.0*, McGraw–Hill, Vancouver.
- Yoshioka, K., T. Nakajima and M. Nakamura (1994), *Sources of Total factor Productivity*, Keio Economic Observatory, Keio University.

Chapter 4

4 Kenneth Carlaw¹

The Role of ICT in Australia's economic performance²

**An investigation of assumptions influencing the
productivity estimates**

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4 Kenneth Carlaw

4.1 Introduction

This study is about the economic growth or lack thereof caused by information and communication technology (ICT). Has ICT caused a revolution in global production and communication, or not? The answer to this question lies in separating the diffusion of this technology from measured output or productivity gains generated by it.

There seems to be little disagreement that computers, the Internet and the myriad supporting complementary technologies that they have enabled, have revolutionized production taking the world into the age of the global economy¹— an economy characterised by integrated transportation services, virtually instantaneous global communication, just-in-time or lean production, and un-hierarchical footloose multinational firms that can chase cheap factors of production around the globe. What is debated is whether this technological revolution is having the kinds of revolutionary influences on economic growth that were witnessed with the first and second industrial revolutions, themselves based on the technologies of automated textile manufacturing and steam in the case of the first and electricity, machine tools and chemicals manufacturing in the case of the second. In short, is the revolutionary technology of ICT leading to revolutionary growth?

Economic historians and students of technology agree that technological change is *the* major determinant of very long-term economic growth. If we knew no more than Victorian Age Europeans, our living standards would not be far above theirs, perhaps slightly more, due to such things as more capital accumulation, but not much.² Yet, over shorter periods of time, there is debate over what proportion of measured economic growth is due to technological change and what to other forces, such as the accumulation of physical and human capital. Such debates imply that we are able to separate the effects of technological change from those of the other determinants. Our view is that in order to become productively useful all technological knowledge must become embodied in some real physical component of the work whether it is physical or human capital (including all tacit skills), laws and legal institutions, or social and cultural norms. Furthermore, each of these

¹ However, some economist, such as, Young (1992) and Krugman (1996) commenting on Young argue that the lack of high total factor productivity in the Asian economies that experience exceptional growth in GDP per capita through the 1970s and 1980s is evidence that no technological revolution occurred in these economies.

² Of course, technological change and investment are interrelated, the latter being the main vehicle by which the former enters the production process.

embodiments requires costly investment. So the separation of the contribution of technological change from the contribution measured factors such as physical and human capital to economic growth is difficult. The key to connecting technological change to economic growth lies in identifying specific embodiments of new technology and determining their contribution to economic growth over a long horizon.

Currently ICT is the technology at the centre of the debate on long-run productivity growth. Also at the centre of this debate is the so called productivity paradox, namely, the combination of a number of stylised and anecdotal observations about the proliferation of computers and ICT with the statistical observation of a decline in the growth rate of total or multi - factor productivity (TFP or MFP)³ in many OECD countries, starting in the early 1970s and running through to the middle of the 1990s. This paradox is typified by Solow's (1987) quip that the computer is everywhere except in the productivity statistics. The erroneous presumption that underwrites the paradox is that TFP measures technological change in a perfectly contemporaneously correlated fashion.

One view in this debate holds that the paradox has been resolved by the emergence of the New Economy in the United States as evidenced by the measured increase in TFP growth starting in the mid 1990s. (See for example Baily 2002.) An alternative view is that there is no paradox at all because the productivity statistics show that no technological revolution has occurred. For one example, see Young 1992 and Krugman 1996 commenting on the growth experience of Hong Kong, Singapore, Taiwan and South Korea. For another example see Triplett (1999) and Gordon (2000) arguing that there is no exceptional growth driven by the introduction of computing technologies.⁴

Yet another view is that there is no paradox because there is a real technology cycle that causes real productivity slowdowns.⁵ David (1990) and David and Wright (1999) observe such a cycle with the introduction of electricity in to US manufacturing in late 19th and early 20th centuries. In line with this view a number of students of general purpose technologies (GPTs)⁶ argue that the introduction of new GPTs can cause large structural adjustment costs as the economy exploits the new technology. (See for example Helpman and Trajtenberg (1998a and b), Howitt (1998), Aghion and Howitt (1998) and Lipsey, Bekar and Carlaw (1998b)). These theoretical views reconcile the observed facts of large-

³ TFP and MFP are treated as synonyms for the purposes of this .

⁴ Triplett's argument is based on the observation that it is not sufficient to observe that there are a number of new products introduced as the result of a new technology. The important factor is that the rate of introduction of new products has increased from one technology to the next. Only in the latter case will TFP growth show an increase. Gordon argues that despite productivity numbers that match or exceed those of the second Industrial Revolution, the current productivity boom in the US driven by computing technology is not as large as that experienced between 1870 and 1913.

⁵ See Helpman (1998) for a number of theoretical and historical views on how major new general purpose technologies maintain and affect long-run economic growth.

⁶ Lipsey, Bekar and Carlaw (1998a) define GPTs as technologies that have massive scope for improvement, come to have pervasive range and variety of use in an economy and that have myriad technological complementarities with existing and yet to be invented technologies.

scale technological change with initial declining productivity numbers by noting that some technological change brings with it a costly adjustment process.

Lipsey, Bekar and Carlaw (1998b) argue that the pattern is not necessarily inherent in the new GPTs themselves, but it is a possible outcome of the interaction between new GPTs and the existing economic structure into which they are introduced. If there is sufficient friction between the new technologies and the existing economic structure, including necessary redesigns of physical capital, reskilling of human capital and changes in the organisational technology of firms then a real productivity slowdown can follow the introduction of a transforming GPT for a time. But the introduction of the GPT ultimately rejuvenates growth and there is a long term productivity benefit.

This last view of the productivity slowdown points to an obvious disagreement in the literature on the interpretation of TFP. Carlaw and Lipsey (2003) and Lipsey and Carlaw (2004) highlight three different interpretations that the literature on productivity gives to TFP. In one interpretation already illustrated by the references to Young and Krugman, TFP change is taken as a measure of contemporaneous technological change. An alternative interpretation espoused by Jorgenson and Griliches (1967), Nelson (1964), Rymes (1971) and Hulten (1979 and 2000) is that TFP change is not a measure of technological change but is ideally a measure of the productivity bonuses associated with technological change. Carlaw and Lipsey (2003) and Lipsey and Carlaw (2004) agree with this view if the measurement of TFP change can be taken under ideal conditions. However, they argue that such conditions do not often exist in real world circumstances and demonstrate that TFP will not measure productivity bonuses under these circumstances. A third interpretation is that TFP is a measure of ignorance and nothing more. (See Abromovitz 1956) Obviously all three interpretations of TFP cannot be correct.

We adopt the second interpretation that TFP change is ideally a measure of the productivity bonuses associated with technological change but with the caveat that it often does not even measure these properly. This requires that we explain why TFP change is not a measure of technological change. We also argue that the diverging interpretations of TFP stem from differing definitions of technological change used by various authors. One definition of technology is derived from observed outputs in relation to measured inputs, making no explicit accounting of actual underlying technology or processes of change associated with technology. An alternative definition explicitly defines technology by specific characteristics that are independent of output. This view seeks to understand the process of change driven by particular new technologies in terms of these characteristics and in terms of interrelationships new technologies have with existing technology and the economic structure that embodies it. We adopt this second view in our analysis that follows.

In the next two sections, we examine in turn the issues of what TPF change measures and how technological change is defined. We next turn our attention to modelling the

relationship between technology and economic performance with the model of GPT-driven endogenous growth developed in section 4. Having developed our theoretical model we are able to return our attention to the issue of TFP. In section 5 we use simulated data from our model to determine under what if any conditions TFP measures technological change. In section 6 we return to the empirical evidence for Australia and show that the pattern of ICT diffusion and measured TFP change among industries in Australia matches with the pattern of these to rates of change predicted from a model of GPT-driven growth with explicit structural adjustment costs. Section 7 concludes.

4.2 TFP change is not a measure of technological change

There are two ways to demonstrate that TFP change is not a measure of technological change. First, endogenous technological change is brought about by the allocation of resources that have opportunity costs to the activity that generates the new technology. Second, measures of technological change, which are independent of measures of economic performance, show a negative correlation with the pattern of TFP change.

4.2.1 Costly technological change

Virtually all technological change becomes embodied in one form or another: new or improved products, capital goods or other forms of production technologies, and new forms of organization in finance, management or on the shop floor. Almost all of technological change results from resource-using activities and the costs involved in creating such change are more than just conventional R&D costs. They include costs of installation, acquisition of tacit knowledge, learning by doing in making the product, and learning by using it, plus a return on the entrepreneurial investment of funds in development costs. Lipsey and Carlaw (2004) refer to the sum of these as ‘development costs.’⁷

To illustrate the point that TFP change will not measure costly technological change consider the hypothetical case where the new technology is embodied in physical capital (e.g., machines). Rational firms developing such machines will expect to recover all of their development costs in the selling price of the new capital good. This implies that the price of the capital good will capitalize all development costs. Consider the example taken from Lipsey and Carlaw (2004) where an existing machine is improved so that it does more work on the same job than its predecessor. The value of the production version of the new machine’s marginal product in the user industry is assumed to be v , which is also the maximum price that users will be willing to pay for each new machine. Assume that the

⁷ Jorgenson and Griliches (1967) argued that changes in TFP would only measure the gains in output that were over and above the development costs of the technological advance that caused the gains.

price required to just recoup the full development costs is w . Lipsey and Carlaw consider three cases.

If $w > v$, foresighted producers will not develop the machine and if they do, $\dot{TFP} < 0$.

If $w = v$, costs are just covered, the rise in the cost of the machine just equals the value of the new output and $\dot{TFP} = 0$. (3)

If $w < v$, profits are made and $\dot{TFP} > 0$.

‘In case (3), there is a return over and above what is needed to recover the development costs that created the innovation. This will be shared between the capital goods producers and the users in a proportion that will depend on the type of market in which the good is sold. In all three cases, we have technological change. This is the sense in which changes in TFP do not measure technological change *per se* but only the profits that it produces (as well as some productivity bonuses). Thus, zero change in TFP does not mean zero technological change. It only means that investing in R&D has had the same marginal effect on income as investing in existing technologies (investment with no technological change) and that there are no external effects that show up in current increases in output elsewhere in the economy without corresponding current increases in inputs.’ (Lipsey and Carlaw (2004))

Lipsey and Carlaw (2004) consider cases where new technology becomes embodied in human capital as well with a similar argument resulting. They also consider the case of costly disembodied technological change and show that ‘None of the above conclusions would be altered if the technological changes were disembodied because all that matters for changes in TFP is whether there is an increase in inputs to offset any observed increase in outputs. Thus, contrary to what is often stated in the literature, disembodied technological change does not necessarily raise TFP.’ (Lipsey and Carlaw 2004)

4.2.2 Some empirical evidence

The contributions of embodied technological change to TFP growth have been studied in the growth accounting literature. Hulten (1992) and Jorgenson (1966) have focused on the measurement of the efficiency of the capital stock and the effects of measurement errors on productivity estimates. These authors argue that quality change (or Investment Specific Technological (IST) change growth) is difficult to observe, and therefore may not be measured accurately in the National Income and Product Accounts (NIPA). In order to obtain an estimate of the size of error associate with the official capital stock estimates, Hulten used quality-corrected data from Gordon (1990). Gordon found that the official deflators for producer durable equipment overstate quality-corrected inflation in capital goods, and therefore understate increases in capital input.

Following Greenwood et al (1997 and 2000), Carlaw and Kosempel (2004) adopt a computable general equilibrium approach to measuring changes in the quality of investment in Canada. They demonstrate that IST made important contributions to Canadian output growth during the 1961-96 period. One of the key results that they establish is that IST is negatively correlated with TFP particularly since 1974.

IST is calculated by making the unrealistic assumption that the economy, sector or industry under examination is in a perfectly competitive general equilibrium which has become characterized as the Ramsey-Cass-Koopmans model following the pioneering work of Ramsey (1928) Cass (1965) and Koopmans (1965). In this framework the microeconomic decisions of consumers determine the saving rates, levels of consumption and stocks of capital in the economy whose aggregate production capacity is characterised by a constant returns-to-scale production function defined over capital and labour.⁸

Within such a framework constant income share weights but an increasing capital to labour ratio can only be reconciled by an increasing quality of capital, which is the result that Carlaw and Kosempel (2004) verify empirically. In their analysis the measure of residual neutral technological growth (RNTG), which would be equal to TFPG in the absence of increases in investment quality, is negative over much of the period from 1974 onward. They interpret this negative measure to potentially indicate a structural adjustment cost associated with the adoption of the new technology implicit in the high quality capital investments of the sort discussed by David (1990) and Lipsey, Bekar and Carlaw (1998b). We return to this issue later in the study when we discuss the industry level Australian data.

The analysis of change in investment quality and TFPG for 16 OECD countries where comparable data was available reveals a negative relationship between ISTC and TFPG for most of the countries. The data span the period 1970 to 1997, although the time series are shorter for some of the countries included in the analysis. Correlations and their significance are calculated by linearly regressing TFPG on ISTC. This simple procedure allows for easy calculation of correlation between the two rates of change and its statistical significance, but makes some obviously flawed assumptions in that it is unlikely that the relationship between TFPG and ISTC is linear. It is useful, however, to demonstrate that there is clearly something wrong with TFPG as a contemporaneous measure of technological change. We report these results in Table 2.1. Plots of TFPG and ISTC over the period investigated are provided in Appendix I.

Table 2.1

⁸ It is important to note that the assumption of constant returns to scale is a very strong one and one on which the entire calculation depends. In the absence of constant returns to scale it is not clear that IST is solely a measure of investment quality. We maintain the assumption here and use the measure as being indicative of the point that TFP does not measure changes in technology even though our independent measure of technological change, IST, is itself likely imperfect.

	<i>Correlation</i>	<i>Significance</i>	<i>Ave. TFP growth</i>	<i>Ave. IST growth</i>
<i>Australia</i>	-0.2003968	-1.625798274	0.005659614	0.030617859
<i>Austria</i>	0.08229683	0.797660716	0.006229159	0.014620765
<i>Canada</i>	-0.0352858	-0.45167094	0.004854536	0.066904922
<i>Germany</i>	-0.9011252	-1.908711555	0.002441211	0.01003906
<i>Denmark</i>	0.05655763	0.486804643	0.006646929	0.013692764
<i>Spain</i>	-0.1684784	-1.193274005	0.007006918	0.017480885
<i>Finland</i>	-0.355621	-1.485503129	0.009873589	0.00124906
<i>France</i>	0.0950263	0.664095684	0.008940826	0.022266437
<i>United Kingdom</i>	-0.3561123	-3.451808317	0.008177637	0.011128314
<i>Greece</i>	-0.1231186	-2.570949582	0.000862841	0.025734561
<i>Ireland</i>	-0.0474524	-0.350604117	0.015489796	0.017249422
<i>Italy</i>	-0.029527	-0.184041154	0.005292738	0.010806238
<i>Japan</i>	0.42931646	2.932067842	0.009564838	0.039670992
<i>Netherlands</i>	0.29245471	2.300423326	-1.94774E-05	0.01748624
<i>New Zealand</i>	-0.2171726	-1.299822494	-0.00088776	0.049056889
<i>Sweden</i>	0.06241575	0.559180659	0.003969073	0.020516658

The results shown in Table 2.1 indicate that TFP and IST do not appear to be positively related to each other. In most cases there is a negative relationship, in two cases a significant one. Only in two cases is there a significant positive relationship. Given the assumptions necessary to make these calculations we do not draw any strong conclusions. But we take this as weak evidence that there is no general positive relationship between our independent measure of technological change and TFP growth. There is possibly a negative relationship over the period examined for some economies.

This limited empirical investigation points to two avenues of investigation. One option is to maintain the assumptions of the Ramsey-Cass-Koopmans model and analyse the potential for structural adjustment cost as being measured by negative RNT that shows up in both the Carlaw and Kosempel analysis and in the Analysis of the 16 OECD economies. But because of the highly abstract and aggregate nature of the model we think this may be less fruitful than the alternative that we will follow. In the next section we provide two definitions of technological change that are consistent with two interpretations of TFP. Then, in the section 4 we build two models based on the second definition and explicitly model structural adjustment rather than detecting it as an aggregate measurement phenomenon. The approach means that we are not forced to rely on the abstract assumptions of the stationary CGE model to compute measures of investment quality but rather can model technological change explicitly. We can then directly test whether TFP changes track technological changes and can return to the data with a more explicit set of empirical tests generated from the predictions of the model.

4.3 Definition of technology

As we noted in the introduction, measures of TFP change are often interpreted to be an indication of the rate of technological progress within an economy. This interpretation, predicated on a definition of technology in terms of output and its associated inputs at some level of aggregation, dates back at least to Solow (1956). In other words technology is not defined and measured independently. Rather it is implicitly defined by observations of economic performance variables and is measured as a residual of observed economic output net of observed inputs. Thus, in this view the measurement of technological change does not require observations that are independent of output. Nor is it necessary to develop a theory that explains how technology leads to economic growth because the two are conceptually inseparable. It does, however, require that the specific assumption of the theory of aggregate output and economic growth to hold in order for the measurement to be valid.

Again as noted in the introduction there are a number of economists that study productivity, economic history, technological change and economic growth who have argued that TFP is not a measure of technological change. This different view is predicated in part on recognition that technological change is largely endogenous to economic choices and bears the cost of the resources used, and as embodiment of technology requires investment, these resource costs are capitalized in the input measure of the TFP calculation. The view is also in part based on a definition of technological knowledge that is independent of the traditional aggregate outputs and inputs measures. Thus, Lipsey and Carlaw (2004) define technological knowledge ‘as the idea set that specifies all activities that create economic value. It comprises knowledge about product technologies, the specifications of everything that is produced, process technologies, the specifications of all processes by which goods and services are produced, and organisational technologies, the specification of how productive activity is organized. All these are often referred to as just technology...’ Technological knowledge for the most part enters the economic system by costly investment which embodies it in such things as human and physical capital, institutional and productive infrastructure, conventions, laws, and social norms.

In their monograph (Forthcoming 2005) *Economic Transformations: General Purpose Technologies and Long Term Economic Growth*, Lipsey, Carlaw and Bekar outline in great detail how the economic structure of a society is altered by certain GPTs that they call ‘transforming GPTs’. It is often the case that there are long lags between the invention of such technologies and the economic bonus that they yield. Some reasons for these lags are that: all technologies start out crudely and relatively under developed; the system into which they become embodied must be altered via costly investment to exploit them; there are often entrenched interests that fight the technologies’ introduction to the system because the introduced technology may destroy rents enjoyed by those interests; and,

myriad complementary technologies have to be invented and then commercialized before the full potential of such GPTs can be exploited.

For these and other reasons detailed in Lipsey, Carlaw and Bekar (2005 forthcoming) there is no positive contemporaneous relationship between technological change and productivity change. In fact in a number of cases the theory predicts that productivity growth will slow or even fall as a result of the introduction of a new transforming GPT.

Furthermore a theory that explains how technologies enter the economy and come to have an influence on economic performance requires that the definition and measurement of technology be independent of economic performance. In section 2 we provided one such measurement of technological change in the form of IST growth. In section 5 we can directly measure technological change independent of economic performance because we know the necessary detail through the simulation model developed in the next section. Then, in section six, we are able to proximately measure the ICT diffusion rate with measure of the contribution of computers and software to the productive capital stock in Australia.

4.4 Models of GPT-driven growth

In this section, we first list the assumptions of our baseline model, which is based on Carlaw and Lipsey (2001), Carlaw and Lipsey (2005 forthcoming) and Lipsey, Carlaw and Bekar (2006 forthcoming, chapter 14). These assumptions capture the key stylized facts concerning GPTs, such as those listed in Carlaw and Lipsey (2005 forthcoming) and Lipsey, Carlaw and Bekar (2005 forthcoming). We use a series of footnotes to compare our assumptions with those made in other GPT models, many of which are reviewed in Chapter 11 of Lipsey, Carlaw and Bekar (2006 forthcoming). We then develop the model to include the endogenous structural adjustment that accommodates some new GPTs as noted by David (1990) in his observations of the economic impacts that followed the introduction of computers and the electric dynamo.

Our baseline model has three sectors: (i) a single consumption good, which we refer to as ‘the consumption sector’ (ii) R&D that produces applied knowledge that is used to develop applications of each GPT to specific purposes, called ‘the applied-R&D sector’ and (iii) fundamental research that produces the pure knowledge that leads to new GPTs, called ‘the pure research sector.’ In all cases, the sectors employ the same generic resource and are, therefore, related to each other by their resource opportunity cost as measured by the foregone current consumption that permits the productivity enhancing accumulation of technological knowledge.⁹ The production function in each sector displays diminishing

⁹ Aghion and Howitt (1998) employ three sectors in their model, and Helpman and Trajtenberg (1998b) employ m identical sectors in their diffusion model, most other GPT models use two sectors.

returns to the resources used. The models also display diminishing returns to accumulation in the absence of new GPTs, which are interrupted when a new GPT arrives by the temporary bursts of historical increasing returns of the sort discussed in Chapter 12 of Lipsey, Carlaw and Bekar (2005 forthcoming). But these increasing returns are only a temporary phenomenon because in all cases there are limits to the scale effects that can be exploited by each new GPT. So we do not have the kind of permanent increasing returns to accumulation found in many endogenous macro growth models.¹⁰

This allows us to focus attention on the complementarities and to model knowledge that grows irregularly. Our model's growth process is largely conditioned by the characteristics of each new GPT, such as those micro observations reviewed in Lipsey, Carlaw and Bekar (2005 forthcoming, Chapter 4).

We know that new GPTs create technological complementarities that rejuvenate the growth process. They enable new product, process and organisational technologies and the development of these sustain the productivity growth of both fundamental and applied research as a long-term trend. In our base-line model, we confine these complementarities to process technologies. When a new GPT is developed, it has a direct complementarity with pre-existing knowledge and current resources in the applied R&D sector, making them more productive. Output from the applied R&D sector enables the GPT to have an indirect complementarity with the consumption and pure knowledge sectors, as applied R&D knowledge goes into those sectors, making resources and prior knowledge in each more productive.^{11 12}

We use an individual logistic curve to represent the evolution of each GPT's impact on the marginal productivity of applied R&D, and hence on the consumption sector. The logistic curve models the observation that GPTs start crudely and only slowly develop a wide range of uses and many complementarities.¹³

¹⁰ For examples of endogenous growth models with increasing returns see Romer (1986) and Lucas (1988).

¹¹ Bresnahan and Trajtenberg's (1992) vertical and horizontal complementarities are similar to our technological complementarities. Other GPT models have a complementarity only between the GPT and its supporting components, which are created by the R&D sector for use along side the GPT in the final output sector. The components themselves are substitutes for each other, which does not mirror what we see with many complimentary components that comprise technology systems such as those described in Carlaw and Lipsey (2002).

¹² In Helpman and Trajtenberg (1998a), the effect of GPTs is registered through the rate of component development, which is linear. In Helpman and Trajtenberg (1998b) the effect of the GPT is registered through the combined effect of component development and the diffusion process, which holds back the impact of the GPT until all sectors that can use it have developed a threshold number of complementary components. Thereafter the GPTs impact linearly on the economy. Aghion and Howitt (1998) have an epidemic effect where the development of the GPT actually causes a reduction in output after a period of constant output. An increase in output finally occurs as a result of an epidemic diffusion process in their model.

¹³ This is the first major departure from the models of Carlaw and Lipsey (2001) and Carlaw and Lipsey (2006 forthcoming). Those models allowed the full productive impact of a GPT to enter the system upon the GPTs discovery. It is also in contrast to Helpman and Trajtenberg (1998a and 1998b) and Aghion and Howitt (1998) where once the GPT arrives in a given sector, its efficiency depends linearly on the development of

In common with all other models of GPTs, technology is assumed to have a hierarchical structure, meaning that some technologies are necessary antecedents for others.¹⁴ This is in contrast to standard aggregate growth models where technology is modelled by a single scalar multiple of the aggregate production function.

Technological change is modelled as a succession of GPTs that set the path dependent research agenda for further applied R&D.¹⁵

We introduce uncertainty in pure knowledge production in three ways: (i) the productivity of resources devoted to pure research in every period is subject to random fluctuations; (ii) the time period between arrivals of successive GPTs is of uncertain duration (but typically long); and (iii) the effect of a newly arrived GPT on productivity in the applied R&D sector is partly determined endogenously by the amount of resources devoted to the pure research sector since the last GPT was invented and partly by a random variable.¹⁶

For any given period, we assume that agents allocate resources among the three sectors according to the current expected marginal product of resources in each sector, which, under certain assumptions, is equivalent to perfect competition.¹⁷ Whatever the specific rule agents use for making allocations among the three sectors, we require only that they respond to relative differences in perceived rates of returns in the three sectors.¹⁸

In our model, agents do not know the precise future horizon of consumption payoffs to resources allocated to pure research because they do not know the probability distributions that are generating the disturbances on the outcomes, nor can they infer them from the behaviour of previous GPTs. So they form simple expectations of the payoffs to

components. Helpman and Trajtenberg (1998b) and Aghion and Howitt (1998) develop detailed theoretical mechanisms for diffusion of the GPT into applications. In each of these cases, the pattern of output is determined by the diffusion process across firms and sectors where the efficiency of the GPT in each sector increases with the development of components up to some maximum.

¹⁴ For example, as we have noted elsewhere, the electronic computer cannot exist without the power technology of electricity.

¹⁵ All other GPT models surveyed in Chapter 11 of Carlaw, L:ipsey and Bekar (monograph) verbally describe this succession of GPTs but concentrate on the formal dynamics of a single GPT from the time that it is exogenously introduced into the economy until it reaches full maturity.

¹⁶ In contrast, the impact and arrival date of new GPTs are exogenous in all other models except Aghion and Howitt (1992 and 1998). There the arrival rate of technologies/GPTs is subject to a Poisson arrival process but in the steady-state equilibrium that arrival rate is constant and conditional on the first moment of the Poisson distribution.

¹⁷ Within the framework developed here we could model the consumption sector and/or the applied R&D sector as being characterized by monopolistic competition. The sector in question would comprise several products differentiated by a parameter. Adding the complication of monopolistic competition does not affect the qualitative results so we retain the simpler assumption of perfect competition.

¹⁸ None of the GPT models reviewed in Chapter 11 of Carlaw, L:ipsey and Bekar (monograph) have endogenously generated GPTs. Therefore, there is no allocation of resources to a sector that generates new GPTs such as our pure knowledge sector. Aghion and Howitt (1992) have endogenously generated technological change where the allocation of labour to producing technological change is derived from a perfectly foresighted maximization based on a stationary Poisson distribution. In all of the GPT models allocations of resources to the sectors developing components and templates for the newly arrived GPT is based on forward looking expectations with stationary distributions.

investments based on their perceptions of the current period's marginal productivities. Given these expectations, they allocate resources so as to maximise the value of current consumption.¹⁹ This is meant to model agents as groping into an uncertain future in a profit oriented way.

In all other treatments, agents are modelled as having perfect foresight about the future evolution of new GPTs. Our assumption of no foresight seems closer to what we observe than the assumption that agents are sufficiently foresighted to maximise over the whole of a GPT's lifetime. Nonetheless, one might wonder if agents could learn over successive GPTs and thus eventually be able to anticipate the course of each new one. We reject this possibility because GPTs are technologically distinct from each other so that the histories of past GPTs provide little quantitative evidence about how new ones will behave. For example, knowing how electricity affected the economy over its evolution would tell agents virtually nothing about the details of the evolutionary paths to be expected over subsequent decades for all of the economic impacts of the computer at the time when Turing's machine was invented.²⁰ And this is in spite of the fact that electricity is necessary for computers.

The model generates a non-stationary equilibrium, such that neither the levels nor the rates of change of the endogenous variables converge to constants. There is a transitional competitive equilibrium in every time period, given the expected marginal productivities of inputs in each sector. But because of technological advance, the nature of the spillovers, and the absence of perfect foresight, the marginal products change from one period to the next in unanticipated ways. Although growth never stops, a very productive new GPT can accelerate the average growth rate over its lifetime while a less productive new GPT can slow it. This last characteristic allows us to focus on the historical, path dependent and variable pattern of growth. In contrast, other models typically use a steady state equilibrium concept.²¹

To summarize, our model has the following key characteristics. GPTs arrive at randomly determined times with an impact on the productivity of applied R&D that is determined by

¹⁹ As an alternative to our simple assumption, we could have assumed that agents are forward looking but do not foresee changes in the marginal products in all lines of production, which implies that they perform the dynamic programming problem each period taking the perceived marginal products in all lines of activities as being constant at the current period level. In the subsequent period, they repeat the procedure with the new marginal products encountered then. Since in our model these amount to the same thing qualitatively, we adopt the first assumption which is simpler.

²⁰ We add that, even if successive GPTs did substantially duplicate each other, learning about the future behaviour of a current GPT by studying the past behaviour of previous GPTs, would require that entrepreneurs knew more about economic history than does the typical economist, to say nothing of the typical business person.

²¹ Because agents are assumed to be able to foresee and to maximize over the life time of the GPT in all other GPT models, a stationary equilibrium is derived from the infinite horizon utility maximization. Even in Aghion and Howitt (1992), where there is randomness in the arrival rate of new technologies, the rate of innovation is constant in equilibrium. This is because their innovation arrival rate is derived from the expected value of the Poisson distribution with a parameter determined by the equilibrium flow of labour services into research.

the amount of pure research knowledge, which has been endogenously generated since the last GPT and elements of randomness. The sources of randomness defined above imply that short term outcomes are influenced by the particular realizations of the random variables, allowing the average growth rate of output over the lifetime of each successive GPT to differ from that of its predecessor. However, the average growth rate over long periods of time in which several GPTs succeed each other is determined by the accumulated amount of pure knowledge. This is partly endogenous (determined by the allocation of resources to pure research), and partly exogenous (determined by random factors affecting the productivity and timing of those resources). Furthermore, while some GPT driven research programs are richer than others, successive GPTs will not always either accelerate or decelerate growth on average over their lifetimes. There is no expectation that each new GPT will produce a productivity bonus in the form of acceleration in productivity growth.

4.4.1 Baseline three-sector model

There is a generic input called resources, R_t , that is initially allocated between the consumption sector, $r_{c,t}$, the applied R&D sector, $r_{a,t}$, and the pure knowledge sector $r_{g,t}$.²²

$$(1) \quad R_t = r_{c,t} + r_{a,t} + r_{g,t}.$$

The flow of consumption output, c_t in equation (2) is a function of the resources allocated to the consumption sector, $r_{c,t}$, and the productivity coefficient μA_{t-1} . We subsequently simplify the model by not lagging the stock of applied R&D in the production function for consumption. The parameter μ is used to apportion the stock of applied knowledge between consumption and pure knowledge production.

$$(2) \quad c_t = (\mu A_{t-1})^{\alpha_1} r_{c,t}^{\alpha_2} \text{ with } \alpha_i \in (0,1], \quad i = 1,2 \text{ and } \alpha_2 < 1.$$

The restrictions on the exponential parameter α_1 allows for the possibility of constant or diminishing returns to applied knowledge while that on α_2 ensures that there are diminishing returns to resources allocated to consumption. In subsequent models, we use both constant and diminishing returns to illustrate specific points about TFP calculations and spillovers.

The flow of applied R&D knowledge a_t in equation (3) is a function of the resources allocated to the applied R&D sector, $r_{a,t}$, and the productivity coefficient G_{t-1} . For consistency in the initial set up we have lagged the time subscript on G , however, we ultimately simplify by removing the lag in the effect of the stock variables on the production functions they enter. (See equation 3' below.)

²² The subscript t indicates a time index.

$$(3) \quad \begin{aligned} a_t &= \nu (G_{t-1})^{\beta_1} r_{a,t}^{\beta_2} \quad \text{with } \beta_i \in (0,1), \quad i=1,2 \text{ and } \beta_2 < 1. \\ A_t &= a_t + (1-\varepsilon)A_{t-1} \end{aligned}$$

The parameter ν is a calibration parameter for the subsequent simulations. The restrictions on the exponential parameters β_i ensure that there are diminishing returns to resources allocated to consumption and the possibility of constant or diminishing returns to pure knowledge. As in the case of the consumption sector, we use both constant and diminishing returns to illustrate specific points about TFP calculations and spillovers. The current stock of applied knowledge, A_t , is the accumulated flow of produced knowledge, a_t , plus the appropriately depreciated past accumulations of knowledge, A_{t-1} where the depreciation is due to an obsolescence factor, ε .

The flow of new pure knowledge, g_t is generated by:

$$(4) \quad g_t = ((1-\mu)A_{t-1})^{\sigma_1} \theta_t (r_{g,t})^{\sigma_2}, \quad 0 < \sigma_i \leq 1 \quad i=1,2, \text{ and } \sigma_2 < 1.$$

The restrictions on the exponential parameters σ_i ensure that there are diminishing returns to resources allocated to pure knowledge, $r_{g,t}$, while allowing for the possibility of constant or diminishing returns to applied knowledge, A_t . The productivity of the resources in this sector is affected, θ_t , which is a random variable distributed uniformly with support $[0.8, 1.2]$, mean 1, and variance $(0.4)2/12$. It models the observation that there is uncertainty about how much knowledge will be produced by a given amount of resources. The first part of this production function, $((1-\mu)A_{t-1})^{\sigma_1}$, allocates a proportion of the knowledge produced in the applied sector to be useful in the consumption sector and acts as the productivity coefficient for resources allocated to the pure knowledge sector. The current stock of pure knowledge, G_t^p , is the accumulated flow of produced knowledge, g_t , which is added to all past accumulations of knowledge, G_{t-1}^p , themselves depreciated by the obsolescence factor, δ , as follows,

$$(5) \quad G_t^p = g_t + (1-\delta)G_{t-1}^p.$$

Useful pure knowledge only enters the system and becomes G_t when a GPT is discovered. This occurs as a result of pure and applied R&D and when the realization of the random variable λ_t surpasses a threshold value λ^* . The model is calibrated by manipulating the parameters ν and η , which are defined below so that this realisation occurs infrequently.

$$(6) \quad G_t = G_{t-1} + \left(\frac{e^{\tau+\gamma(t-t_z)}}{1+e^{\tau+\gamma(t-t_z)}} \right) (G_t^h - G_{t-1}),$$

where

$$(7) \quad G_t^h = \begin{cases} G_{t-1}^h + \mathcal{G}(G_t^p - G_{t-1}^h) & \text{if } \lambda \geq \lambda^* \\ G_{t-1}^h & \text{otherwise} \end{cases},$$

and t_z is the arrival date of the z^{th} GPT and γ and τ are calibration parameters controlling the rate of diffusion.

λ^* is the threshold value of λ and \mathcal{G} is a random number that takes on only positive values (many of which are fractions). \mathcal{G} is a random variable that reflects the fact that the applied potential of GPTs vary in ways that cannot be predicted. Both λ and \mathcal{G} are derived from beta distributions, where each distribution is defined as $\text{beta}(x | \nu, \eta) = \frac{x^{(\nu-1)}x^{(\eta-1)}}{\text{Beta}(\nu, \eta)}$ with support $[0,1]$, mean $(\nu/(\nu+\eta))$ and variance $\frac{\nu\eta}{(\nu+\eta)^2(\nu+\eta+1)}$. $\text{Beta}(\nu, \eta)$ is the Beta

function, and ν and η are parameters which take on positive integer values. $\mathcal{G} = s(x_t)$ where s is a calibration parameter that can be set greater than one to allow occasional productivity bonuses with the arrival of some GPTs.²³

The evolution of actually useful pure knowledge (equation (6)) can most simply be seen as follows. Assume that the potential of the existing GPT has been fully exploited so that $G_t^h = G_{t-1}$. Now let a new GPT be discovered ($\lambda t > \lambda^*$). There is a discrete jump in $\mathcal{G} (G_t^p - G_{t-1}^h)$ in (7) and this amount slowly diffuses through each period of the GPTs existence into actually useful pure knowledge according to the logistic diffusion coefficient $\left(\frac{e^{\tau+\gamma(t-t_z)}}{1+e^{\tau+\gamma(t-t_z)}} \right)$

in (6). When another GPT arrives, there is a further discrete jump in G_t^h and the diffusion process begins again.

Once again the maximization problem can allow for intertemporal substitution and discounting. The Bellman equation for the three sector model is,

$$V(A_t, G_t, t) = \max_{\{r_{c,t}, r_{a,t}, r_{g,t}\}} c_t + \rho E[V(A_{t+1}, G_{t+1}, t+1)] + \rho^2 E[V(A_{t+2}, G_{t+2}, t+2)]$$

s.t.

$$(9.1) - (9.3),$$

$$\bar{g}_t = \nu \left((1-\mu)A_{t-1} \right)^{\beta_1} r_{g,t}^{\beta_2}$$

$$\bar{G}_t = \bar{g}_t + (1-\varepsilon)G_{t-1}$$

²³ \mathcal{G} can also be made endogenous in the following way: $\mathcal{G} = (s_t)(x_t)$, where $s = \kappa(G_t)^\omega$ and $\omega \in (0,1)$. (See Carlaw and Lipsey (2001) and Carlaw and Lipsey (2006) forthcoming for a detailed illustration of the model with this assumption.) This is a possibility that we don't explore further in this but it implies that the productivity impact of all future GPTs can increase through time as a result of the realisation of past GPTs.

where the upper bars indicate expected rather than the actual values of g_t and G_t . This is a complicated problem in two dimensions of state variables. We simplify by allowing the stocks of applied and pure knowledge to have immediate impact in the production functions for consumption, applied R&D and pure knowledge as follows:

$$(2') \quad c_t = (\mu A_t)^{\alpha_1} r_{c,t}^{\alpha_2} \text{ with } \alpha_i \in (0,1], \quad i = (1,2), \text{ and } \alpha_2 < 1$$

$$(3') \quad a_t = v(G_t)^{\beta_1} r_{a,t}^{\beta_2} \text{ with } \beta_i \in (0,1), \quad i = (1,2), \text{ and } \beta_2 < 1$$

$$(4') \quad g_t(r_{g,t}) = ((1-\mu)A_t)^{\sigma_1} \theta_t(r_{g,t})^{\sigma_2}, \quad 0 < \sigma_i \leq 1 \quad i = 1,2, \text{ and } \sigma_2 < 1$$

This allows for an easier expression of the maximization problem without affecting any of the qualitative results.

Maximization problem is:

(9)

$$\max_{\{r_{c,t}, r_{a,t}, r_{g,t}\}} c_t = (\mu A_t)^{\alpha_1} (r_{c,t})^{\alpha_2}$$

s.t.

$$R_t = r_{c,t} + r_{a,t} + r_{g,t}$$

$$A_t = a_t + (1-\varepsilon)A_{t-1}$$

$$a_t = vG_t r_{a,t}^{\beta_2}$$

$$\bar{G}_t = \bar{g}_t + (1-\delta)G_{t-1}$$

$$\bar{g}_t = ((1-\mu)A_t)^{\sigma_1} r_{g,t}^{\sigma_2}$$

Recursive substitution of the constraints into the objective function yields the following reduced form:

$$c_t = \left\{ \mu \left[v((1-\mu)E[A_t])^{\sigma_1} (r_{g,t})^{\sigma_2} + (1-\delta)G_{t-1} \right]^{\beta_1} (r_{a,t})^{\beta_2} + (1-\varepsilon)A_{t-1} \right\}^{\alpha_1} (r_{c,t})^{\alpha_2}.$$

The expectations operator is applied to the Stock of applied knowledge in this equation because there is a problem of simultaneous determination. We adopt the simplest of assumption of expectations by setting $E[A_t] = A_{t-1}$.²⁴

²⁴ Lipsey, Carlaw and Bekar (forthcoming 2005) provide a lot of detail on the transitions from one GPT to another giving four different versions of the model that deal with different nuances. Here we adopt their transition model one for convenience. In this case the new GPT comes into use immediately upon its arrival regardless of its productivity enhancing effects in the applied R&D sector relative to the old GPT.

4.4.2 Model of structural adjustment

A new GPT may be well or poorly adapted to the existing facilitating structure.²⁵ Typically real resources must be invested in substantial adjustments to many of the elements of the structure to accommodate the new GPT.²⁶

We begin with the simplifying assumption that all of the structural adjustments takes place in the applied R&D sector, which we justify on the grounds of simplicity and that this is where much actual structural adjustment takes place. Having the structural adjustment in one sector is sufficient to demonstrate the qualitative outcomes. Many of the actual structural adjustment problems do occur in the application of the GPT to various uses (e.g., the application of electricity to factories required a new organisational technology as well as several innovations in the applications of electricity to machines and tools).

Much of the previous model of the previous section is preserved when economic structure is explicitly included. Equations 2 and 4–9 are unaltered. The resource constraint is altered to reflect the fact that resources must be allocated among four instead of the original three lines of activity:

$$(10) \quad R_t = r_{c,t} + r_{a,t} + r_{g,t} + r_{s,t}$$

Where, r_s , is the resource allocated to structural adjustment. This adjustment is assumed to have effect only in the applied R&D sector. As with the previous model, the arrival of a new GPT increases G_t in equations (11). However, the arrival of the new GPT comes with a structural adjustment cost SA_t (equation 12) below, which reduces the immediate impact of the new GPT.

$$(11) \quad a_t = v \left((\chi G_t) (SA_t)^{\beta_3} \right)^{\beta_1} (r_{a,t})^{\beta_2} \quad \text{with } \beta_i \in (0,1), \quad i = (1,2), \quad \text{and } \beta_2 < 1.$$

$$A_t = a_t + (1 - \varepsilon) A_{t-1}$$

Where $\chi \in [0,1]$ apportions the amount of realised pure knowledge that influences applied R&D. (This assumption is made to simplify the subsequent total factor productivity calculations.) SA_t is defined as follows:

$$(12) \quad SA_t = \frac{S_t}{SC_t}.$$

²⁵ This observation is made by a number of historians and students of technological change such as David (1990), Freeman and Perez (1988), Freeman and Louca (2001), Perez (2002), Lipsey and Bekar (1995) Lipsey, Bekar and Carlaw (1998b), Lipsey, Carlaw, and Bekar (forthcoming 2005).

²⁶ Although we do not introduce labour explicitly in the model, we note that these structural adjustment costs can be severe when the arriving GPT causes big dislocations by separating significant numbers of workers from their work when an old technology is made obsolete.

This is a decreasing function of the total impact of the new GPT, defined as SC_t (equation 13), and an increasing function of the structural adjustment effort, S_t , that accumulates from the point that the GPT arrives (equation 14).

$$(13) \quad SC_t = SC_t + \left(\frac{e^{\tau_s + \gamma_s(t-t_2)}}{1 + e^{\tau_s + \gamma_s(t-t_2)}} \right) (SC_t^h - SC_{t-1})$$

$$SC_t^h = \psi_t (G_t^h - G_{t-1}^h).$$

SC_t is the cost of structural adjustment defined as a function of the total impact of the new GPT, which we model by taking the difference between the total value of the new GPT relative to the old and a random variable ψ_t drawn from a Beta distribution. The structural adjustment costs are assumed to follow a logistic diffusion process similar to the GPT itself. So that as the GPT has a bigger impact it creates more structural adjustment costs. However, in order to match the empirical observations that structural adjustment costs are up front and productivity benefits of GPTs are occur later made in earlier chapters we assume that $\gamma_s > \gamma$ $\tau_s < \tau$ so that the structural adjustment impacts occur more quickly than the productivity diffusion of the GPT.

S_t is the accumulated effort to adapt structure to a new GPT.

$$(14) \quad S_t = s_t + S_{t-1}(1 - \phi_t),$$

where

$$s_t = ((1 - \chi)G_t)r_{s,t}, \text{ and}$$

$$\phi_t = \begin{cases} \zeta & \text{if } \lambda \geq \lambda^* \\ 0 & \text{otherwise} \end{cases},$$

s_t is the output flow of structural adjustment and $(1 - \chi)$ is the proportion of pure knowledge that influences the productivity of resources in structural adjustment. s_t is dependent on the amount of resources devoted to producing adjustment in structure, $r_{s,t}$, and a portion of the stock of useful pure knowledge, $(1 - \chi)G_t$. This last assumption is made to ensure that resources devoted to producing structural adjustment increase in productivity at a rate similar to resources in all other lines of production in the system.

The two key sources of structural adjustment costs observed when a new GPT arrives, the new investment in structure that the new GPT requires due to its new complementarities with its many new applications and the amount of the old structure that is rendered useless by the new GPT are modelled as random variables. This is done to reflect the uncertainty about their size from GPT to GPT. The first random variable, ψ_t , conditions SC_t^h reflecting the amount of new investment in structure that is required due to the novelty of the

technology and its complementarities with new applications. The second random variable, ϕ_t depreciates or makes obsolete the previously accumulated investments in structure measured as the stock, S_t . During the life of an incumbent GPT, ϕ_t is zero and upon the arrival of the new GPT, ϕ_t is a random variable between 0 and 1 chosen from a uniform distribution. This implies that some of the structure that was adjusted to the existing GPT is not useful in facilitating the new GPT.

$$(15) \quad \psi_t = s_c [\text{beta}(x | \nu, \eta)], \quad 0 < s_c < 2$$

The constant s_c allows the random variable drawn from the beta distribution to take on values larger than one. This, combined with the calibration of ν and η , determines the probability that ψ_t is greater than or less than one. ζ is drawn from a Uniform distribution with support of $[0, 1]$.

The maximization problem includes the allocation of resources to structural adjustment as follows:

$$(16) \quad \begin{aligned} & \max_{\{r_{c,t}, r_{a,t}, r_{g,t}, r_{s,t}\}} c_t = (\mu A_t)^{\alpha_1} (r_{c,t})^{\alpha_2} \\ & s.t. \\ & R_t = r_{c,t} + r_{a,t} + r_{g,t} + r_{s,t} \\ & a_t = \nu \left((\chi G_t) (S A_t)^{\beta_3} \right)^{\beta_1} (r_{a,t})^{\beta_2} \\ & A_t = a_t + (1 - \varepsilon) A_{t-1} \\ & \bar{G}_t = \bar{g}_t + (1 - \delta) G_{t-1} \\ & \bar{g}_t = ((1 - \mu) A_t)^{\sigma_1} r_{g,t}^{\sigma_2} \end{aligned}$$

and equations 12 – 15

4.4.3 Simulation of the model

The model is solved using numerical simulation which requires calibrating parameter values. We choose values in order to achieve long run average growth rates of approximately 2% and GPT arrival rates of on average 30-35 periods. The qualitative results are robust to a wide range of parameter values that meet the restrictions specified in the model.

Table 4.1: Model parameters

Baseline three sector model

The parameter values chosen for this simulation are illustrative of a wide range of possible values that meet our assumptions. We have tested a range of these values to ensure the robustness of the qualitative results.

$$\begin{array}{llll} \alpha_1 = 1 & \alpha_1 = 0.34 & \beta_1 = 1 & \beta_2 = 0.34 \\ \sigma_1 = 1 & \sigma_2 = 0.34 & \nu = 1 & A_0 = 1 \\ G_0 = 1 & R = r_{c,t} + r_{a,t} + r_{g,t} = 1000 & \varepsilon = 0.01 & \delta = 0.01 \\ \gamma = 0.06 & \tau = -6 & \mu = 0.5 & \end{array}$$

For λ we choose $\nu = 5$ and $\eta = 10$. The threshold value of $\lambda^* = 0.64$.

For ϑ we choose $\nu = 10$, $\eta = 5$ and $s = 1$.

As stated in the text θ_t is a random variable distributed uniformly with support $[0.8, 1.2]$, mean 1, and variance $(0.4)^2/12$.

Structural adjustment, four sector model

The parameterization for the model of structural adjustment is the same as the baseline model with the following additions

$$\begin{array}{lll} \chi = 0.8 & R = r_{c,t} + r_{a,t} + r_{g,t} + r_{s,t} = 1000 & \beta_3 = 0.85 \\ \gamma_s = 0.08 & \tau_s = -8 & \end{array}$$

All other parameter values are defined in the text

The growth properties of this model are discussed at length in Carlaw and Lipsey (2001, 2006 forthcoming) and in Lipsey, Carlaw and Bekar (2005 forthcoming, Chapter 14). In this we wish to apply the model to an analysis of the assumptions of TFP measurement. It is this task that we turn our attention to next.

4.5 Calculating TFP and knowledge growth from simulated data

In this section we calculate TFP and technological knowledge growth rates using artificial data simulated from the models. This allows us to make predictions about the relationship between TFP growth and technological change and identify what assumptions of the model are critical to these relationships. Thus, we begin the process of developing a theory of TFP as it relates to technology driven economic growth. In particular we focus on the effect that structural adjustment has on the relationship between TFP growth and technological change as this is often an identifiable feature of what Lipsey, Carlaw and Bekar (2005 forthcoming) call transforming GPTs. (i.e., GPTs that require large transformations of the existing production system and open myriad previously impossible lines of production activity.)

4.5.1 TFP and technological change in the baseline model

In this section, we calculate TFP growth using our simulated data and ask under what conditions, if any, changes in TFP measure technological change.²⁷ These calculations illustrate our more general argument (given in the Appendix to Chapter 4 of Lipsey, Carlaw and Bekar (2005 forthcoming), Carlaw and Lipsey (2003) and Lipsey and Carlaw (2004)) that changes in TFP ideally measure only a small subset of the spillovers associated with technological change and not technological change itself.²⁸

To calculate total factor productivity growth we start with an accounting identity that includes all of the inputs and outputs of our baseline three sector model

$$(17) \quad p_c c + p_a a + p_g b \equiv q_{rc} r_c + q_{ra} r_a + q_{rg} r_g + q_{Ac} \mu A + q_G G + q_{Ag} (1 - \mu) A$$

where p_i 's, $i \in \{c, a, g\}$ are output prices and q_j 's, with the subscripts $j \in \{rc, ra, rg, Ac, Ga, Ag\}$, are input prices. The first letter of the input price sub-scripts indicates the input and the second letter the sector in which the input is used. For example, q_{rc} means the price of the resource input used in the consumer goods sector, while q_{Ga} means the price of pure knowledge in the applied R&D sector. We choose to measure everything in consumption units and take the price of consumption as the numeraire. This requires dividing through the identity by p_c to establish relative prices.

$$(17') \quad c + \frac{p_a}{p_c} a + \frac{p_g}{p_c} g \equiv \frac{q_{rc}}{p_c} r_c + \frac{q_{ra}}{p_c} r_a + \frac{q_{rg}}{p_c} r_g + \frac{q_{Ac}}{p_c} \mu A + \frac{q_G}{p_c} G + \frac{q_{Ag}}{p_c} (1 - \mu) A$$

Given the assumption of perfect competitive equilibrium in each time period (but not a stationary equilibrium over time), the price of resources must be the same in all uses.

Letting this common price be q , we can write:

$$(18) \quad \begin{aligned} q &= q_{rc} = p_c MP_{rc} \\ q &= q_{ra} = p_a MP_{ra} \\ q &= q_{rg} = p_g MP_{rg} \end{aligned}$$

which implies :

²⁷ In what follows we use technological knowledge, pure and applied knowledge and technology interchangeably. In our model it is the technological knowledge generated in the pure and applied knowledge sectors that is technological change which drives growth.

²⁸ As we noted in the introduction we are not the first to argue that TFP does not measure technological change. See, for example, Jorgenson and Griliches (1967) and Hulten (2000). However, we go further than these other authors by arguing that TFP is only an imperfect measure of a small subset of the spillovers associated with technological change and that sustained growth with zero TFP change is possible.

$$\frac{p_a}{p_c} = \frac{MP_{rc}}{MP_{ra}}$$

$$\frac{p_g}{p_c} = \frac{MP_{rc}}{MP_{rg}}$$

Similarly we can derive input prices relative to the price of the consumption good as follows:

$$(19) \quad \frac{q_{rc}}{p_c} = \frac{q_{ra}}{p_c} = \frac{q_{rg}}{p_c} = \frac{p_c MP_{rc}}{p_c} = MP_{rc}$$

$$\frac{q_{Ac}}{p_c} = \frac{q_{Ag}}{p_c} = \frac{p_c MP_A}{p_c} = MP_A$$

$$\frac{q_{Ga}}{p_c} = \frac{p_a MP_G}{p_c} = \frac{MP_{rc}}{MP_{ra}} MP_G$$

Resources can be used in all three activities. So the first line of equation (19) shows all of the resource input prices equal to each other and determined by the marginal product of resources in the consumption sector. The input prices of the knowledge stocks are not the same in all production functions because A and G are not substitutes. So, while A used in the consumption sector can be substituted for A used in the pure knowledge sector G used in the applied knowledge sector is not a substitute for A anywhere else. Thus the second line of equation (19) shows the price of the applied knowledge stock being equal in both the consumption and pure knowledge sector. Also a specific adjustment for the price of the stock of pure knowledge is made in the last line of equation (19) to make it consistent with all other prices.

Since the data generated by our model are discrete, we use a Törnqvist index to calculate TFP. Our model allows us to measure the rate of growth of technology directly as the rate of change of the knowledge stocks A_t and G_t^a . These stocks are also aggregated using a Törnqvist index.

Letting Y_i 's represent the outputs of the three sectors and X_j 's represent their inputs, the Törnqvist index of TFP changes is:

$$(20) \quad \Delta TFP_t = [\ln(Y_t) - \ln(Y_{t-1})] - [\ln(X_t) - \ln(X_{t-1})]$$

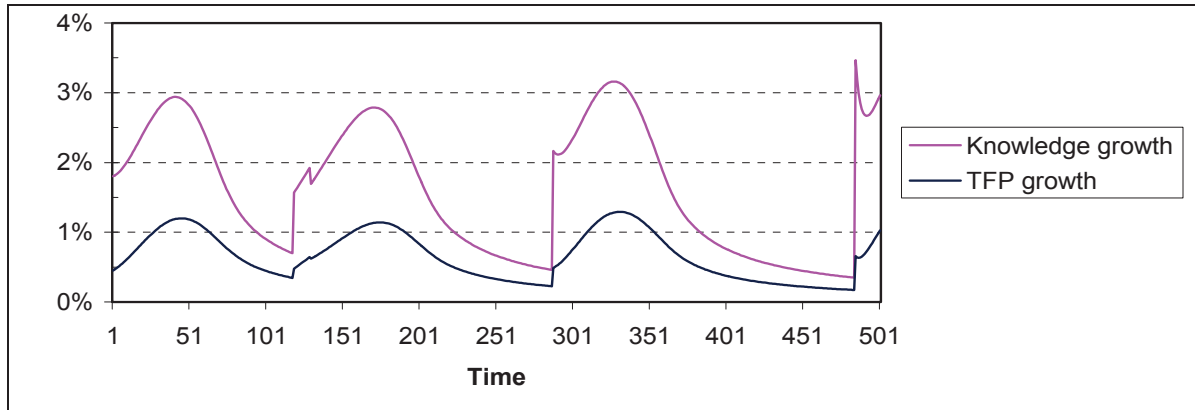
$$= \sum_i 0.5(w_{i,t} + w_{i,t-1}) [\ln(Y_t) - \ln(Y_{t-1})] - \sum_i 0.5(v_{j,t} + v_{j,t-1}) [\ln(X_t) - \ln(X_{t-1})]$$

Measuring TFP and knowledge growth for the individual sectors is straight forward in our framework since we know the exact specifications of the production functions. So, for example, TFP change in the consumption sector is measured as:

$$(21) \quad \Delta TFP_{c_t} = \ln(c_t) - \ln(c_{t-1}) - \alpha_1 [\ln(A_t) - \ln(A_{t-1})] - \alpha_2 [\ln(r_{c,t}) - \ln(r_{c,t-1})]$$

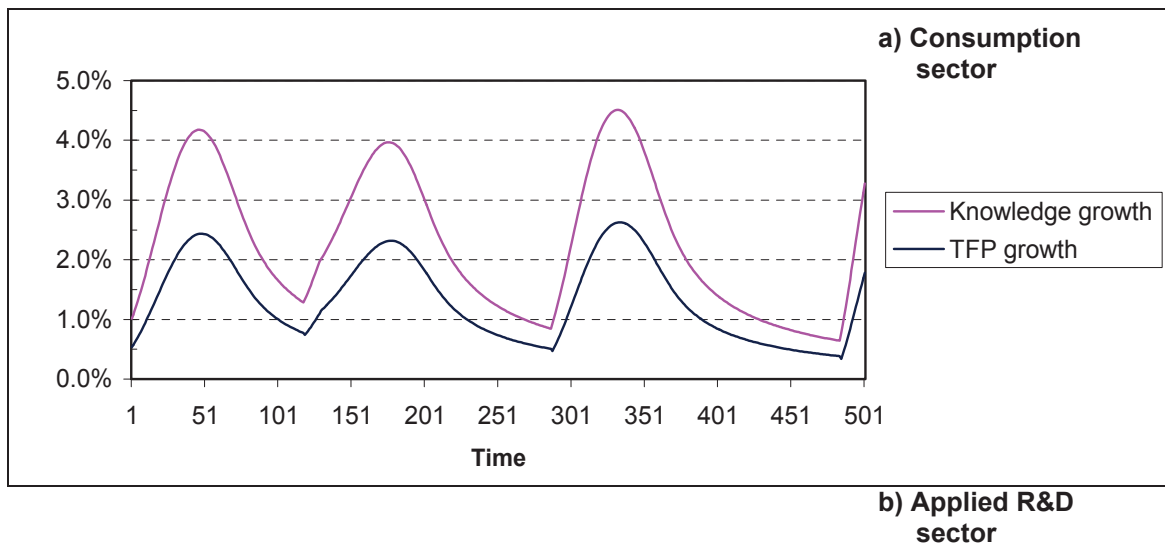
Figure 5.1 plots the growth rate of aggregate TFP and the growth of aggregate knowledge through a simulation of 500 periods where the time increment can be interpreted to represent annual data. Clearly, the rate of TFP change is everywhere below the rate of knowledge growth.

Figure 5.1: Aggregate TFP and technological knowledge growth rates

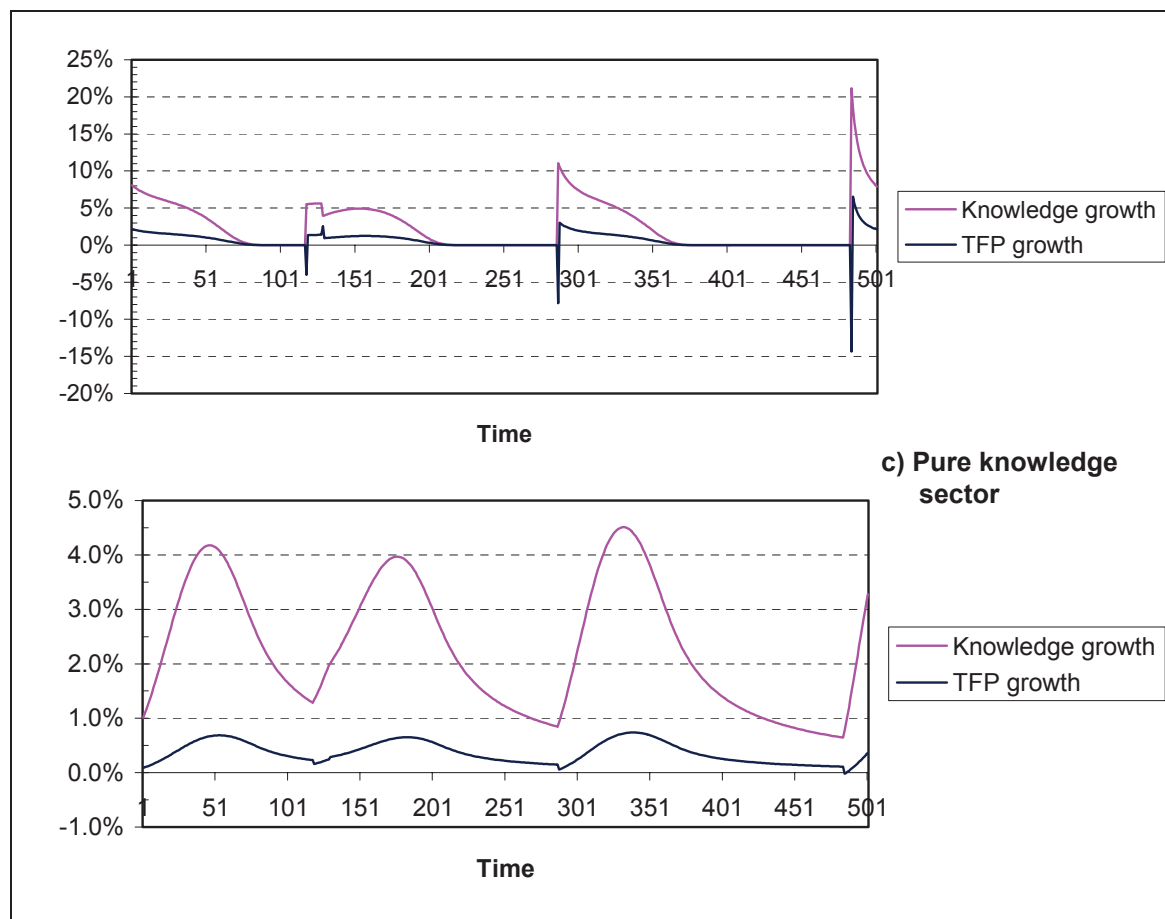


The correlation coefficient between TFP change and aggregate knowledge growth is 0.846 over the five hundred time periods shown. However, the average growth rate of technological knowledge is 1.6% while the average growth rate of TFP is 0.6%. So clearly TFP is measuring only a small amount of the technological change that is occurring in the system.²⁹ Next, we disaggregate to calculate the growth rates at the sector level (figure 2).

Figure 5.2: TFP and technological knowledge growth rates for:
a) Consumption sector, b) Applied R&D sector, c) Pure knowledge sector



²⁹ In simulations with uncertainty turned off TFP is slightly positive but everywhere significantly below technological knowledge growth. The Positive TFP growth rate is due to the increasing returns to scale in each production function. If the model exhibited constant returns to scale TFP change measured with the Tornqvist index would be zero.



Figures 5.2a-c show that in the consumption and pure knowledge sectors, TFP is everywhere below knowledge growth but positively correlated. The applied R&D sector has a TFP growth rate that is near zero and everywhere lower than the growth rate of the pure knowledge stock. TFP change becomes sharply negative with the arrivals of new GPTs in the applied R&D sector. But this is due to the transitions assumption we use between GPTs. When the new GPT arrives it is utilized regardless of whether its contribution to increases in the marginal productivity of resources in the applied R&D sector is larger or smaller than the incumbents. This produces the temporary spike downward. Because of our assumption that each GPT arrives in a crude form and diffuses logistically the probability that the new GPTs contribution is lower than in the incumbents is high. Alternative transition assumptions remove this spike.

Alternative simulation runs provide different realization of the random variables and thus different quantitative results. However, figures 5.1 and 5.2 illustrate the general qualitative results.

To reinforce the result that TFP does not measure technological change we reduce the amount of variability in the system by making the probability of an arrival of a GPT in each period equal to one. Figures 5.3-5.6 shown in Appendix 2 demonstrate that in all cases TFP growth is everywhere significantly below the growth rate of technological knowledge. The

reason that TFP is positive at all in the system is because the parameterizations used in the simulations are such that all lines of production have increasing returns to scale and the Törnqvist index number aggregation method used imposes share weights that imply constant returns to scale. Figures 5.3 and 5.4 show the case where the exponents on knowledge in all lines of activity are equal to one (as in the base case). Figures 5.5 and 5.6 show the case where the exponent on applied knowledge in consumption is reduced to 0.66. Aggregate TFP growth falls reflecting the fall in TFP growth in consumption. TFP growth in consumption moves close to zero but remains slightly positive due to the increasing returns elsewhere in the system.

If the actual exponential parameters of the individual production functions are used to calculate TFP growth in each sector rather than the share weights of the Törnqvist index, each sector's TFP growth is zero while the growth in technological knowledge is positive. This result is shown as figure 5.8 in appendix 2. Figure 5.7 shows that aggregate TFP calculation with a positive TFP growth rate, which occurs as the result of the aggregation procedure. The demonstration that this Törnqvist aggregation yields a positive overall TFP growth is not intended as an argument that Törnqvist aggregation is inappropriate. In fact, it might be argued that allowing the procedure to detect increasing returns to scale is indeed appropriate. What this indicates is that if the TFP growth rate numbers are interpreted to measure technological change, that interpretation is wrong. In all cases we have technological change. But what the Törnqvist index is detecting is the increasing returns to scale of the system and not technological change per se.

4.5.2 TFP and technological change in the structural adjustment model

We now include all of the inputs and outputs of our four sector structural adjustment model in the accounting identity.

(22)

$$p_c c + p_a a + p_g b + p_s s$$

$$\equiv q_{rc} r_c + q_{ra} r_a + q_{rg} r_g + q_{rs} r_s + q_{Ac} (\mu A) + q_{Ga} (\chi G) + q_{Gs} ((1 - \chi)G) + q_{Ag} ((1 - \mu)A) + q_{As} SA$$

where once again p_i 's, $i \in \{c, a, g, s\}$ are output prices and q_j 's, with the subscripts $j \in \{rc, ra, rg, rs, Ac, Ga, Gs, Ag, As\}$, are input prices. Note that we include SA_t as an input rather than just S_t because it is the ratio of S_t to SC_t that matters in the production function for applied R&D. Again we divide through the identity by p_c to establish relative prices.

(22')

$$c + \frac{p_a}{p_c} a + \frac{p_g}{p_c} g + \frac{p_s}{p_c} s$$

$$\equiv \frac{q_{rc}}{p_c} r_c + \frac{q_{ra}}{p_c} r_a + \frac{q_{rg}}{p_c} r_g + \frac{q_{rs}}{p_c} r_s + \frac{q_{Ac}}{p_c} \mu A + \frac{q_{Ga}}{p_c} (\chi G) + \frac{q_{Gs}}{p_c} ((1-\chi)G) + \frac{q_{Ag}}{p_c} (1-\mu)A + \frac{q_S}{p_c} SA$$

Input prices are established as in the previous case:

$$(23) \quad \begin{aligned} q &= q_{rc} = p_c MP_{rc} \\ q &= q_{ra} = p_a MP_{ra} \\ q &= q_{rg} = p_g MP_{rg} \\ q &= q_{rs} = p_s MP_{rs} \end{aligned}$$

which implies:

$$\begin{aligned} \frac{p_a}{p_c} &= \frac{MP_{rc}}{MP_{ra}} \\ \frac{p_g}{p_c} &= \frac{MP_{rc}}{MP_{rg}} \\ \frac{p_s}{p_c} &= \frac{MP_{rc}}{MP_{rs}} \end{aligned}$$

Similarly we can derive input prices relative to the price of the consumption good as follows:

$$(24) \quad \begin{aligned} \frac{q_{rc}}{p_c} &= \frac{q_{ra}}{p_c} = \frac{q_{rg}}{p_c} = \frac{q_{rs}}{p_c} = \frac{p_c MP_{rc}}{p_c} = MP_{rc} \\ \frac{q_{Ac}}{p_c} &= \frac{q_{Ag}}{p_c} = \frac{p_c MP_A}{p_c} = MP_A \\ \frac{q_{Ga}}{p_c} &= \frac{p_a MP_{Ga}}{p_c} = \frac{MP_{rc}}{MP_{ra}} MP_{Ga} \\ \frac{q_S}{p_c} &= \frac{p_s MP_S}{p_c} = \frac{MP_{rc}}{MP_{rs}} MP_S \end{aligned}$$

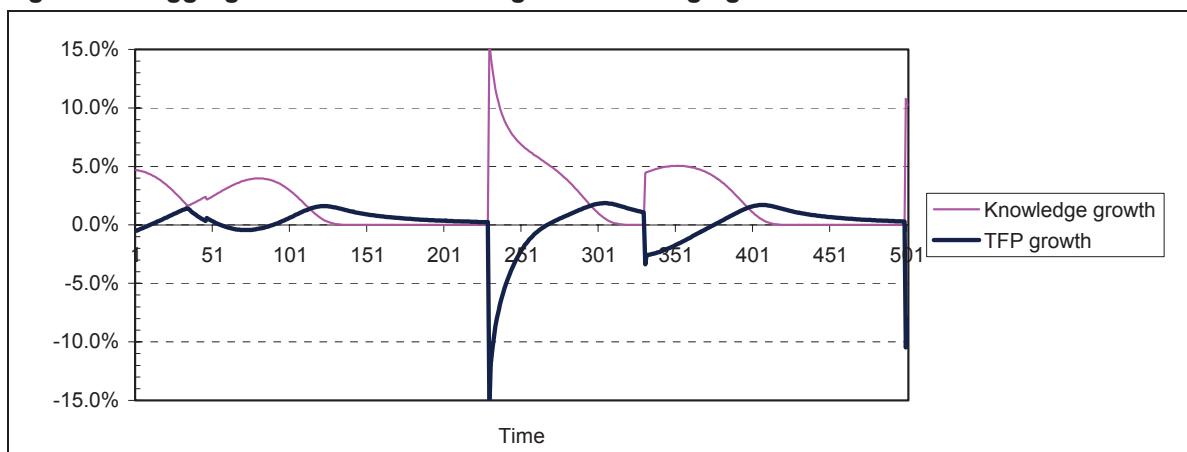
Resources can be used in all four activities. So, the first line of equation (24) shows all of the resource input prices equal to each other and determined by the marginal product of resources in the consumption sector. Again, the input prices of the knowledge stocks are not the same in all production functions because A , G and S are not substitutes. So, while A used in the consumption sector can be substituted for A used in the pure knowledge sector G and S used in the applied knowledge sector are not a substitutes for A anywhere else.

Again, we use a Törnqvist index to calculate TFP and to aggregate the knowledge stocks. The sector specific TFP growth rates are again calculated from the production functions.

In the present model, there are four outputs, four resource inputs, four knowledge inputs and a stock of structural adjustment input. Technological knowledge comprises the four stocks of knowledge which are just the accumulated flows of output from the pure and applied research sectors divided among the four production activities. These are aggregated using a Törnqvist index. We assume that the stock of accumulated structural adjustment is not included in aggregate knowledge for this illustration, though it is arguable that it should be included. When we do include investment in structural adjustment as knowledge it strengthens the result that TFP change is either unrelated or negatively related to technological knowledge growth.

Figure 5.9 plots the growth rates of aggregate TFP and knowledge. TFP is now negatively correlated with knowledge growth. The correlation coefficient between the two rates of change is -0.82 . When a GPT arrives, the TFP growth rate drops and in many cases becomes negative for several periods. Furthermore, as some GPTs mature TFP growth increase and over estimates actual technological change. The implication is that when new GPTs require adjustments in the facilitating structure, changes in measured TFP will slow down even though actual technological change is accelerating over several periods.

Figure 5.9: Aggregate TFP and technological knowledge growth rates



In the case shown, a maximum of 4.6 percent (an average of 1.8 percent) of the economy's total resources are allocated to structural adjustment. Yet, this small resource cost has significant implications for TFP growth rates and their interpretation as measures of technological change. A small diversion of resources out of other productive activities into the activity of structural adjustment can cause significant drops in the TFP growth rate (in some cases the rate becomes negative).

Furthermore, our results are consistent with the kind of 'New Economy' productivity bonus experienced in the USA from the mid 1990 into the new Millennium. However, our theory

predicts that the productivity bonus coincides with a technological knowledge growth rate slow down, at least in the model as we have specified it.

Next, we disaggregate to calculate TFP sector by sector. Figures 5.10a-d show the TFP change and the growth rate of the knowledge stock that goes into production in each sector. In all but the applied R&D case TFP change is positive and positively correlated with, but everywhere below the growth rate of knowledge in that sector. TFP change is negatively correlated with knowledge growth in the applied R&D sector and negative when GPTs arrive.

Once again it can be shown that if the exponential parameter values in each line of production in the system are used to calculate TFP, then the TFP growth rates are very close to zero in each sector and become slightly negatively correlated with TFP in some sectors. The results are shown in figure 5.11 in Appendix 2.

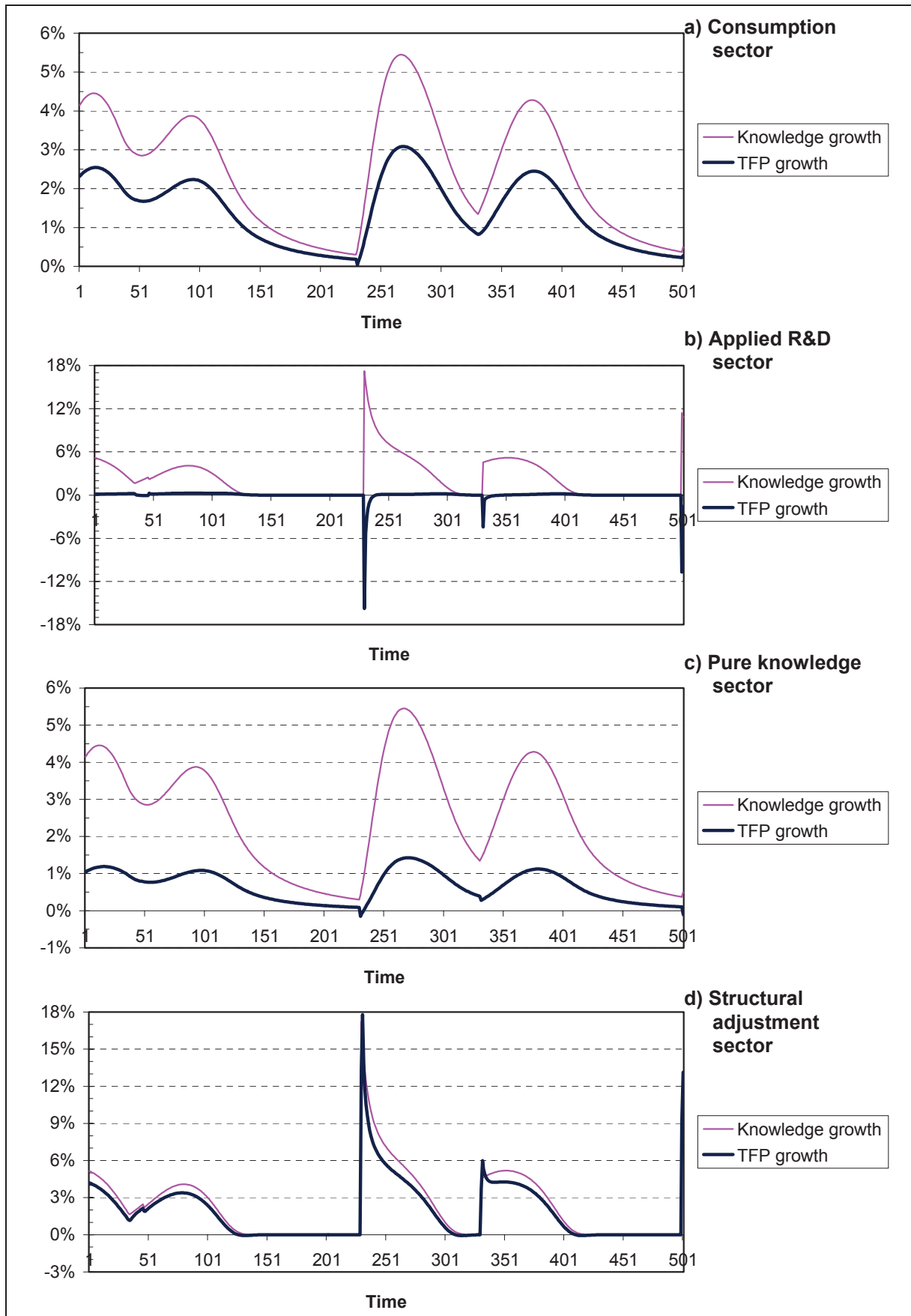
4.5.3 Section summary

The analysis demonstrates that TFP growth does not reflect technological change, at least within the framework. What TFP growth does reflect is the increasing returns in the production functions of the system. What is also clear is that in the aggregate, sufficiently high structural adjustment costs cause TFP growth to become strongly negatively correlated with technological change, which manifests in the model as knowledge growth.

It should also be noted that our aggregate is artificial in the sense that we have one consumption sector, two knowledge producing sectors and in the second model an additional structural adjustment sector. In reality it is often the case that all of these production activities take place within a given measured sector in the national accounts. For example, the steam engine was invented by the mining sector and spread in its application to many other sectors of the first industrial revolution economies. What we have called the applied R&D and structural adjustment sectors certainly exist as components of the industrial sectors measured in the national accounts of most economies.³⁰

Figure 5.10: TFP and technological knowledge growth rates for the four-sector model with Consumption, Applied R&D, Pure knowledge and Structural adjustment sectors

³⁰ It is debatable whether pure knowledge is more appropriately treated as a separate sector in today's world of science based bio-technology and nano-technology driven primary research.



For example, in the sectors of the Australian economy that we examine in the next section, applications of ICT are being undertaken by firms within the sectors for which data is reported. Firms within these sectors are adopting ICT technologies and adapting it to their needs, through a process of costly investment and internal innovation. In this sense the results that our simulated aggregate TFP calculation is generating are most appropriately interpreted to reflect the kind of TFP calculation we should expect to see in each of the industries in the Australian data examined in the next section.

One further note of qualification is required. The model and simulation exercise is one where there is only ever one GPT operating in the system at any moment in time. In contrast, real economies comprise several GPTs, all at different stages in their own logistic diffusions, and which all affect the system in myriad interrelated ways. For examples, Australia is currently experiencing the rapid diffusion of ICT along side applications of lasers and made to order materials. It is continuing to experience the impact of electricity through an ever increasing development of applications for this power GPT. There are many other examples that could be noted but this suffices to make the point. All of these technologies have influences on the measures of performance even at the disaggregated industry level discussed in the next section. Furthermore, these different technologies have different impacts in these different industries or sectors.

Lipsev, Carlaw, and Bekar (2005 forthcoming) provide the algebra to suggest that a model of multiple GPTs is possible within their framework, but to date it has not been implemented in a computer simulation. However, the framework developed here provides for the possibility of a quick-and-dirty multiple GPT simulation. If we aggregate data from the baseline model and the structural adjustment model to calculate TFP growth and knowledge growth we find that a number of possibilities emerge.³¹ Depending on the realizations of the random variables in each model the correlation between TFP growth and knowledge growth becomes less negative and less significant. In some cases the correlation is not significantly different from zero. This simulated result comes close to some of the empirical results we observe in Section 2.2 and Section 6 below. But, until the complete formal model has been constructed and a proper calibration made for each measured sector or industry under analysis, nothing more than casual inference can be made. Thus, a note of caution is warranted when interpreting the statistical results derived from the forthcoming section on Australian data and the previous section on investment quality measures. These cannot be viewed as supporting evidence for the theory, and simulation of the GPT model is warranted. The empirical analysis is consistent with the theory, but does not constitute a rigorous test of it.

³¹ The aggregation was done by taking crude averages of the growth rate of TFP and knowledge. A more sophisticated analysis requires the fully integrated computer simulation code suggested in the Lipsey, Carlaw and Bekar (2005 forthcoming) multiple-sector model.

The empirical analysis is an indication that TFP growth is not measuring technological change and the model and simulation analysis suggest an avenue of investigation as to why that might be the case. Furthermore, the model if judged to be appropriate begins to offer a theoretical interpretation of TFP that is at least consistent with observed productivity slowdowns and a sometimes negative contemporaneous correlation between TFP growth and technological change.

4.6 What do the Australian data tell us?

In this section we show that the real Australian data which provide an independent measure of technological change and MFP growth generate results that match the simulation findings of the previous sections. MFP growth is shown to be either uncorrelated or negatively correlated with the rate of ICT diffusion, and almost everywhere below it.

The data currently being produced by the Australian Bureau of Statistics (ABS) provide a rare opportunity to obtain an independent measure of the rate of technological diffusion. The data include measures of the contribution to the productive capital stock of computers and software in 12 industrial sectors.³² From these data it is possible to calculate the rate of diffusion of the software and computer components of ICT in the 12 industrial sectors and compare the diffusion rates to the rate of MFP/TFP growth within each sector.

We take the rate of growth of productive services from computers and software in productive capital stock as a proximate measure of the rate ICT diffusion in each sector. Clearly this is an incomplete measure of ICT diffusion, since it excludes Internet capital services that are embodied in such things as fibre optic cable, satellites, etc. and potentially a number of other things. However, it does provide an independent measure of a large component of ICT diffusion in the industrial sectors of Australia. With this independent measure of technological change we are able to obtain a comparison between MFP growth and ICT growth that is comparable to the measure generated by the simulation undertaken in the previous sections.

The ABS data set also provides the aggregate contributions of capital services, labour hours and value added output in each of the twelve sectors. By using a Törnqvist index that incorporates the sector specific factor share weights, which are also provided in the data set, we calculate MFP growth in each sector.³³

³² The productive capital stock is calculated by ABS using a chain volume methodology.

³³ Diewert and Lawrence are testing some of the assumptions used to generate these share weights and report on some modifications in there for the Asia Pacific Productivity Conference. I use these data with the caveat that they may be subject to some minor revision subsequently.

Appendix 3 provides a set of figures in which the rates of ICT diffusion and MFP change are plotted for the period 1987-2003 for each of the twelve sectors.³⁴ Two things are immediately obvious in these figures. First, MFP growth is on average below the rate of ICT diffusion. Second, the rate of ICT diffusion in many sectors appears to be uncorrelated or negatively correlated with the rate of MFP change.

To see the degree of correlation between the two rates of change in each industry we once again linearly regress MFP growth on ICT diffusion, noting again the flawed assumptions of a linear relationship between MFP growth and the rate of ICT diffusion again we use it here because it reveals that there is clearly something wrong with MFP as a contemporaneous measure of technological change. Table 6.1 reports the correlation coefficients and t statistics for each sector.

Table 6.1

	<i>Coefficient</i>	<i>Sig. (t stat.)</i>	<i>MFP Growth (Avge)</i>	<i>ICT diff. rate (Avge)</i>
<i>SECTOR</i>				
<i>Agriculture</i>	-0.3187	-0.5785	0.0184	0.1968
<i>Mining</i>	0.0026	0.0095	0.0318	0.2075
<i>Manufacturing</i>	-0.0299	-0.4306	-0.0027	0.2305
<i>Electricity, Gas and Water</i>	-0.0102	-0.0636	0.0339	0.1895
<i>Construction</i>	-0.2923	-1.3126	0.0026	0.2141
<i>Retail Trade</i>	-0.1518	-3.0050	-0.0169	0.2269
<i>Wholesale Trade</i>	-0.2126	-1.4738	0.0198	0.2159
<i>Transport and Storage</i>	-0.1942	-2.9127	0.0195	0.1927
<i>Communications</i>	-0.2518	-2.6261	0.0259	0.2183
<i>Accommodation, Cafés & Restaurants</i>	-0.2833	-2.7934	-0.0376	0.2255
<i>Finance and Insurance</i>	0.0626	0.6501	0.0163	0.2207
<i>Cultural and Recreational Services</i>	-0.0550	-0.3794	-0.0589	0.2245

The analysis of the Australian sectoral data supports the findings of the simulation model and the theoretical predictions of Carlaw and Lipsey (2003) and Lipsey and Carlaw (2004). MFP growth is not correlated with an independent measure of the diffusion of ICT in the Australian economy. For the most part MFP growth and ICT diffusion are not significantly correlated and in some cases there is significant negative correlation over the time period covered.³⁵

³⁴ The data are of an annual frequency with the observation taken for the month of June.

³⁵ Again these results are to be interpreted with caution since the time period consists of only 17 observations in each sector so that any interpretation of statistical significance is suspect.

4.7 Conclusion

We set out in this to begin the development of a theory of TFP by developing a multi-sector model of endogenous GPT-driven growth. Such a theory is needed to resolve ambiguities arising from the various, mutually incompatible, interpretations of TFP in the literature. Such a theory also can resolve inconsistency between different measures of technological change, with the TFP-based measure appearing to be uncorrelated or even negatively correlated with such independent measures as IST.

To begin the process of developing a theory of TFP we build two models of GPT-driven growth—a basic three sector model and a four sector model that includes structural adjustment costs. The models are based on the historical and theoretical research of Lipsey, Carlaw and Bekar (2005), and on a cruder early version of the three sector model (Carlaw and Lipsey (2001 and 2006 forthcoming). In the models, a sequence of GPTs arrive, each at uncertain times and with uncertain productive impacts that diffuse according to a logistic process. The models result in resource allocations with non-stationary equilibria. They have the property that in the absence of future GPTs there are diminishing returns and growth asymptotically approaches zero. But the arrival of new GPTs rejuvenates the growth process.

Because this model requires a numerical solution procedure that is iterated through several periods it provides a ready opportunity for Monte Carlo analysis of the assumptions that underlie both endogenous growth modelling and TFP growth calculations. We do such an exercise here and confirm the arguments of Carlaw and Lipsey (2003) and Lipsey and Carlaw (2004) that TFP is not a measure of technological change. We find that while under some conditions TFP is positively correlated with direct and independent measures of technological change it persistently under estimates such technological change. Under other conditions, such as structural adjustment to accommodate a new GPT, TPF growth is negatively correlated with measured technological change and persistently underestimates technological change when a new GPT arrives and overestimates technological change as the GPT matures. In both models TFP fails detect the arrival of GPTs appropriately (i.e., as big technological shocks).

The findings in the IST empirical analysis and the simple empirical analysis of the Australian productive capital stock data are consistent with the view that ICT is a major new transforming GPT that generates structural adjustment costs of the kind that is discussed in Lipsey, Bekar and Carlaw (1998b) and Lipsey, Carlaw and Bekar (2005) and that is modelled in section 5.2 above. In ten of the twelve sectors of the Australian economy and in ten of the sixteen OECD economies examined, TFP showed a negative correlation, and in a number of cases this correlation was significant. Only in two of the OECD economies where TFP growth was compared to IST growth did a significant positive relationship occur. All of these empirical findings have to be viewed with a critical

eye because there are a number of assumptions necessary to interpret the measures of technological change as being valid. However, they do have the property that they are independent measures of technological change and therefore provide some basis of comparison and testing of the various interpretations of TFP growth. They also point in common direction. TFP does not measure technological change. Furthermore, it may be negatively correlated with technological change when that change is driven by a transforming GPT such as ICT, which is something that the theory predicts.

References (chapter 4)

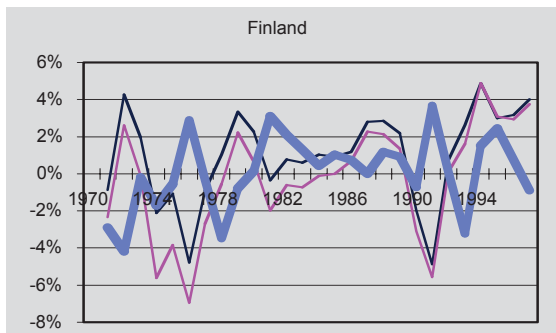
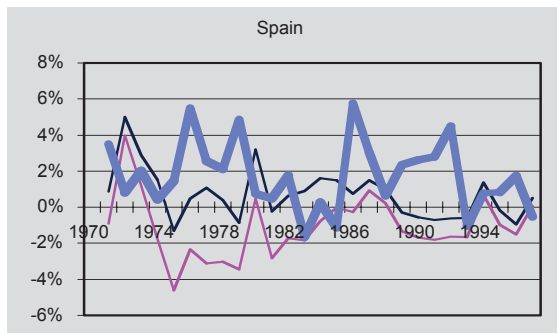
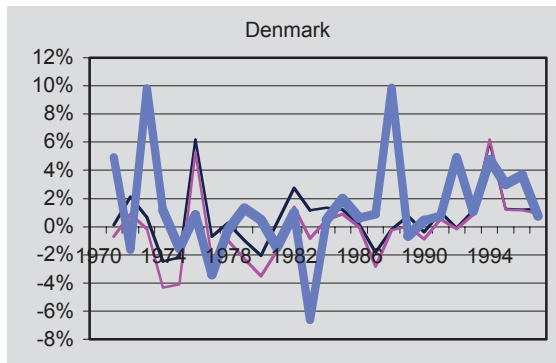
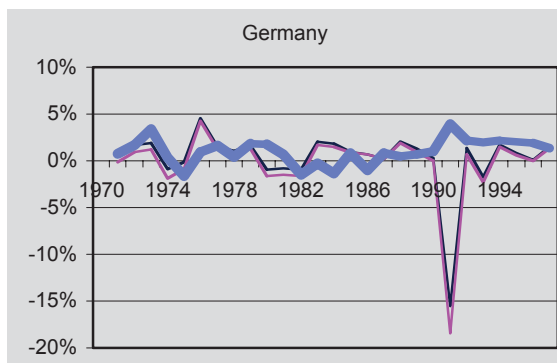
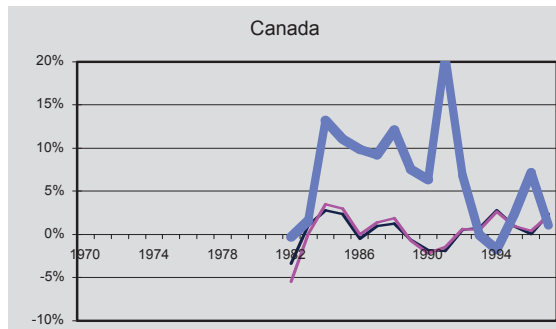
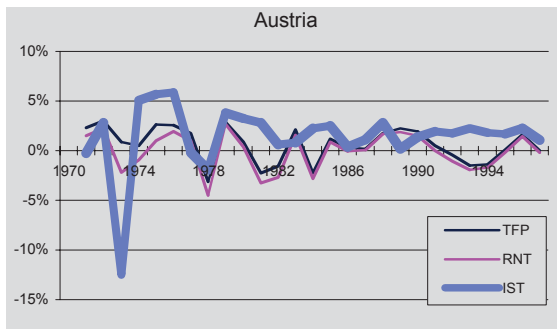
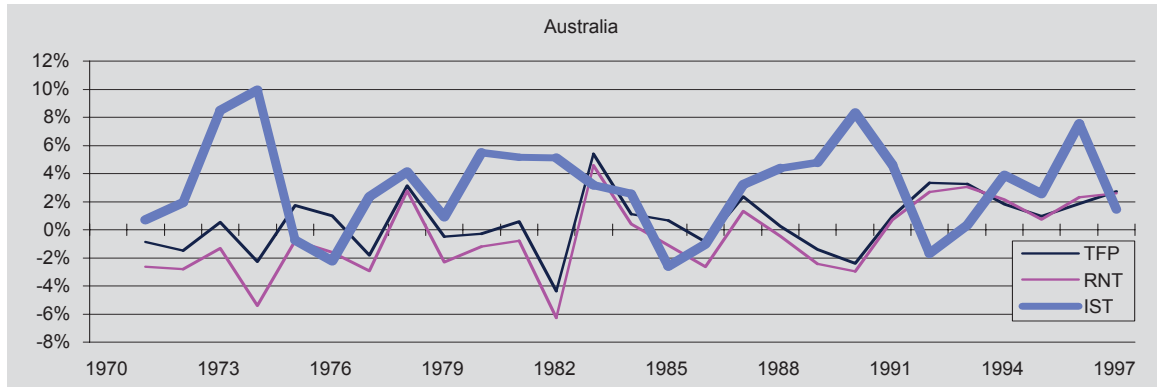
- Abramovitz, M. (1956) 'Resource and Output Trends in the U.S. Since 1870,' *American Economic Review*, 46, 5-23.
- Aghion, P. and P. Howitt (1998), 'On the Macroeconomic Effects of Major Technological Change', in E. Helpman (ed), *General Purpose Technologies and Economic Growth*, (Cambridge: MIT Press), 121-144.
- Aghion, P. and P. Howitt (1992), 'A Model of Growth Through Creative Destruction', *Econometrica*, 60, 232-396.
- Baily, M.N., (2002) 'Macroeconomic Implications of the New Economy,' Institute for International Economics Working , 2002.
- Bresnahan, T. and Trajtenberg, E. (1992) 'General Purpose Technologies: Engines of Economic Growth?' *NBER Working Paper* No. 4148.
- Carlaw, K. I. and R. G. Lipsey (2006 forthcoming) 'GPT-Driven, Endogenous Growth', *The Economic Journal*.
- Carlaw, K. I. and S. Kosempel (2004) 'The sources of total factor productivity growth: Evidence from Canadian data' *Economics of Innovation and New Technology*, 13(4), 299-309.
- Carlaw, Kenneth I. and R. G. Lipsey (2003) 'Productivity, Technology and Economic Growth: What is the relationship?' *Journal of Economic Surveys*, 17(3).
- Carlaw, K. I. and R. G. Lipsey (2002) 'Externalities, Technological Complementarities and Sustained Economic Growth,' *Research Policy*, 31 (8-9), 1305-1315.
- Carlaw, Kenneth I. and Richard G. Lipsey (2001), 'Externalities versus Technological Complementarities: a model of GPT-driven, sustained growth', A Paper Presented at The Conference in Honour of the 20th Anniversary of Nelson and Winter's book *An Evolutionary Theory Of Economic Change*, Aalborg Denmark, 12-15 June 2001.
- Cass, D. (1965) 'Optimum Growth in an Aggregate Model of Capital Accumulation' *Review of Economic Studies*, 32, 233-240.
- David, P. and G. Wright (1999) 'General Purpose Technologies and Surges in Productivity: Historical Reflections on the Future of the ICT Revolution', *University of Oxford Discussion s in Economic and Social History*, Number 31.
- David. P. (1990) 'The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox' *American Economic Review*, 80(2), 355-61.
- Freeman, C. and C. Perez (1988) 'Structural Crises of Adjustment, Business Cycles and Investment Behaviour,' in Dosi, G. et al (eds.) *Technical change and economic theory*, (London and New York: Pinter; distributed by Columbia University Press, New York), 38-66.
- Freeman, Chris and F. Louca (2001) *As Time Goes By: From the Industrial Revolution to the Information Revolution*, (Oxford: Oxford University Press).
- Gordon, R. J. (1990) *The measurement of durable goods prices*, National Bureau of Economic Research Monograph series Chicago and London: University of Chicago Press.

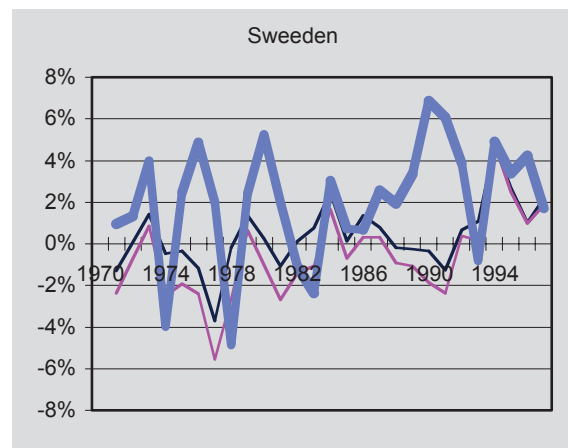
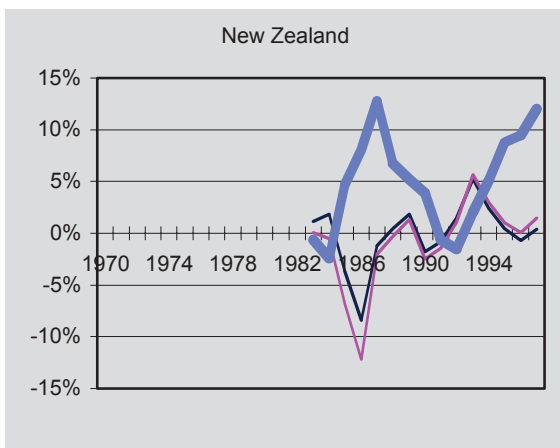
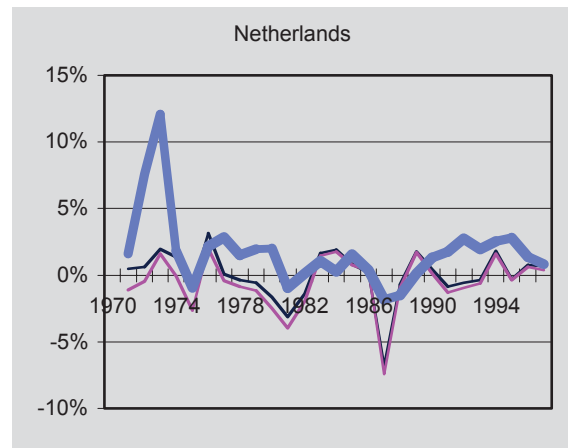
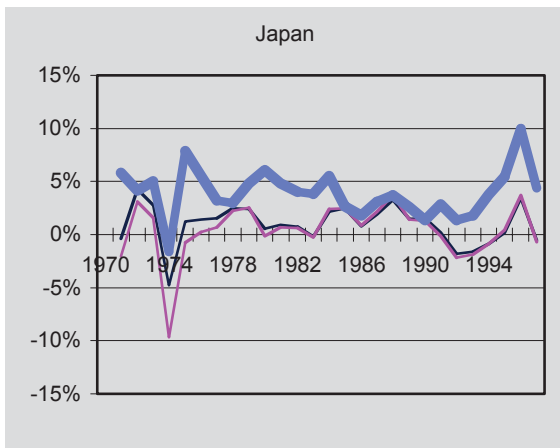
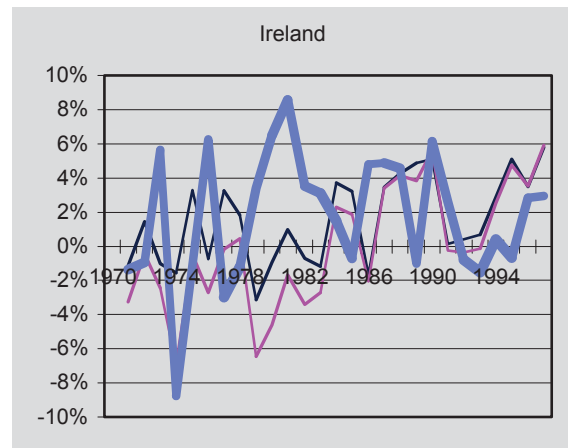
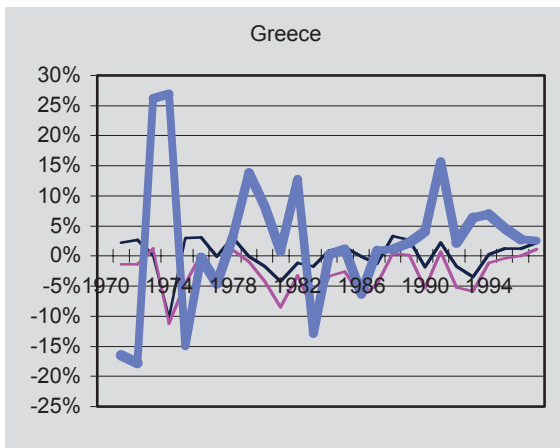
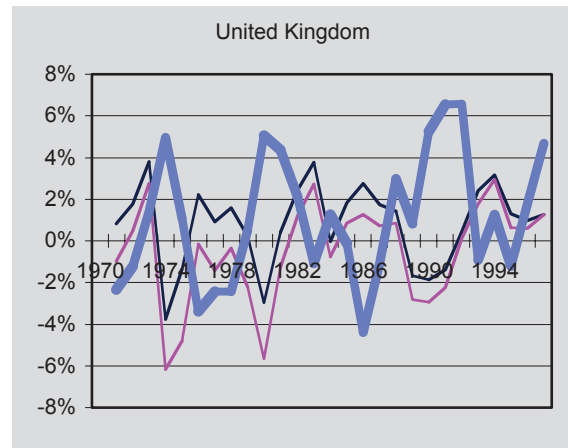
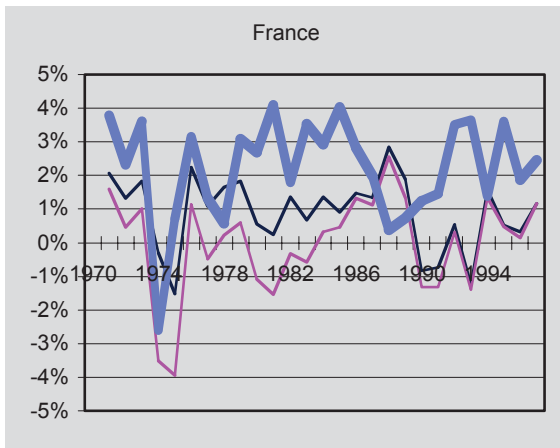
- Gordon, R.J., (2000) 'Does the 'New Economy' Measure up to the Great Inventions of the Past?,' *Journal of Economic Perspectives*, 14(4), 49-74.
- Greenwood, J., Z. Hercowitz and P. Krusell. (1997). 'Long Run Implications of Investment-Specific Technological Change,' *American Economic Review* 87(3), 342-62.
- Greenwood, J., Z. Hercowitz and P. Krusell. (2000). 'The Role of Investment-Specific Technological Change in the Business Cycle,' *European Economic Review* 44(1), 91-115.
- Griliches, Z. (1994), 'Productivity, R&D, and the Data Constraint', *AER*, 84(1).
- Helpman, Elhanan, (ed) (1998) *General Purpose Technologies and Economic Growth*, (Cambridge: MIT Press).
- Helpman, E. and M. Trajtenberg (1998a), 'A Time to Sow and a Time to Reap' in E. Helpman (ed), *General Purpose Technologies and Economic Growth*, (Cambridge: MIT Press), 55-84.
- Helpman, E. and M. Trajtenberg (1998b), Diffusion of General Purpose Technologies, in E. Helpman (ed), *General Purpose Technologies and Economic Growth*, (Cambridge: MIT Press), 85-119.
- Howitt, P. (1998) 'Measurement, Obsolescence, and General Purpose Technologies', in E. Helpman ed. (1998) *General Purpose Technologies and Economic Growth*, MIT Press: Massachusetts, 219-251.
- Hulten, C. R. (1992). 'Growth Accounting when Technological Change is Embodied in Capital,' *American Economic Review*, 82(4), 964-980.
- Hulten, C. R. (2000) 'Total Factor Productivity: A Short Biography,' *NBER Working Paper*, 7471, (Washington: National Bureau of Economic Research).
- Jorgenson, D.W. (1966). 'The Embodiment Hypothesis,' *Journal of Political Economy*, 74(1), 1-17.
- Jorgensen, D. and Z. Griliches (1967) 'The Explanation of Productivity Change,' *Review of Economic Studies*, 34, 249-83.
- Koopmans, T. C. (1965) 'On the Concept of Optimal Economic Growth' in *The Economic Approach to Development Planning* (Amsterdam: Elsevier).
- Krugman, Paul (1996) 'The Myth of Asia's Miracle,' in *Pop Internationalism* (Cambridge: MIT Press).
- Lipsey, R. G., C. Bekar and K. I. Carlaw (1998a) 'What Requires Explanation,' Chapter 2 in Helpman (1998).
- Lipsey, R. G., C. Bekar and K. I. Carlaw (1988b) 'The Consequences of Changes in GPTs,' Chapter 7 in Helpman (1998).
- Lipsey, R. G., K. I. Carlaw, and C. Bekar, (2005) *Economic Transformations: General Purpose Technologies and Long Term Economic Growth*, (Oxford, UK: Oxford University Press).
- Lipsey, R. G. and K. I. Carlaw (2004) 'Total Factor Productivity and the Measurement of Technological Change', *Canadian Journal of Economics* 37(4), 1118-50.

- Lucas, R. E. (1988) 'On the Mechanics of Economic Development,' *Journal of Monetary Economics*, 22(1), 3-42.
- Nelson, R. R. (1964) 'Aggregate Production Function and Medium-Range Growth Projections,' *American Economic Review*, 54, 575-606.
- Perez, C. (2002) *Technological Revolutions and Financial Capital*, (Cheltenham, UK: Edward Elgar).
- Ramsey, F. P. (1928) 'A Mathematical Theory of Saving' *Economic Journal*, 38, 543-559.
- Romer, P. (1986) 'Increasing Returns and Long-run Growth,' *Journal of Political Economy*, 94(5), 1002-37.
- Rymes, Thomas K., (1971) *On Concepts of Capital and Technical Change*, (Cambridge: Cambridge University Press).
- Solow, R. (1956) 'A Contribution to the Theory of Economic Growth,' *Quarterly Journal of Economics*, 70, 65-94.
- Solow, R. (1987) 'We'd Better Watch out,' *New York Times Book Review*, pp. 36.
- Triplett, J.E. 'Economic Statistics, the New Economy, and the Productivity Slowdown' *Business Economics*, 34(2), 1999, pp. 13-17.
- Young, A. (1992) 'A Tale of Two Cities: Factor Accumulation and Technical Change in Hong Kong and Singapore,' *NBER Macroeconomic Annual*, (Cambridge: MIT press).

Appendices to chapter 4

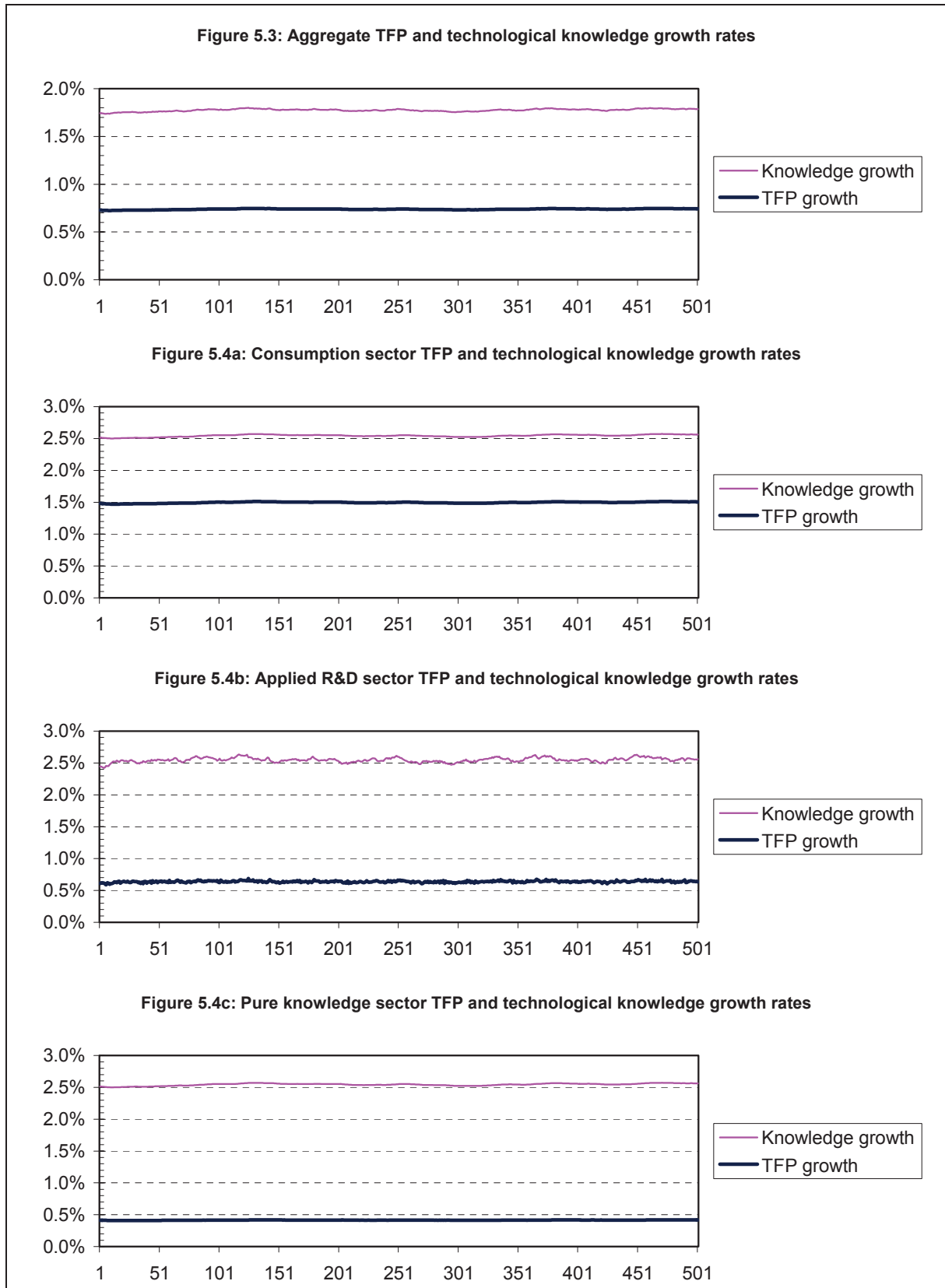
A4.1 ISTC and MFPG for 16 OECD economies



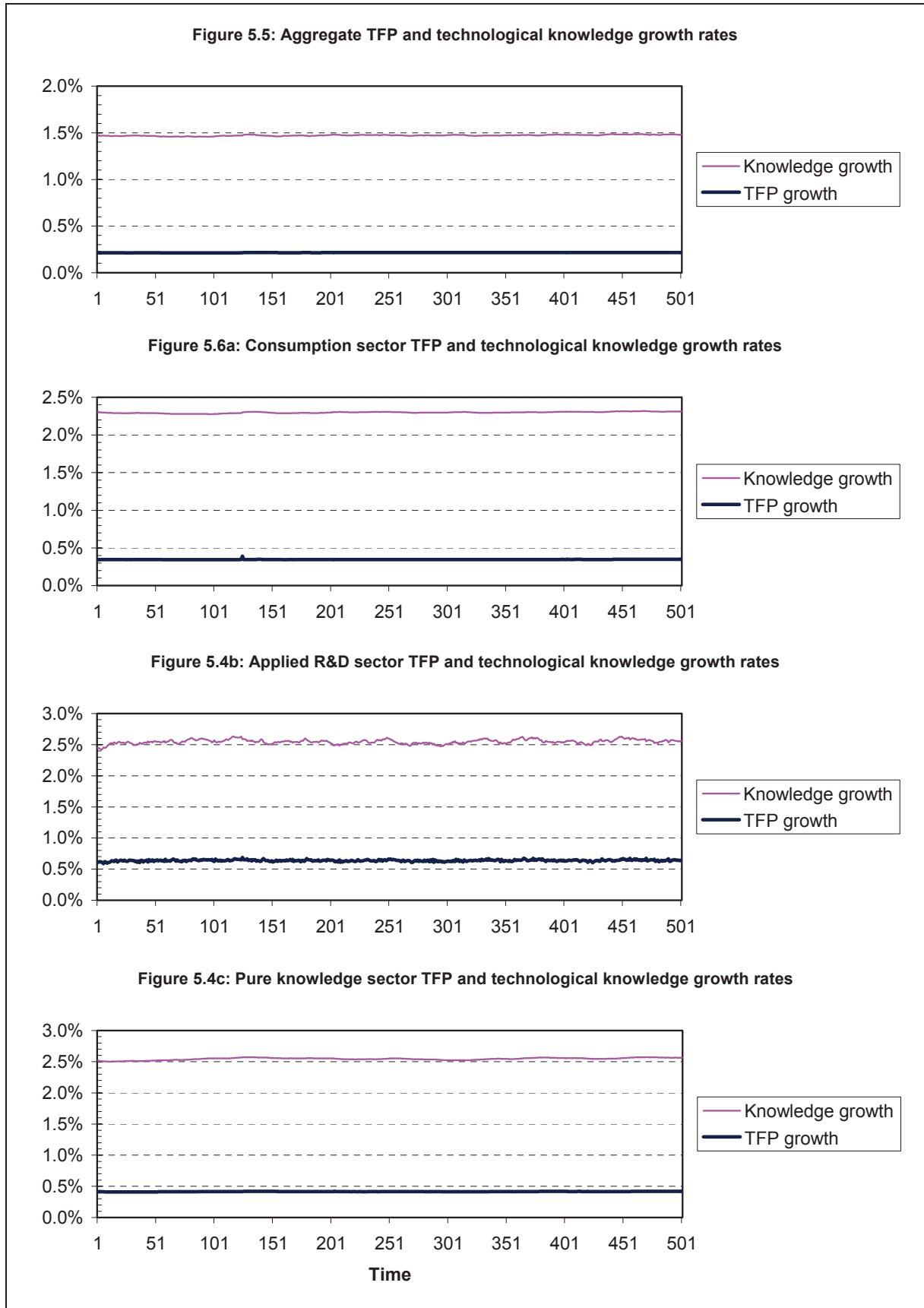


A4.2 Sensitivity analysis

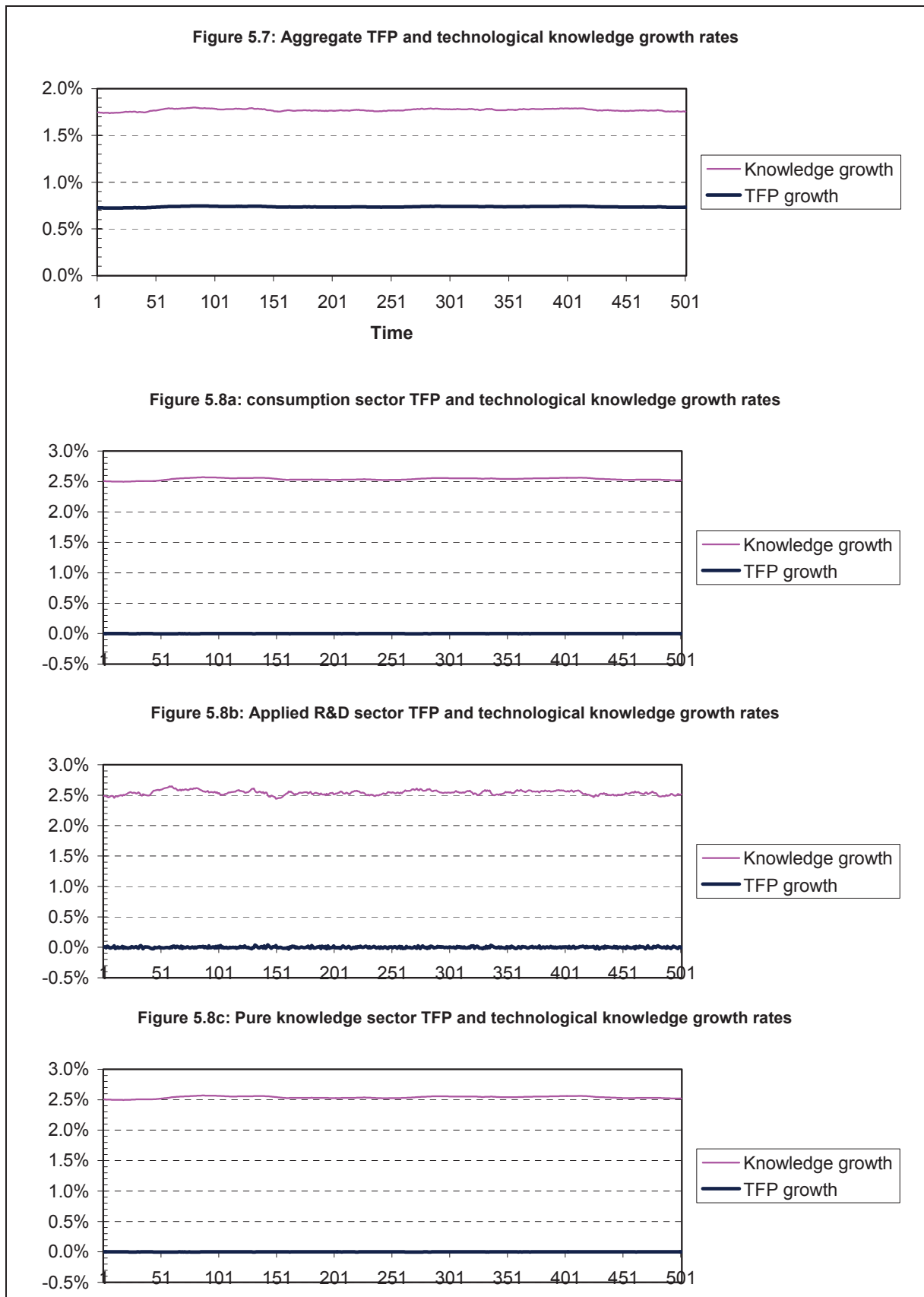
Figures 5.3 and 5.4 show the TFP and technological knowledge growth rates calculated when technological knowledge has constant returns in all line of production activity.



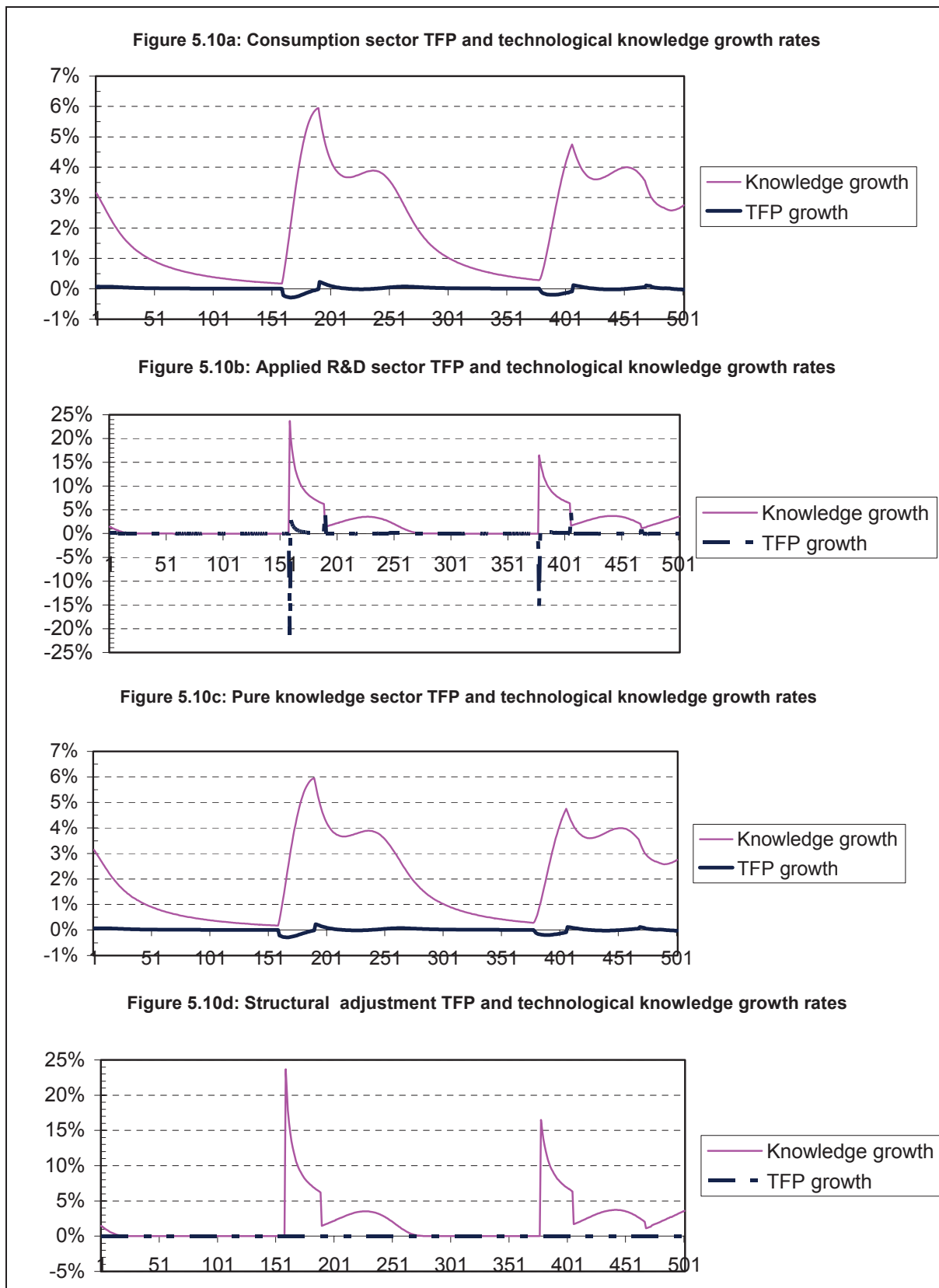
Figures 5.5 and 5.6 show TFP and technological knowledge growth when the consumption sector has decreasing returns to technological knowledge, and all other sectors have constant returns.



Figures 5.7 and 5.8 show TFP and technological growth rate calculations for using a Torqvist index to aggregate but using the actual exponential parameters from the production functions of each sector.

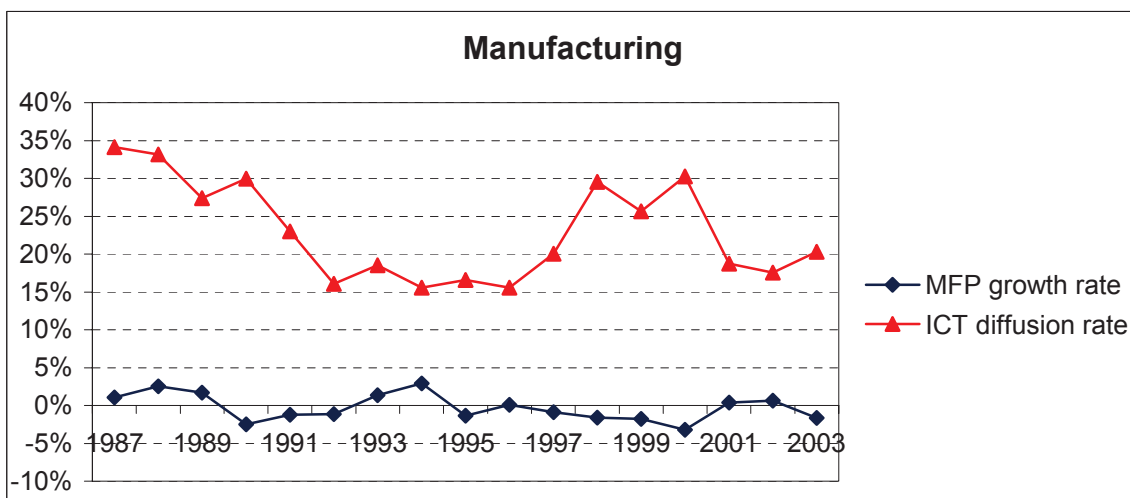
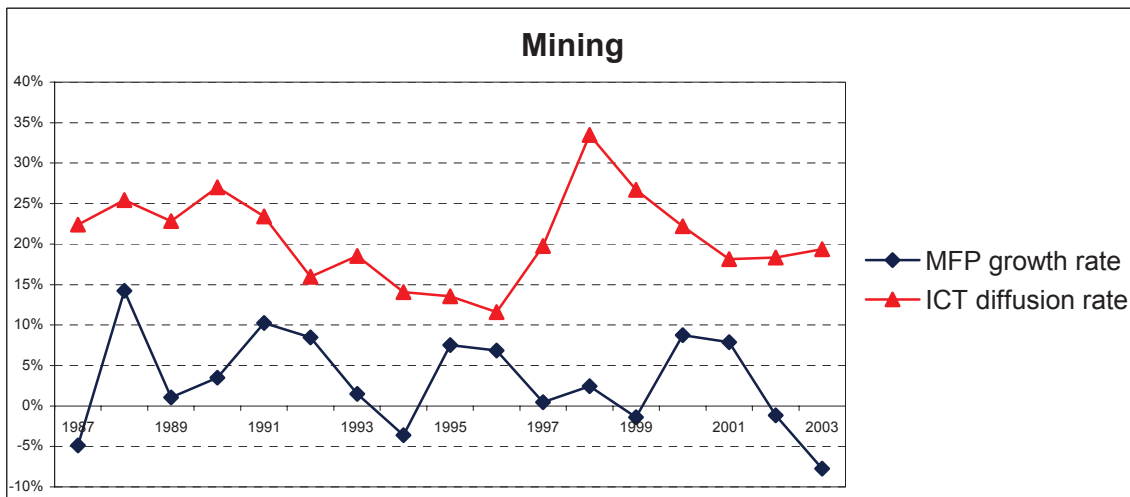
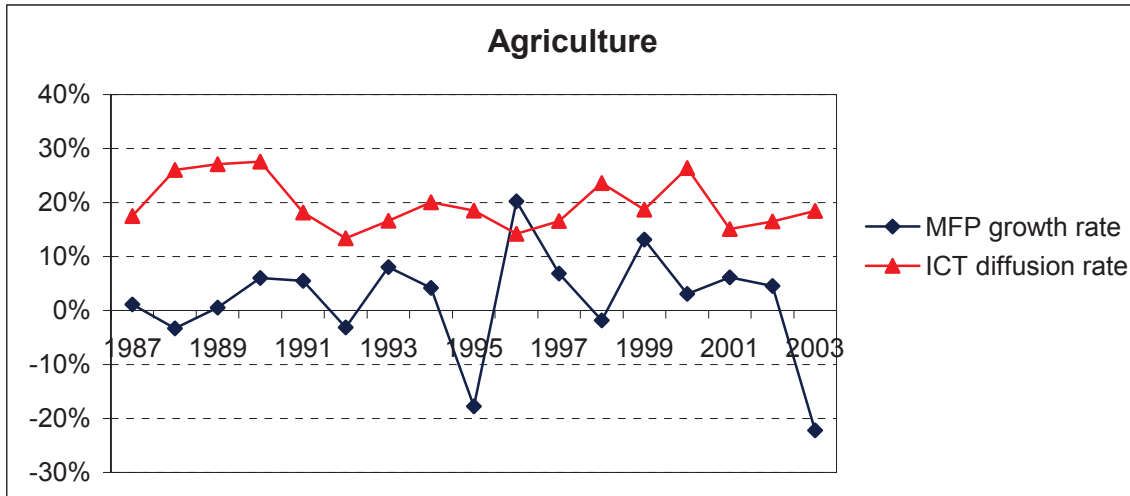


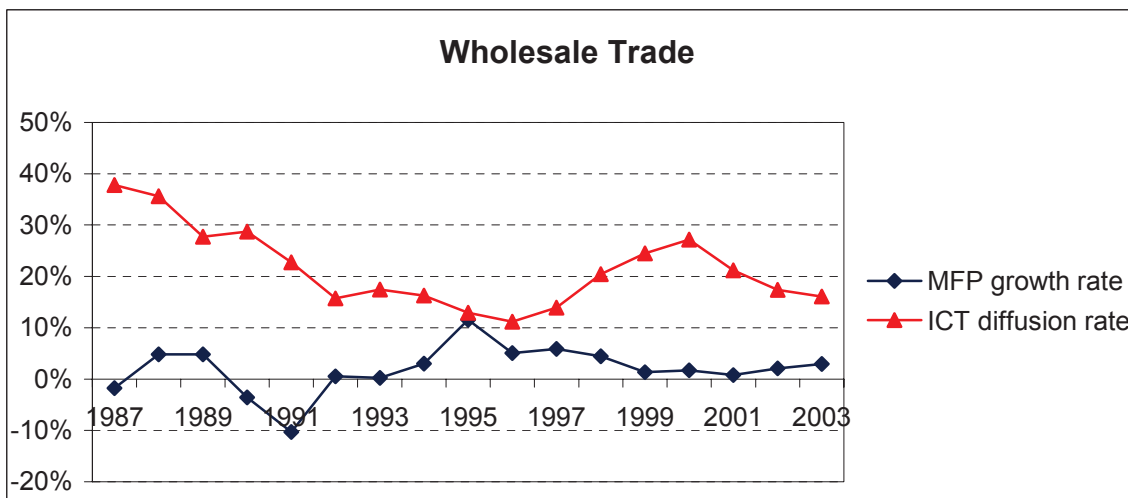
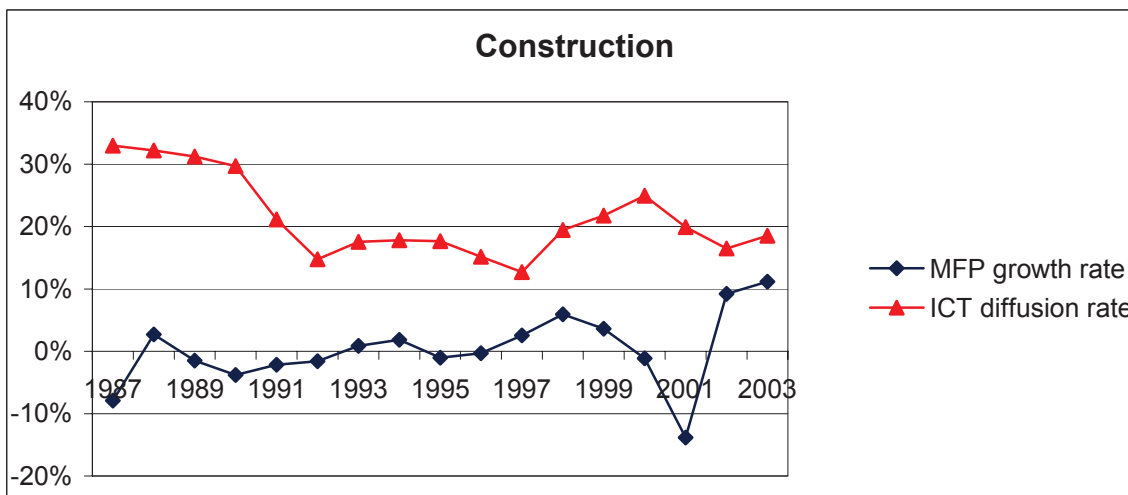
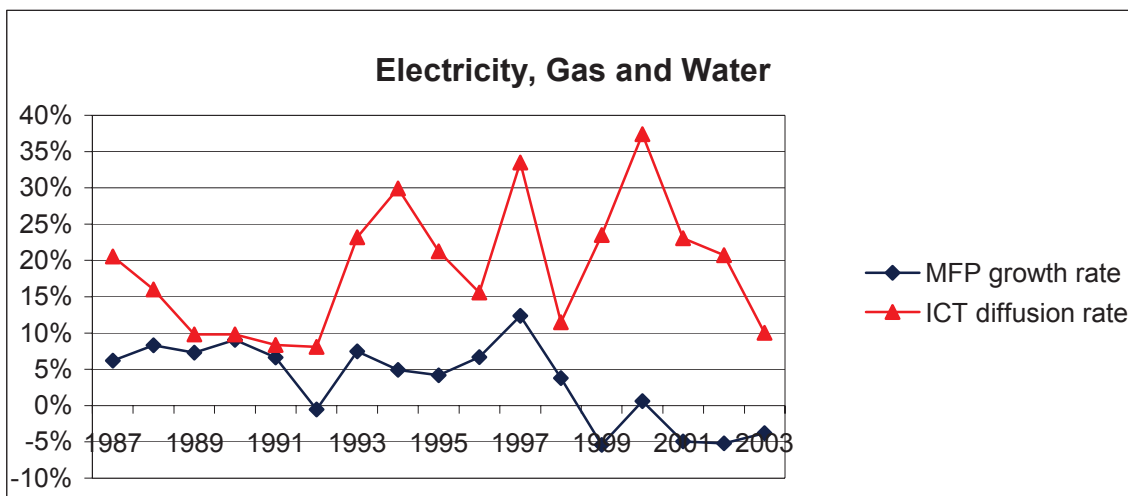
Figures 5.10a-d show the sector specific calculations for TFP and technological knowledge growth where TFP growth is calculated using the actual production function parameters rather than a Törnqvist index to calculate share weights on factors of production.

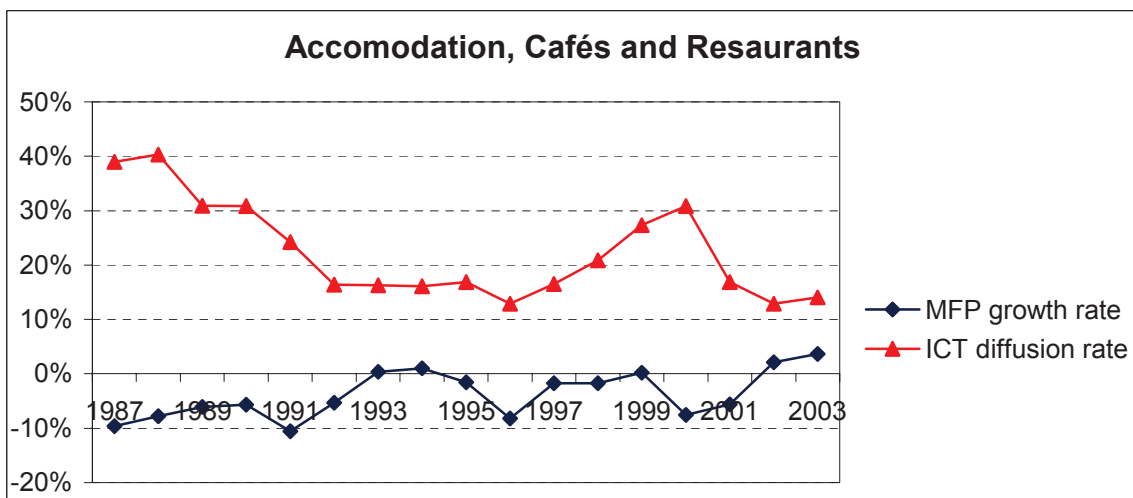
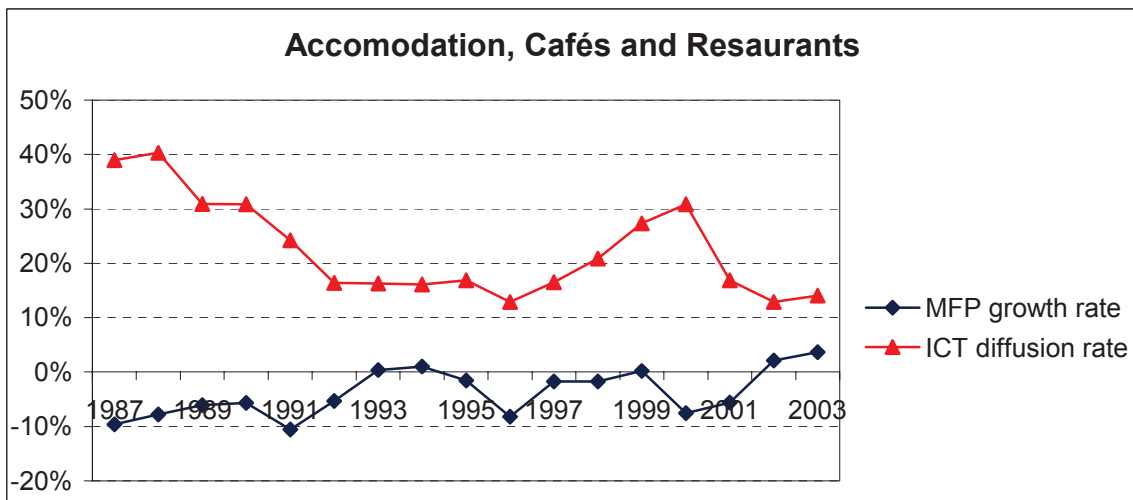
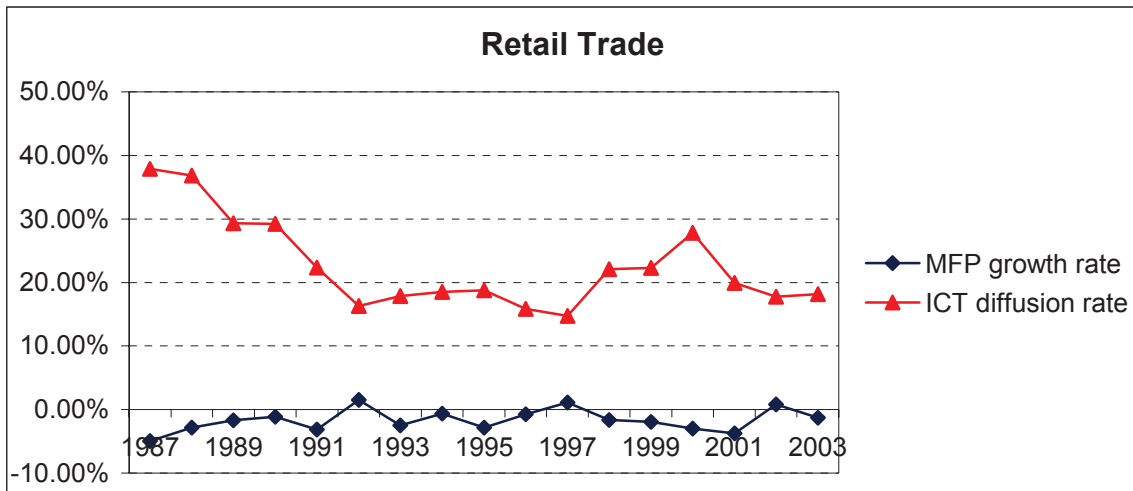


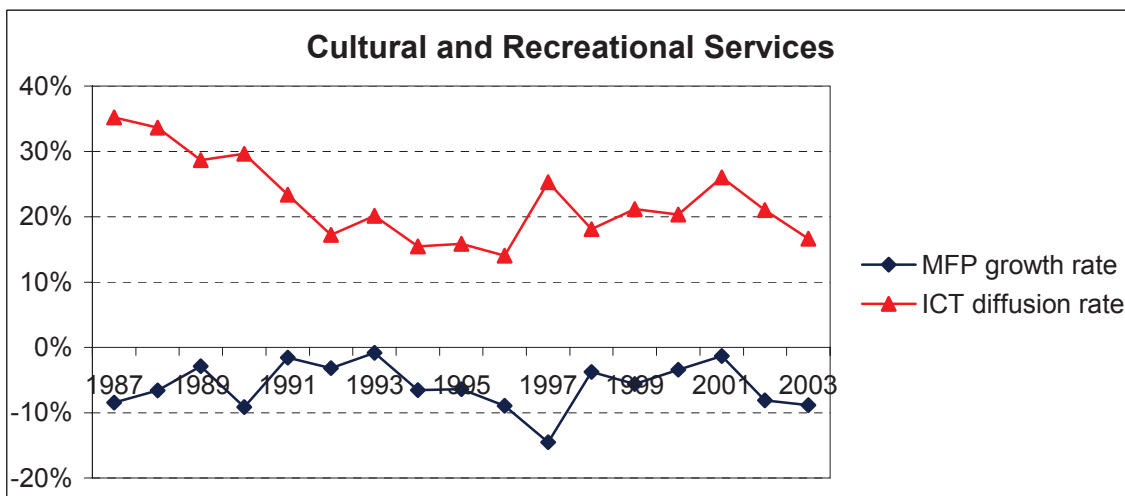
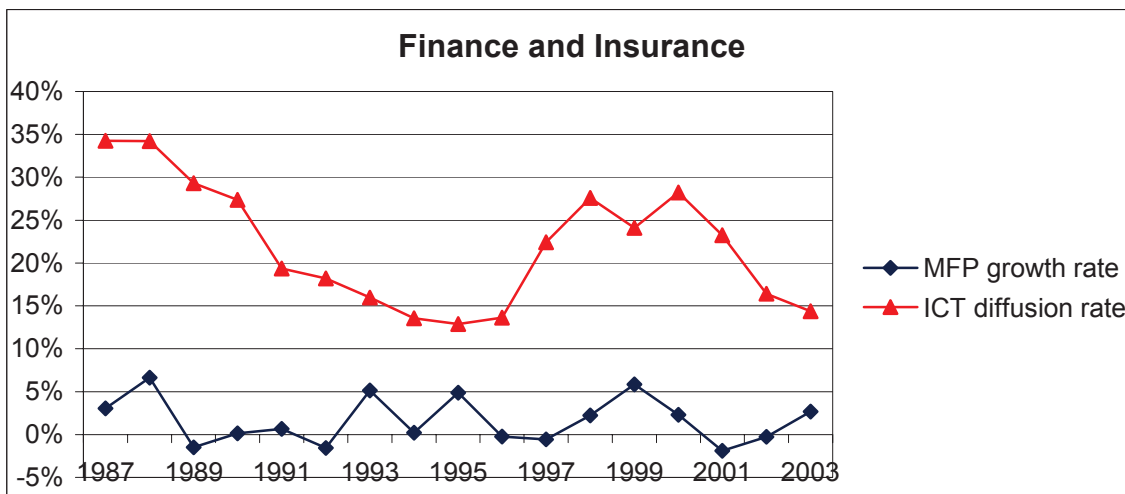
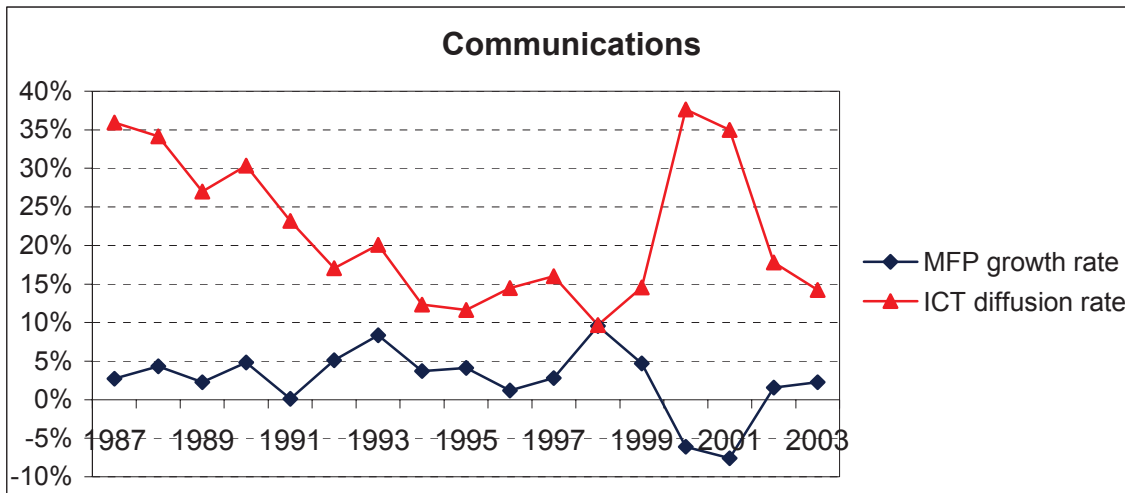
A4.3 MFPG and ICT diffusion in Australian industry sectors

MFPG growth rates and ICT diffusion rate for sectors of the Australian economy.









Chapter 5

5 Reviewing the evidence ¹

... as more and more countries have made efforts to improve their macroeconomic and policy environments, technology and technological innovation appear to have entered a 'golden age', a time when they are emerging as the key drivers of growth and development. (Prof Klaus Schwab, Global Information Technology Report 2004–05, preface)

¹ In house DCITA research. The study combines elements of two earlier studies: first 'Paradoxes and Paradigms: Australia's Productivity in an Information Age' presented at the Asia-Pacific productivity Conference (APPC2004) in July 2004; second, a more technical refereed paper, 'Estimating change in Australia's trend productivity' covering the Aspden MFP growth cycle approach and the Error Correction Model (ECM) estimation.

5 Reviewing the evidence

5.1 Background

It is now widely accepted in international economic circles including the OECD that firm level studies have conclusively demonstrated that ICT is having a significant impact on productivity growth. However, as indicated in the preceding chapters, the macroeconomic measurement of that influence involves serious data and conceptual issues.

Such measurement involves aggregate National Account estimates of growth in either national production or national income. The compilation of these estimates, however, is a difficult task. Additionally, these are often taken as surrogates for welfare improvement which is the ultimate focus of policy interest. Objections have, however, been raised to such a use. It is by no means clear that welfare improvement is rigidly related to growth of GDP in the longer-term particularly for developed countries because of the way in which those estimates are compiled, what they include and exclude and because of price/volume indexation issues.¹ Nevertheless, those GDP estimates remain the usual focus of attention because they provide the only convenient composite indicators of overall economic performance. Furthermore, explaining differences in overall economic performance across time and between countries remain critical issues for economic researchers and policy makers. Nevertheless, the above objections need to be borne in mind in any subsequent decomposition of the National Account estimates into the contributions of labour, capital and the residual MFP, such as we find in productivity estimates.

The measurement of productivity growth is complicated still further by the lack of consensus around theories of economic growth.² Important for this chapter, however is the fact that there is a large emphasis on the importance of accumulating technological knowledge in both neoclassical and endogenous growth models. This accumulation is seen as depending on a wide range of other economic and cultural issues.

These issues have given rise to long discussion among productivity researchers who, in the absence of a generally accepted formal growth model, are forced to look for statistical relationships in an ad hoc way between conventional statistical measures or proxies for variables of interest. As Rogers (2003) suggests ‘this is less than ideal but the lack of an

¹ For example, increases and decreases in leisure time are not measured as is the contribution of domestic and voluntary work.

² Rogers, Mark, 2003, A Survey of Economic Growth, *The Economic Record*, Vol 79, No 244, March, pps 112-135

encompassing model makes it necessary'.³ Rogers, acknowledging a host of econometric and data issues involved in cross-country empirical growth analysis, highlights four particular issues:

- Difficulties in obtaining data on the real variables of interest;
- The results of any specific regression may be influenced by relatively few, perhaps unusual countries or time periods;
- There are hundreds of possible explanatory variables that could be included in a growth regression; and
- There are considerable problems in interpreting regression coefficients particularly in relation to causality.

Rogers goes on to emphasise the frailty of the results suggesting that it is unrealistic to expect econometrics, however sophisticated to reveal the mysteries of economic growth.

A further consequence of these numerous difficulties is that much uncertainty surrounds particular estimates. Thus caution needs to be taken not to read too much into particular estimates as they typically involve measurement difficulties and problematic assumptions.

Australian research on the influence of ICT on productivity growth has been limited but included work by the Productivity Commission, the Reserve Bank of Australia, Dawkins and Rogers (1998), Toohey (2000) Wilson (2000), Dowrick (2001) and Quiggin (2001), as well as recent work by DCITA. Dawkins and Rogers 1998, in a contribution to a Productivity Commission/ANU Workshop on Microeconomic Reform and Productivity Growth in 1998 surveys recent Australian productivity analyses. This survey covered firm, industry and economy level studies. Among other things the review highlighted important variations in productivity performance across sectors and suggested that there was a need for various extensions to the existing research. Gregory (1998), in summing up the Workshop, noted that while the long-term impact of microeconomic reform was not questioned, the short-term productivity gains may have been oversold.⁴ Dowrick found in a study of 21 OECD countries that the acceleration in multi-factor productivity growth is unexplained in the same way that the residual was unexplained by Solow's methodology.

One further study was contributed to an OECD workshop on ICT and Business Performance in December 2002 by Gretton, Gali and Parham. It established complementarity at firm level between ICT take-up and other innovations using data from the ABS Growth and Performance Survey, a longitudinal survey of small business between 1994-95 and 1997-98 (Parham 2002). This study estimated that when the ICT coefficients

³ Rogers 2003, p122

⁴ Gregory 1998

were converted to form an ICT-based market-sector MFP acceleration, the result was a contribution of about 0.2 percentage points MFP acceleration on average over this period. This was followed by a further review of Australian studies in the Australian *Economic Record* of June 2004 (Parham 2004). The review also cites some relevant overseas studies. It concluded that the evidence on the sources of the productivity revival was not extensive. The review also presents some numerical estimates warning that specific magnitudes remain uncertain and that the orders of magnitude should be treated with caution. In particular, the review drew attention to cautionary points which it saw arising when drawing on the range of evidence employed. In brief these were:

- the applicability of parameter estimates from cross-country studies to Australian circumstances;
- the failure to allow explicitly for important institutional and policy differences;
- how well theoretical concepts are captured in measured variables
- the hybrid or ad hoc specification of theoretical relationships in measured variables; and
- the use in some studies of concepts and measures that differ from those generated by the Australian Bureau of Statistics.

It suggested that there was a one per cent acceleration in multifactor productivity (MFP) growth in the 1990s. It goes on to cite a wide range of indicative evidence to infer that half a percentage point of this acceleration could be attributed to increased openness, three-tenths of a percentage point to increased domestic business R&D, and two-tenths to ICT-related innovations. The study noted, however, that it was by no means clear that these influences were additive. The above estimates were derived from several sources. The half a per cent due to increased openness is based on Dowrick's (1994) estimated elasticity of productivity growth with respect to changes in the trade ratio. In regard to R&D, empirical models suggest that the gains in MFP growth from domestic R&D could be around three tenths of a percentage point. It suggests that Australia could benefit from ICT-related MFP spillovers up to the limit of those evident in the US and interpretation of the US evidence suggests the presence of ICT-related MFP gains of one or two tenths of a percentage point. Because it is based on a synthesis of different estimates from different sources the decomposition raises questions about the consistency of the underlying studies.

In addition, the review saw a need to distinguish between proximate and underlying factors, seeing ICT as being towards the proximate range of causal relationships while increased openness was seen as being more related to underlying causation. Whether the causal relationships can be differentiated in this way in practice is, however, problematic, given the complex causal typology being employed, the difficulty of devising any testable regime

for such a typology, and of separating influences given the possibility of interaction. Consequently, it is hard to assess that synthesis.

The review draws attention to a range of studies regarding the timing of the Australian productivity revival, suggesting that the timing remains difficult to pinpoint because of the influence of the business cycle. Nevertheless it is concluded that the structural break in productivity may have commenced as early 1990-91 and was well established by 1994-95. The Productivity Commission, subsequently drew upon this research in its review of national competition policy reform to conclude that ‘at the aggregate level it is difficult to attribute the productivity surge witnessed over the 1990s to other factors [than microeconomic reform]’. The review acknowledges that ‘the rapid diffusion of technological advances has been a feature of past periods of faster global productivity and economic growth’ but argues that during the 1990s, there was no evidence of a widespread international productivity acceleration’ and that this suggests ‘the change in Australia’s relative position from productivity laggard to front runner was due to easing of domestic constraints’. This usage points to the policy significance of productivity analysis and the need for care in their conduct and use.

Questions relating to the estimates in the numerous underlying studies will not be dealt with here. Rather, this Chapter is to examine the particular measurement and conceptual issues involved in the use of ABS statistics in deriving the extent and timing of the productivity surge and of the influence of ICT. It goes on to explore the implications of this analysis for the above estimates. This examination illustrates the difficulties involved in such analysis.

5.2 The ABS growth cycle methodology

Research by Charles Aspden (1989 & 1990) laid the foundation for the growth cycle methodology that today generates official estimates of Australia’s productivity growth by the ABS. Much of the Australian research makes substantial use of the growth cycle methodology to strip out the impact of low capacity utilisation during the early 1990s growth cycle.

Productivity researchers generally acknowledge that it is the level and change in trend productivity growth that is significant for economic analysis and policy and that, in consequence, the transient and cyclical effects should be stripped from the data prior to such use. In reality, this practice has frequently been ignored. Productivity Commission researchers (Parham, Roberts and Sun 2001) stand out as an important exception with their analysis taking this need into account. On the understanding that the official growth cycle methodology would effectively remove the cyclical effect these researchers have treated the ABS growth cycle estimates as robust estimates of productivity trends.

The evidence presented in this chapter suggests the methodology cannot adequately distinguish the upturn in the second half of the 1990s from movements in the longer run business cycle. The chapter proceeds by describing how the Aspden method is not capable of stripping out cyclical effects from productivity estimates. Empirical evidence is then examined in light of Quiggin's (2001) contention that the growth cycle averages could contain significant residual cyclical. The chapter goes on to consider possible smoothing modifications and the issues they raise. It then turns to explore whether the clouding effect of the year-to-year volatility in MFPG on robust estimation of trend MFP can be better addressed with an Error Correction Model (ECM) framework.

The effect of this analysis is to open to question the above separation of productivity growth into cyclical and trend components. A consequence is that analyses using that methodology may underestimate the relative importance of ICT in productivity growth.

5.3 ESTIMATING TRENDS IN TIME SERIES DATA

5.3.1 The market sector MFPG cycle

One issue of interest is how to obtain reliable robust unbiased estimators of trend productivity in Australia's market sector, given the presence of cycles and one-off and persistent shocks. Aspden (1990) contends that MFPG is best measured at peaks in the business cycle. He notes that:

Cyclical variation in utilisation of capital and labour are reflected in conventional estimates of multifactor productivity'. As an economy declines from a peak in the growth (or business cycle) some labour is shed, and some is kept but underutilised. Capital stock is less flexible and a greater proportion is likely to be under-utilised. Unless account is taken of the underutilisation of these inputs, then the MFP estimates will inevitably be affected and distorted. (p.4)

Aspden proposes that MFPG be estimated from change in the MFP index between peaks in the MFP growth-cycle. In effect, the MFP growth-cycle peaks are taken as indicator of the full and efficient utilisation of resources in the expansionary phase of the business cycle.⁵ He contends, in respect of these peaks, that:

⁵ Aspden may have considered using business cycle peaks to determine when productivity measures would not be biased by capacity under-utilisation. However he preferred the growth cycle peak in MFP. This choice assumes a close correspondence between the peaks of the MFP growth cycle and the classic business cycle. It eliminates hard-to-explain differences between peak estimates in MFP and market sector GDP. However the use of MFP as a statistically reliable indicator series is not without controversy. Solow, the father of growth accounting, regarded MFP growth as an unexplained residual attributable mainly to technological progress. Solow (1987) does not agree with the Real Business Cycle (RBC) use of MFP growth series as a statistical proxy for technological shock explaining disturbances to an equilibrium world (Prescott et al, 1982). Nevertheless, interest in RBC was high when Aspden developed the MFP cycle methodology. See McTaggart et al (2004, p.762) or Hall (1994, p.380) for a simple introduction into RBC.

Providing the utilisation rates at the cyclical peaks are the same, this should give estimates free of the effects of changing capital and labour utilisation. (p4)

The coarse-grained annual data of the MFP series is much less amenable to cycle identification than the fine-grained monthly or quarterly time series typically used to explore cycles. Nevertheless, the changes in economic relationships that characterise the business cycle are contained within both fine- and coarse-grained data series—the ability to identify such characteristics is the difference.

5.3.2 Determining turning points in volatile data

In time series analysis, one-off transient effects are generally neglected to better focus on broad patterns of change in economic activity and on equilibrium relationships between economic forces. Yet there is no agreed method for separating cycles from trends in volatile economic data. Indeed the determination of business cycle peaks and troughs remains contentious. Yet these turning points date the business cycle and signal a changing relationship between economic variables.

Graphical techniques are the simplest way of discerning patterns in data. However, time series data is often so crowded and volatile that a smoothing function is needed to reveal the underlying cyclical patterns.⁶ Some rules of thumb may be required to ensure adjacent peaks (or troughs) are not too close or too distant, and perhaps to separate major peaks (and troughs) from minor ones. Nevertheless, such simple approaches have proved deficient in practice.

Cycle peaks are particularly difficult to identify early. The growth phase of the economy often shows a sequence of local maxima. Consequently, a newly formed ‘local’ peak may not identify a ‘cycle’ peak. Dating troughs is perhaps easier because the recession phase is typically short and sharp.

In addition there is a wide range of macroeconomic indicator series that could potentially assist dating the cycle. Aggregate chained volume series for production, labour and investment feed into productivity measurement, but each has its own characteristic, with some preceding and some lagging a ‘reference’ business cycle. Moreover, the impacts of transient demand or supply side disturbances can differ in magnitude and timing across the indicator series. Statistical measurement can also contribute to phase differences between these indicator cycles. A peak in one series, but not another, may be due to a positive transient causing a peak, or a negative transient hiding a peak. For this reason, business cycle specialists accept that business cycle turning points cannot be robustly determined

⁶ See Dowrick 2001 and Gordon 2003 respectively for MFP treatments in Australia and the US.

from only the output index but should take account of related indicators of economic activity, such as employment and investment.⁷

As a result of these difficulties, the task of identifying the underlying cycle of economic activity from a collection of economic series involves a large measure of expert judgement. In the US the NBER has vested a special committee with authority to date turning points of a 'reference' business cycle. Australian economists, Harding and Pagan (2004) have recently developed statistical techniques to determine a fundamental underlying cycle common across the indicator series, and thus date peaks and troughs of the reference cycle. This approach is a move towards a less subjective analysis. However success requires consistency of data collections and uniformity in statistical treatments across countries, and more sophisticated modelling may be required to account for particularly influential disturbances.⁸

5.3.3 Classic and growth cycles

Distinguishing the growth cycle

A strong cyclical pattern that shows when the *growth rates* of an economic indicator⁹ are plotted against time is called the 'classic cycle'. The reference business cycles studied by Harding and Pagan (2004) and the NBER are based on the classic cycle. There is an alternative, the 'growth cycle'. The 'growth cycle' is the cyclical pattern that shows when the divergence between the actual and a smoothed time-series data is plotted against time. We call the resultant time series the 'de-trended' series since it is obtained by subtracting the trend (or smoothed) index from the actual index. It can be also defined as the periodic variation in the levels of a 'de-trended' index.

A rationale underlying the growth cycle approach is that the factors responsible for long-run economic growth are separate and distinct from the factors responsible for cyclical and transient disturbances. For example, expectation formation, monetary policy, elections, or labour market disturbance may impact on the cycle but not trend (see Grenville 1997 for a discussion in the Australian context). Economists preferring the growth cycle approach may argue that it is a better tool for application and evaluation of stabilisation instruments because it removes unwanted long-run effects from the series, bringing the appropriate target series into focus.

⁷ An extension is to develop composite leading and lagging indicator series. An example is the ABS experiment with leading coincident indexes to predict business cycle which was ceased in September 2003 because of changed relationships between economic variables in the 1990s.

⁸ An example is the East Asian Financial Contagion of 1997 for cross-country comparisons with Thailand, Korea, Philippines or Indonesia.

⁹ The variables are generally untransformed or lightly transformed.

The techniques used to identify cyclic peaks work equally well on growth data (to get classic cycles) and de-trended data (to get growth cycles). If the original index series is 'well behaved', the peak in the classic cycle will lead that of the growth cycle, and vice versa for the troughs. This effect may not be apparent if the actual data series is volatile or coarse grained.

Issues with the growth cycle

There are three issues with the growth cycle approach. First, variability in choice between de-trending techniques means an agreement on the best approach is unlikely, given that the different approaches will generally lead to differences in findings and methodological debate between researchers.

Second, the growth cycle approach to the analysis of macroeconomic change is not consistent with models that treat demand and supply responses to economic disturbance as interrelated. For example, the seminal research on RBC theory in the early 1980s provided a foundation for a new class of dynamic models that integrate, rather than separate, medium term fluctuations and long-run trends (Prescott 1986, Solow 1987 & 2001, Engle and Issler 1993)

Third, the identification and separation of trend from economic series cannot be achieved as cleanly as growth cycle advocates would wish. For example, global technology shocks have complex impacts. In particular, responses to new transforming GPTs (eg modern ICT) require hard-to-measure intangible complementary investments in skills and re-organisation, with potential productivity gains lagging by 7 years (Gordon 2003a, Brynjolfsson and Hitt 2003, Gregor et al, 2005). Transforming GPTs not only cause change in trend productivity, but also, through expectation formation, can generate macroeconomic bubbles and cycles.

Thus, the superiority of the macroeconomic growth cycle methodology over the classical cycle approach has not been established. The growth cycle approach may prove superior in particular cases, for example, if generalised statistical procedures can separate out the impact of the long-run and cyclical forces that combine to generate the original data. Such separation depends on independence between the forces that generate cycles and those that cause growth. Such independence should not be assumed as a matter of course.

When researching time series properties, it is often wise to let the data choose between alternative approaches, rather than assuming a particular method is best. Thus, in researching the productivity time series, a possible approach would be to explore both cyclic patterns shown in the data, and perhaps use the relationship between 'classic' and 'growth' cycles to more robustly identify the phases of the cycles.

Business cycles, productivity cycles and capacity utilisation

While both business and productivity cycles derive from the same data, they use the data in very different ways to achieve different objectives. The business cycle uses data on production (output), employment, and investment essentially as substitute indicators of economic activity. The relationship between indexes of output and input activity is what generates the productivity index. If one could measure exactly the labour services and capital services used in production, ie if there were no technical progress and improvements in managerial efficiency and if returns to scale were constant, then their addition should equal production. In fact, this relationship is assumed true for one year, the base year of the productivity series, which is given the reference index of 100. Trend productivity is positive because over time, the production index grows faster than the combined labour/capital input index. Cyclical variation in productivity can reflect inability or slowness of business to adjust inputs to (unanticipated) change in demand. Fixed factors suggest that productivity cycles and business cycles are closely related and rise and fall together, while lags in response to unanticipated change in demand suggest that the productivity cycle lags the business cycle (perhaps by about one to two quarters of a 16 quarter cycle). Such theoretical regularity is seldom apparent in real data. Irregularities and transient effects cause productivity data to be volatile.

Aspden expressed concern that underutilisation of resources in business downturns might distort the measure of productivity growth at those times, and so suggested MFPG is best measured at peaks in the MFP-growth cycle. In the low growth phase of the MFP growth cycle, the values of the actual MFP index should all fall below the corresponding values of the smoothed MFP index. Actual values less than the trend suggest the under utilisation that was of concern to Aspden. Conversely, the high growth phase of the MFP growth cycle could indicate a period when resources are fully used, perhaps unsustainably so.

However distinguishing the low from high growth phases is not the only way to split the cycle in two. One could use the turning points of the cycle to identify an expansion phase (trough to peak) and a recessionary phase (peak to trough).

For the classic business cycle, the high growth phase has been split into two regimes (Anas et al, 2003). One is the rapid growth possible in early recovery when resources needed to fuel output are present but under utilised. The other is the slow expansion when sustained growth requires creation of new resources and/or technological or organisational innovation. Such a split may not be feasible for the more symmetric growth cycle.

Identification of the different phases and regimes of a cycle could be useful if the relationships between the variables that make up both business and productivity cycles change in predictable ways between the phases. Moreover it is possible that a parametric

relationship such as that between labour productivity and capital deepening might hold during a particular phase of a cycle, but not over the cycle as a whole.

Empirical research on dynamic factor models with regime switches uses these relationship changes to explore business cycle effects (Anas *et al*, 2003). The systematic relationship change that characterises the business cycle would be expected to differ from complex relationship changes that characterise GPT-based technological growth. Such longer-run effects may be captured in the economic models that explicitly model technological change (Carlaw and Kosempel 2004 and Pakko 2002).

Anas *et al* (2003) in contrast focuses on cycle analysis, integrating growth and classic cycles in a single econometric framework. They relate the part of the growth cycle spent above trend to the fast growth regime of the business cycle, and the part spent below trend as the slow expansion and the recessionary regimes. They demonstrate that despite the difference between these models of cyclic behaviour, common sequencing relationships allows them to be combined to form a richer data set. Such relationships are however very complex, with, for example, the time spent in the different regimes likely to be asymmetric, with the probability of switching regimes being much higher in the recession regime than in the slow-expansion regime.

It is not possible to presently integrate such concepts into national productivity models based on a single aggregate time series of coarse-grained annual data. Nevertheless, an understanding of the ideal may provide a useful perspective as to both the potential and the challenges for methodological advances in the analysis of growth and cycles. If the relationships that generate the MFP growths can be classified by cyclical phase, then the high variability in MFPGs might be reduced. For in the ideal case at least, a splitting of the cycle into its component phases may reduce variability relative to the cycle as a whole. The variability of the MFP index would be reduced in the case of the growth cycle, and the variability of the MFPGs reduced in the case of the classic cycle.

Macroeconomic and sectoral productivity

Arguably the forces that drive the business cycle are macroeconomic in nature and cut across industries, albeit not in a simple way. So it is appropriate that the Aspden productivity estimates take into account the variation in capacity utilisation over the business cycle.

There is no reason to think that different productive sectors that make up the economy will all experience the business cycle in a similar way. For example, while all industries may experience declining output in a recession, the timing and rate of recovery varies across industries, sometimes significantly. As an example, our interest-rate-sensitive building and construction sector has often taken up the economic slack after growth in our traditional primary-based industries has slowed.

Thus the Aspden peaks, based on an aggregate productivity growth cycle, are not necessarily appropriate for industry analysis, and caution is advised before using the industry data to estimate industry contributions to the Aspden averages. The Productivity Commission's comprehensive 2003 research report into manufacturing explored the relationship between the manufacturing sector and the economy as a whole. It found that the five cyclical peaks in manufacturing do not have corresponding peaks in the market sector. To the PC, this suggests the 'the potential importance of estimating different peak-to-peak periods for different sectors' (2003, p.210). It finds that:

lagged values of Δ (unemployment rate) were more correlated with MFP change for manufacturing than the market sector, suggesting that cyclical effects may just have different timing for different sectors. Overall, this suggests that peak-to-peak periods are probably best constructed on a sector by sector basis. (PC, 2003, p220)

Nevertheless, such broad assumptions have been used in some analysis of ICT take-up. There is often an expectation that ICT is a technology with one-off characteristics, and that ICT investment can be modelled as a single economic shock, indeed one whose impacts will show as simple, readily discernable, patterns across all industries, with productivity gains being contemporaneous with investment, and in proportion to the intensity of ICT use. However, the reality is of lagged benefits that build as investment in organisational and technological innovation develops and diffuses as new specialisations. The end result is a complex pattern of cycles associated with progressive waves of new but related technologies.

In consequence, simple short-period criteria for evaluating the importance of ICT take-up through common time-series patterns may be suspect. Brynjolfsson and Hitt (2003) comment on the lack of consistency in industry findings. Basu, Fernald, Oulton and Srinivasan (2003) more firmly discount some of the judgements that are typical of such studies. The OECD (2004) used firm-based studies because of difficulty in interpreting the macroeconomic data that such industry studies typically rely on. To study the productivity cycles and trends associated with supply-side general-purpose technologies such as ICT, researchers might use firm-level statistics (eg the ABS BLD data as used by Breunig and Wong 2004) complemented by statistical analysis of more detailed data on technology use within firms (eg Grigor *et al*, 2005)

5.4 Explaining the Aspden peak-to-peak average

5.4.1 The Aspden estimation of average MFPG

Recognising that the under-utilisation of capital and labour in business cycle troughs can bias down the value of the MFP index, Aspden prefers to use the peaks in the growth cycle

rather than the troughs, to determine the averaging interval. He indicates that if utilisation rates at adjacent cyclical peaks are the same, growth in MFP between the peaks would be free of the distorting impact of resource under-utilisation during troughs in the cycle.

It is clear that the MFP growth could be biased if not calculated between identical points in a cycle. But this does not mean that selecting non-identical positions in a cycle for the end points will necessarily generate unacceptably biased estimates of average MFP growth.

The probability of a significant bias might be tolerably low, if the length of time is long, at least four or five years or more, *and* there is relatively little bias in the end MFP indexes, that is, if both end points occur in the relatively long and stable expansion phase of the classic business cycle. On the other hand, the probability of significant bias in average MFPG could be unacceptably high, if the period is short (less than four years) or either endpoint is in the relatively short and unstable recessionary phase of the classic cycle.

Aspden's preference for peaks over troughs in determining average MFPGs could have advantages in that a peak-to-peak growth cycle estimate might be less sensitive to an incorrect or late declaration of the cycle end than would other alternatives, such as the trough-to-trough growth cycle estimate. However, Aspden (1989, p.5, para 5.26) has been interpreted as implying a much stronger preference for the peak-to-peak MFP growth cycle approach than that just suggested. It has been assumed that the MFP growth cycle has some inherent or theoretical advantage over other cycles, that the peak-to-peak interval likewise has some inherent advantage over alternative cyclic periods, and that their combination is so superior to alternatives on theoretical and practical grounds that the alternatives need not be even examined. The validity of such assumptions is explored below.

Let 't' represent any year, A_t the value of the level of the MFP index in that year, and a_t be the MFPG between 't-1' and 't'. So $\{A_t\}$ is the time series of annual MFP indexes, and $\{a_t\}$ is the corresponding time series of the annual MFPGs.

The natural log/exponential function is used to relate the annual MFPGs to the annual MFPs and vice versa, eg

$$a_t = \ln(A_t) - \ln(A_{t-1}) \text{ so that } A_t = A_{t-1} \exp(a_t) \quad (1)$$

For the small growth rates typical of MFPGs, the equation (1) growth formula gives virtually identical results to the compound average growth rate (CAGR) formulae more common in the business world. For a one-period change, a CAGR equivalent of (1), using mid-point formula to correct for end-point bias, can be written as ¹⁰

¹⁰ Aspden uses the conventional business approach to calculating growths. Interestingly the base year where the MFP level is set to 100 is typically the penultimate in the series, so the index levels are determined backwards from the end rather than forward from the start. The statistical use of the Tornqvist index to

$$a_t = \{A_t - A_{t-1}\} / \{(A_{t+1} + A_{t-1})/2\} \quad (2)$$

The correspondence between the MFP and MFPG series means that either of these series can, after smoothing, yield estimates of trend MFPG, $\{a_t\}$ directly and $\{A_t\}$ by differencing. Moreover the de-trended series used to determine the growth cycle end points (see Section 5.3.3) can be determined by subtracting actual from trend values in either levels or growths.

Gordon (2003b) smoothes the MFPG series $\{a_t\}$ with especially chosen parameters of the Hodrick-Prescott (HP) filter, using the resulting series of smoothed MFPGs, denoted as $\{z_t\}$, as measures of smoothed MFPG. The de-trended series, $\{\delta_t\}$, is equal to $\{a_t\}$ minus $\{z_t\}$ and is the basis for a growth cycle in growths. As the HP filter trades off minimising the sum of squares of the $\{\delta_t\}$ series against the smoothness of the $\{z_t\}$ trend, the amplitude of the growth cycle and its end-points may be influenced by the nature of the de-trending.

This study follows Aspden rather than Gordon, and smoothes (and de-trends) the MFP series $\{A_t\}$, not the MFPG series $\{a_t\}$. Henderson 11-term smoothing gives the trend MFP series, $\{Z_t\}$. The de-trended MFP series, $\{D_t\}$, is obtained as the percentage deviation of the trend MFP indexes $\{Z_t\}$ from the actual MFP indexes, $\{A_t\}$. The $\{D_t\}$ series determine the set of years $\{T\}$ in which the growth cycle has a peak.

For year 't' to be in $\{T\}$, $D_{t-m} < D_t > D_{t+n}$

where $1 \leq m, n \leq 7$ and $m+n \geq 3$

and parameter values taken by m and n vary across the set of peak years $\{T\}$.

This complex procedure is used to determine the set of peak years $\{T\}$. Once peak years are determined, either the growth form $\{a_t\}$ and the level form $\{A_t\}$ of MFP can be used.

While acknowledging that regression analysis is an alternative to peak-to-peak averaging, Aspden suggests non-parametric approach is simpler. He prefers to estimate MFP growth by calculating the 'average annual growth rate between the MFP values at the cyclical peaks.', because this should give estimates free of the effects of changing capital and labour utilisation, providing that the utilisation rates at the cyclical peaks are the same.

Note that the average growth between two cyclic MFP peaks is the average of the annual MFP growth between the peaks. Thus if A_T is the peak ending the last cycle, and the next peak occurs 'n' years later, the average peak-to-peak MFP growth for that cycle, a_{av} , is given by:

$$a_{av} = \{\ln(A_{T+n}) - \ln(A_T)\} / n$$

constantly rebase (chain) index series is consistent with using the average of start and end values, rather than either one, as the divisor for calculating growth rates.

$$\begin{aligned}
&= \{ \ln(A_{T+n}) - \ln(A_{T+n-1}) + \ln(A_{T+n-1}) - \dots \\
&\quad \dots - \ln(A_{T+1}) + \ln(A_{T+1}) - \ln(A_T) \} / n \\
&= \{ \mathbf{a}_{T+n} + \mathbf{a}_{T+n-1} + \dots + \mathbf{a}_{T+2} + \mathbf{a}_{T+1} \} / n \\
&= \sum_{t=T+1}^{T+n} (\mathbf{a}_t) / n
\end{aligned}$$

The next section notes Aspden's concern about the size of the relative standard errors in the annual MFPGs, $\{\mathbf{a}_t\}$. Aspden is as concerned with imprecision in the MFPG estimates as with bias from cyclical under-utilisation.

5.4.2 Using cyclic averages to improve precision

Aspen argues that although the annual growth rates in gross output, capital stock and hours worked are economically related through business cycle effects, they are statistically independent. 'Therefore, using the discrete form of the translog function, an estimate of the relative standard error (RSE) of the annual growth rate of MFP can be derived from the RSE of the annual growth rates of gross output and the inputs.' (p.11) He proceeds to estimate the RSE in any \mathbf{a}_t is 0.77 per cent in the level form (A_t/A_{t-1}). Aspden shows that given a normal distribution, this means that if the at estimate was 2 per cent,

$$\begin{aligned}
&\text{then Prob } [1.2 \leq \mathbf{a}_{t \text{ true}} \leq 2.8] = 2/3 \\
&\text{and Prob } [0.4 \leq \mathbf{a}_{t \text{ true}} \leq 3.6] = 95\%
\end{aligned}$$

While the RSE error of 0.77% implies low confidence in the estimate of any particular annual MFP growth, Aspden (1990 p.12) points out that this RSE estimate ignores input measurement problems, so the true RSE is even larger, with a probable upper limit of 0.92%. He notes three sources of bias, namely: known, but unquantifiable, bias associated with his conventional approach; biases associated with the rapid price decline of computer equipment; and possible biases in length of asset lives and the gross output level. Aspden concludes that the individual members of the $\{\mathbf{a}_t\}$ series are imprecise:

It is clear that the possible size of the relative standard error of MFP growth estimates, taken together with the effects of variation in capacity utilisation, severely limits the usefulness of estimates of year-to-year movements in MFP. (p.12)

He proposes averaging both to improve precision and to control for variation in capacity utilisation over the cycle:

Estimating the average annual MFP growth rate over a growth cycle (from peak to peak) eliminates much of this noise, but at the cost of the loss of detail of MFP growth within a growth cycle.

While averaging reduces the RSE of individual MFPGs, controlling for the impact of cyclical variation in utilisation on MFPGs does not require that cycles be defined on a peak-to-peak basis. Any pair of corresponding cycle positions (classic MFP cycle peaks, classic MFP cycle troughs, etc) can be used to control for cyclical variation in utilisation. The theoretical requirement is a well defined regular cyclic pattern, and if troughs are easier to identify than peaks, trough-to-trough cycles could be preferred. For researching the properties of irregular cycles, a combination of peaks and troughs of both classic and growth cycles could be superior to the sole use of growth cycle peaks.¹¹

Any cyclic averaging of MFPGs will be biased downward by the low and possibly negative MFPs associated with the under utilisation characteristic of troughs. The deeper and longer the cyclical recession that separates the cyclical peaks, the greater is the downward bias in the average MFP growth for a peak-to-peak cycle.¹²

As noted by Aspden, (1990, p12), ‘averaging the MFP growth estimates does nothing to remove bias.’ This is relevant to their use in estimating the contribution of ICT to MFP growth. Aspden finds ICT biases the MFP growths down after 1984-85. Using more recent data, Diewert and Lawrence (chapter 3) also finds that conventional growth accounting understates the contribution of ICT.

The extent to which taking averages reduces the RSE can be estimated using the relationship between the standard deviation of a sample mean and that of the underlying population. The standard deviation of the mean is estimated by dividing the standard deviation of the population by the square root of the sample size. For a three-year growth cycle, Aspden’s RSE would fall from 0.9 to about 0.5 (ie, $0.9/1.73$).¹³ For a seven year cycle, the RSE would fall to 0.3 (ie, $0.9/2.65$). These are significant reductions. However, a greater reduction might be possible if MFP observations could be grouped by phase of the cycle, as suggested earlier. At issue is whether observations of MFP growth taken near cycle troughs could be considered as drawn from a population of MFP growths that have a relatively low average and reduced variability about that low average. Observations near the cycle peak have a relatively high average, but perhaps less variance about it. Thus while averaging does provide some statistical control for varying capacity utilisation,¹⁴ and may be appropriate for ABS use, researchers investigating the properties of the series could well devise methods that directly address this issue.

¹¹ Admittedly using troughs would invite comparison with business cycles where classic troughs are the usual start points (see Stevens 2000). Another possibility discussed later is to use labour productivity quarterly data, as produced by the BLS, for dating a productivity cycle. Such additional methods might help develop more robust estimates of MFP trends.

¹² Here we ignore the effect of phase shifts in the inputs, and the dynamic ‘guitar-string like effects’ often associated with recovery from deep recessions.

¹³ In percentage-point growth terms with a mean annual growth of 2 percentage points and $\{at\}$ as $(A_t/A_{t-1} - 1)$

¹⁴ Providing, of course, that there is no significant variation between cycles.

Interestingly, if the peak years of the growth cycle are used to estimate the average change in MGPG over the interval, that is, if they are used to estimate average MFPA over the interval, then that MFPA estimate could be free of the effect of varying capacity utilisation over the cycle. This is because MFPG estimates at cyclic peaks could be seen as measures of a macroeconomic ‘speed limit’. The ‘speed limit’ term is macroeconomic jargon for maximum sustained non-inflationary full-employment growth, a measure of macroeconomic growth at full-capacity. Thus, a jump in the MFPG from one growth peak to the next might indicate an increase in the ‘speed limit’, while saying nothing about the productivity performance in the short sharp recessions that typically separate growth phases. However, Aspden does not take differences between MFPGs at the cycle peaks. Instead he takes the difference in MFPGs, and that is equivalent to *averaging* MFPGs over the cycle.

Volatility in annual MFPGs is not news to the ABS. Its annual catalogue 5234 *Australian National Accounts Multifactor Productivity*, published to 1996-97, led with the headline caution as to the sources of variability in the index.

When analysing the productivity indexes (labour, capital or multifactor productivity) presented in this publication, it is critical to note that they are subject to the vagaries of the growth cycle, as well as the effects of any measurement error in either output or input. Differences in the amplitude and phase of the output and input cycles can result in productivity indexes deviating substantially from their long-term trend. (p.1)

5.4.3 Variability in the base variables (output, capital, labour)

The caution noted in the ABS productivity catalogue (5234.0) focused on the variability in the index series. However the volatility in year-to-year growth is much reduced when expressed as the variation in the index. Standard deviation (or standard error) is an indicator of volatility (or noise), but does not indicate the statistical importance of that volatility. For this, the standard deviation must be related to the mean, for example by division to get a relative measure. For error estimates, ABS use the RSE calculated at standard error divided by the estimated mean or average value. For volatility, we use standard deviation divided by the mean which we denote as RSD or relative standard deviation.¹⁵

If the volatility is comparable to the average, (that is, an RSD about 100%), then volatility will be of concern. If the average is high relative to the volatility, then volatility may be of little concern. Thus volatility in index values caused by variation in growth rates is of relatively little concern, since the standard deviation in the index is low relative to the average value of the index.

¹⁵ For example, elementary statistics shows that in terms of squared deviations, it is the variance plus mean squared that sums to the expected value of the squared values from zero.

Our interest is the volatility in the year-to-year growth scaled relative to average growth rather than the average value of the index. The value of the index at any point is of little interest. In fact, the value of an index in a given year can validly range widely depending on what year is chosen as the base and set to 100 (in log terms 4.605). The chained volume indexes for inputs and outputs can have the base value of 100 set at the series start or series end. Such rebasing, common to researchers and statisticians, causes all indexes values to change, but the chained structure preserves year-to-year growth detail.

It is the change in the index, whether year to year growth, or growth over a number of years, that is important. This is equally true for labour productivity (LP) and MFP— it is the growth and not the index setting that is a measure of productivity performance. This suggests the Relative Standard Deviations (RSDs) for growth rates should be estimated as standard deviation in growth rates divided by the mean growth (table 1)

Table 1. RSDs in indexes and growths of the base variables (indexes and growth) ¹⁶

<i>Variable</i>	<i>N Obs</i>	<i>Mean</i>	<i>St Dev</i>	<i>Variance</i>	<i>Minimum</i>	<i>Maximum</i>	<i>RSD=</i> <i>St.Dev/Mean</i>
log (Index variable)							(%)
Capital Use	37	3.92	0.43	0.19	3.12	4.64	11%
Labour Hours	37	4.43	0.09	0.01	4.24	4.61	2%
Market Sector Prod'n	37	4.04	0.33	0.11	3.43	4.61	8%
<i>Derived variable: MFP</i>	37	4.40	0.12	0.01	4.18	4.61	3%
Growth variable (%pa)							
Capital Use	36	4.21	1.26	1.59	1.82	7.01	30%
Labour Hours	36	1.00	2.18	4.74	-4.22	3.94	217%
Market Sector Prod'n	36	3.27	2.94	8.66	-6.28	10.60	90%
<i>Derived variable:MFPG</i>	36	1.05	2.23	4.96	-4.68	7.44	212%

Source: ABS (2001) plus DCITA calculations. MFP is included for comparison. As normal in macroeconomics, indexes are in natural logs, and the differences between adjacent index values are measures of the annual growth rates. Since the growth variables are expressed as percent per annum, their variance is scaled up by 10,000 (ie 100 squared).

Table 1 shows the low relative standard deviation (RSD) in the index variability. RSD for labour hours is particularly low at 2%. The reason is that since the average growth rate is low, the index values do not vary much. However this low average growth in the labour hours means that the RSD is very high at 217% as a growth variable. This high RSD is not due to a different volatility, but because it is scaled relative to a very low average growth.

In contrast, the high growth in the capital variable means its RSD of 11% as an index variable is the highest of all the index variables, but its RSD of 30% as a growth variable is by far the lowest of the growth variables.

¹⁶ RSEs are estimated by the ABS based the precision of the data processing. RSDs indicate the importance of volatility in the series. RSDs generally exceed RSEs.

The relative standard errors, as shown in table 1, feed into the variability in LPG and MFPG. However, for labour productivity, the relationship (covariance) between growths in output and labour is also important, since the higher the correlation, the more these growths move in tandem and the lower the RSD in the labour productivity growth. Likewise, the RSD in capital intensity are inversely related to the covariance between growths in use in capital and labour. The covariance matrix is shown in table 2.

The first column of table 2 confirms the low variance in the capital growth variable (1.59×10^{-4}), and shows that this makes for a fairly stable growth rate series and low covariance (a measure of correlation) with the more volatile growth variables (1.42 and 1.81 for the labour and output growth variables). As a growth variable, labour is much more volatile than capital, but much less than output. This volatility in the labour growth variable enables a strong correlation with output (as shown by the covariance of 4.04).

Table 2: Relative variability in the growth variables shown by the covariance matrix.**

	<i>Capital Use</i> <i>(2-term averaging)*</i>	<i>Labour Hours</i> <i>(2-term averaging)*</i>	<i>Market Production</i> <i>(2-term averaging)*</i>
<i>Capital Use</i>	1.59 (86%)		
<i>Labour Hours</i>	1.42 (80%)	4.74 (73%)	
<i>Market Production</i>	1.81 (78%)	4.04 (69%)	8.66 (49%)

Source: ABS (2001) plus own calculations.

The covariance matrix is scaled up by 10^4 for consistency with table 1. In other words, they are consistent with the conventional percentage expressions we use for the mean and standard. The number of observations is 36, and the sum of the squared or cross product deviations for the means are divided by 35 (ie N-1).

* If the adjacent growths are averaged, the variability falls. The term in brackets is the covariance of the 2-term averaged growths expressed as a percentage of the covariance estimates in the table. The value for MFP is 34.7%

**The variability in the variables is correlated to differing extents. The correlation coefficients are 0.5 for both the capital labour and for capital production relationships and 0.7 for labour / production relationship.

There are many sources of volatility. One concern is the importance of year-to year volatility, which shows as a sawtooth pattern in growth variables. Taking a two-term moving average smoothes out much of this volatility. We tested for the importance of this type of volatility by determining the covariance matrix for the two-term moving average or centred growth.¹⁷ These are reported in table 2.

The two-term moving average has relatively little impact on capital growth variable, only reducing its variance to 86% of its previous level (see table 2). However, it dramatically reduces the variance in output (to 49% of its previous level), and to a lesser extent the variance in labour hours (to 73%). These results show that year-to-year variation in labour and output growth variables contribute significantly to their volatility.

¹⁷ The two-term moving average growth is centred on the corresponding index. Its value at time t is calculated as half the difference between the logs of the indexes at time t+1 and t-1.

A further finding from table 2 is the strong fall in the covariance between the labour and output growth variables. This reduction suggests that some part of strong correlation between these untransformed growth variables is due to some part of their year-to-year volatility being related. For the derived variable, MFP growth, two-term averaging reduces the variance to 35% of its previous level. This indicates the combined input variable is far from perfectly correlated with output, and that the interaction between output and inputs contributes to the year-to-year volatility in MFP.

It might be argued that an RSD estimator for the derived growth variables (capital productivity, labour productivity, MFP and capital intensity) should be based on the index rather than the base growth variables (output, labour, capital and combined capital labour).¹⁸ This is because, as a matter of statistical practice, the growths in the derived variables are calculated from their indexes, which in turn are constructed by division of the indexes for the base variables. For example, the annual growth in capital productivity (KP) is calculated from change in the KP index. The KP index is constructed by dividing the output index by the capital index. The processes stop where the output and capital indexes are constructed using Tornqvist indexes to aggregate component growth data for the base variables.¹⁹ This rather circuitous route to productivity estimates does not destroy the underlying relationships between the growths in the derived and base variables.²⁰

This section has examined the significance of the volatility in MFPG and its source in the interaction in the different time series that comprise MFPG. We note that the capital series is relatively stable but that the labour hours series is particularly volatile and thus is an important source of the volatility in annual MFP growth. The next section goes on to examine the volatility in the MFP series and its consequences for obtaining a cycle average.

5.5 Empirical exploration

ABS estimates of the actual and trend MFP values and growth cycles are listed in table 1 and graphically displayed in figure 1. The LHS scale of figure 1 shows the actual MFP index (the thin red line) increasing from about 67 in 1965-66 to about 105 in 2001-02. The index of the trend MFP index (the green line) also increases in line with the actual MFP estimates, but shows the effect of smoothing by an eleven-period Henderson process. The de-trended MFP series, the differences between the actual and trend indexes, is the purple saw-toothed graph using the RHS scale. The cyclic peaks are illustrated with large filled

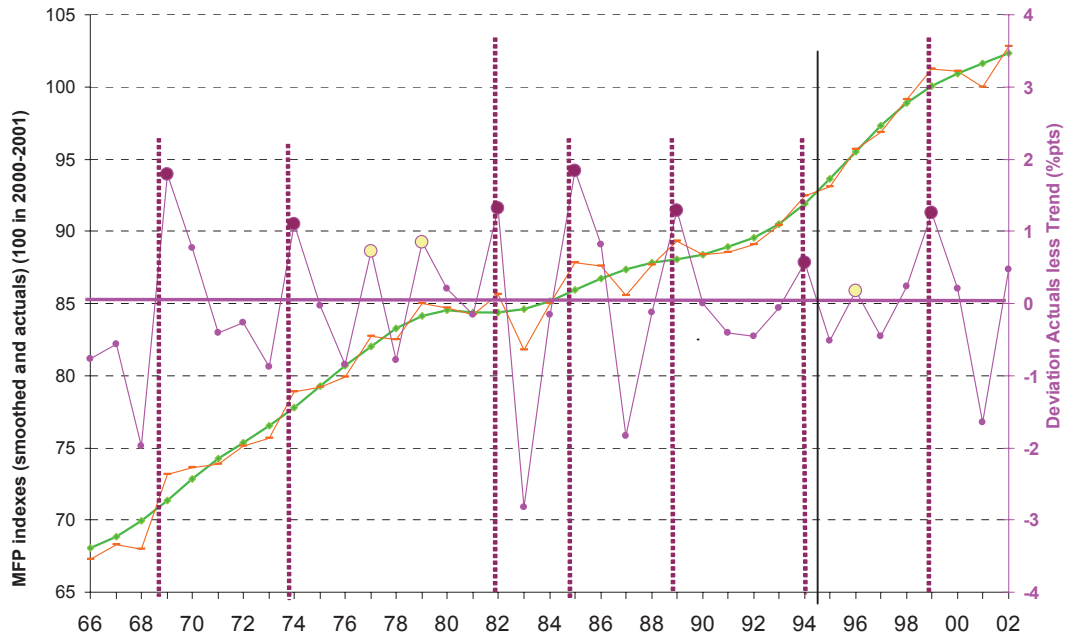
¹⁸ In any event, the estimator of the RSD in LP or MFP growth is not needed, as it can be estimated from the volatility in the derived data.

¹⁹ Simon and Wardrop (2002) describe possible aggregation inconsistency in ABS methodology.

²⁰ For capital productivity growth, the proof is as follows. Let K_t = the capital index at time t , O_t = the output hours index at t , and KPt = capital productivity index at t . Denote natural logs in the indexes as zK_t , zO_t and $zKPt$ and the growths variables as gK_t , gO_t and $gKPt$. Then $gKPt = zKPt - zKPt-1 = \log(KPt/KPt-1) = \log[(O_t/K_t)/(O_{t-1}/K_{t-1})] = \log[(O_t/O_{t-1}) / (K_t/K_{t-1})] = (zO_t - zO_{t-1}) - (zK_t - zK_{t-1}) = gO_t - gK_t$

purple circles. Local maxima that are not cyclic peaks are highlighted with a yellow fill. The graph does not identify the troughs that must split the peaks of a well defined cycle.

Figure 1 The ‘growth cycle peaks’ in Australian MFP, showing 1993-4 as a peak. The latest ‘peak to peak’ complete cycles are from 1988-89 to 1993-94 and from 1993-94 to 1998-1999.



The mean value of the points comprising the figure 1 growth cycle series is close to zero (table 1). The unusual nature of the 1993-94 peak is clear because its deviation from the mean is significantly less than the one per cent of all the other peaks. The graph shows that the 1993-94 peak is far less pronounced than the previous Aspden peaks. Although the local peaks at 1976-77 and 1978-79 were higher, neither was selected as a cyclic peak.

The nature of the 1993-94 peak is further examined in table 3, where the peak selection formula used by Productivity Commission (PC, 2003) for manufacturing sector MFP analysis is followed. The Productivity Commission defines major peaks as local maxima whose magnitude is greater than one standard deviation (1 per cent for manufacturing, but 1.35 for the market sector). It uses 0.66 of a standard deviation for minor peaks while we use 0.75. (0.75 corresponds to 1 per cent).

Table 3: Determination of growth cycles 1964-65 to 2001-02

Multi-factor productivity					
Year ending	Original series	Trend series (11 term Henderson)	Growth cycle series ^a	Published Cycle	Troughs & Peaks ^b
Jun65	69.72	67.43	3.34	1	P*
Jun66	67.27	68.04	-1.14	1	t
Jun67	68.27	68.84	-0.83	1	
Jun68	67.98	69.96	-2.87	1	T
Jun69	73.15	71.36	2.48	1,2	P
Jun70	73.6	72.83	1.05	2	
Jun71	73.83	74.24	-0.55	2	
Jun72	75.12	75.38	-0.35	2	
Jun73	75.65	76.53	-1.16	2	t
Jun74	78.9	77.8	1.40	2,3	P
Jun75	79.23	79.26	-0.04	3	
Jun76	79.88	80.72	-1.05	3	t
Jun77	82.76	82.04	0.87	3	np
Jun78	82.48	83.26	-0.94	3	nt
Jun79	85	84.16	0.99	3	np
Jun80	84.71	84.5	0.25	3	
Jun81	84.25	84.4	-0.18	3	
Jun82	85.66	84.35	1.54	3,4	P
Jun83	81.81	84.63	-3.39	4	T
Jun84	85.02	85.18	-0.19	4	
Jun85	87.79	85.96	2.11	4,5	P*
Jun86	87.57	86.75	0.94	5	
Jun87	85.55	87.39	-2.13	5	T
Jun88	87.67	87.8	-0.15	5	
Jun89	89.32	88.03	1.45	5,6	P*
Jun90	88.41	88.41	0.00	6	
Jun91	88.5	88.91	-0.46	6	dt
Jun92	89.09	89.55	-0.52	6	dt
Jun93	90.45	90.51	-0.07	6	
Jun94	92.46	91.89	0.62	6,7	
Jun95	93.07	93.59	-0.56	7	
Jun96	95.66	95.49	0.18	7	
Jun97	96.88	97.33	-0.46	7	
Jun98	99.09	98.86	0.23	7	
Jun99	101.27	100.02	1.24	7,8	P*
Jun00	101.1	100.89	0.21	none	
Jun01	100	101.64	-1.63	none	T
Jun02	102.8	102.33	0.46	None	
Average			0.019		
Std Dev			1.355		

Source: ABS unpublished data and DCITA estimates

Notes: a Growth cycle values calculated as 'ln (original/trend)%.'

b Major peaks (**P**) and troughs (**T**) (in bold capitals) are local maxima or minima such that the growth cycle value deviates from the mean by more than one standard deviation (ie 1.355). Smaller peaks (**p**) and troughs (**t**) are termed 'minor' when the deviation is more than 1 percent (ie about three-quarters of a standard deviation). This follows the PC (2003a p.209) specification for identifying cyclic peaks in the manufacturing sector. Of these peaks, the PC (2003b, p. 223) rejected 4, namely 68-69, 73-74 and 81-82 on the basis of initial trend testing with the ECM econometric model. 1974 and not 1983 was the start year for the trend variable). The peaks validated by the ECM testing are asterisked. Applying a lower limit of 0.66 per cent, ie $2/3^{\text{rd}}$ of the manufacturing sector's 1 per cent standard deviation, to the market sector would make two more peaks and one more trough around 1976-77 to 1978-79, denoted as np and nt (near minor peak and trough).

The mean value of the points comprising the figure 1 growth cycle series is close to zero (table 1). The ambiguous nature of the 1993-94 peak is clear because its deviation from the mean is significantly less than the one per cent of all the other peaks. Moreover although the local peaks at 1976-77 and 1978-79 were higher, neither was selected as a cycle peak.

The PC (2003) peak-selection criteria are extended by requiring that peaks and troughs alternate with the trough-selection criteria based on and symmetric with the peak-selection criteria. Although not clear from the figure 1, the numerical analysis of table 3 confirms that all the peaks identified by Aspden (1990) meet the specified requirements, but the post 1990 peaks do not.²¹

Table 3 shows that between the two major troughs of 1986-87 and 2000-01, there are two peaks but no trough. This issue is resolved by treating the 'double' local minima in 1990-91 and 1991-92 as a 'double trough'. This double trough is consistent with the recession and slow recovery of the time. To make a further peak of 1993-94 would require a further trough; say 1994-95.

In developing what is now an official ABS methodology, Aspden did not specify statistical measures that could distinguish between major peaks, minor peaks, and local peaks. For ABS delaying publication of a new average annual MFPG has to be traded off against any gain in precision and robustness that might come from delaying the declaration of a new peak. The potential benefit is any delay is not clear in an environment where data revisions can cause peaks to shift.

In other words, Aspden may not have wanted to impose unnecessary conditions on the peak selection process such as requiring the height of any a new peak be comparable with the heights of earlier peaks. After all, the Aspen MFPG average has no simple relationship to the size of the Aspden peak – instead it relates to the difference in the MFP index before de-trending, a difference that we have shown may well depend on the path tracked by the MFP index between the adjacent peaks. The goal of establishing an official time series that robustly tracks MFPG is much less demanding than determining a series that completely strips out the effect of variation in capacity utilisation over the business cycle.

The Productivity Commission's (PC 2003) research into the (relative) performance of manufacturing had very different imperatives. That research did not have to worry about unnecessary delaying of the identification of a new cycle. The complete time series of MFPG was available for analysis, and the researcher could use whatever tools thought best to achieve the research goals. In this sense, there was no imperative for the analysis to use

²¹ Perhaps surprisingly, the Productivity Commission 2003a reports the 1993-94 peak as (just) passing the 'near-minor' peak criterion. Table 1 shows this as failing the identical criterion. In discussion with Dr Lattimore, the difference was attributed to very minor differences between the unpublished ABS data provided to DCITA and the data published on the Productivity Commission website. This reinforces the concern that in near marginal cases, peak selection can be very sensitive to small differences in data.

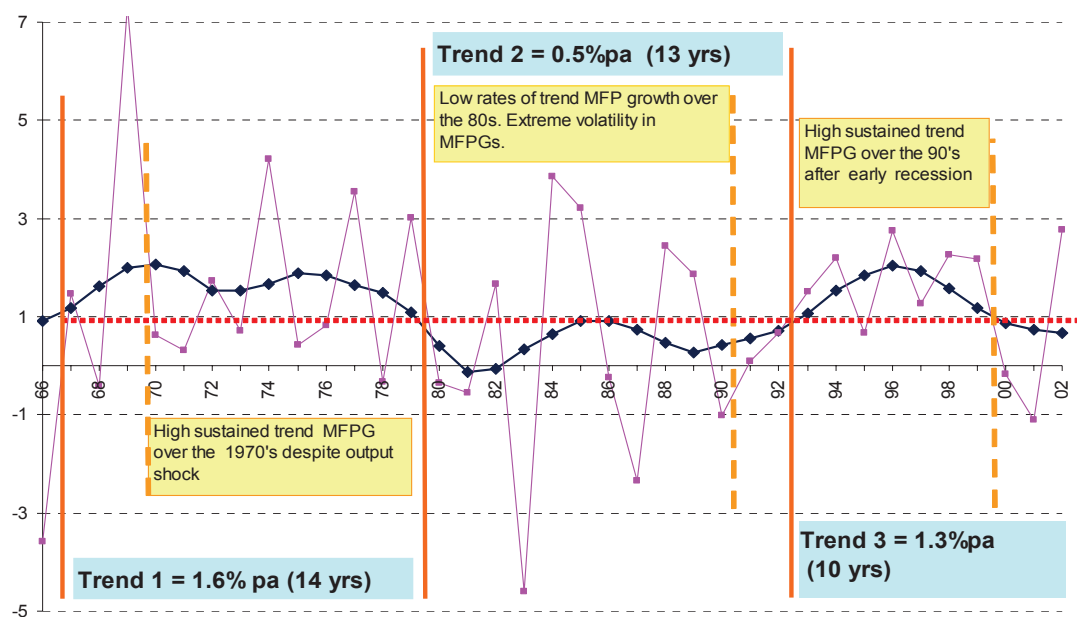
the series of Aspden averages if an alternative dissection of the data met the research purpose better. Thus while Aspden did not find it important to specify conditions attaching to declaring a new peak, it was entirely appropriate for the PC (2003) researchers undertaking the manufacturing study to carefully analyse the ABS peaks to ensure fitness for purpose. This they did.

The same rationale applies to the research of this study. The issue here is not whether the ABS was right to declare 1993-94 as a growth cycle peak. Rather the comparison of the relative heights of the peaks, and the relative depths of the troughs is a useful indicator as to whether change in the Aspden averages at that time might reflect variation in the classic MFPG cycle. The focus of this study is not so much to critique the Aspden methodology, but to shed light on how the Aspden MFPG series should be interpreted, and in particular, to question the assumption that the change in Aspden averages over the 1990s is a robust signal of a productivity revival.

5.5.1 Volatility in the annual MFP growths

The annual and trend growths in MFP corresponding to the index series in figure 1 are shown in figure 2. The volatility in annual MFPGs (the sawtooth purple line) is the source of the statistical ‘noise’ (or high RSE) that was of concern to Aspden. The volatility suggested by the growth cycles of figure 1 (the percentage deviations shown on the RHS scale) seems less than that suggested by the classical cycle of figure 2. The growth cycle approach tends to obscure the variation in annual MFPGs relative to the classic cycle.

Figure 2 Official trend MFPGs confirm low trend productivity over 1980s. A post-recession productivity surge in the early 1980s was not sustained.



Source: ABS unpublished data and own calculations.

The year-to-year volatility is more pronounced in the first half of the series. There are various measures of its extent. One is the proportion of times a local maxima is followed by a local trough, or vice versa. With a four year cycle one expects one local minima (trough) , and one local maxima (peak) every four observations. In contrast, of the nineteen observations to the 1984-85 peak there were 8 local maxima of which 5 were followed by local minima. Over the same period there were 8 local minima, of which 7 were followed by local maxima. The probability of this occurring by chance in a well-defined cycle is remote.

These frequency criteria are complemented by measures of significance, such as the extent of the year-to-year variation relative to the mean growth. For the growth cycle between 1973-74 and 1981-82, six of eight year-to-year changes in MFP exceeded one percentage point. In two of these, MFP growths of two percent per year were followed by a negative MFP growth. However, with the notable exception of the four years that both followed the 1993-94 Aspden peak, the sawtooth pattern has been less frequent since the mid 1980s. Arguably, this recent reoccurrence of the sawtooth pattern is what created the 1993-94 Aspden peak.

The sawtooth pattern is a significant contributor to the high RSEs and RSDs. Of the sawteeth, two are very significant, being identified as outliers both by eye and statistical test. The peak of 1968-69 suggests MFP growth of over five percent between adjacent years. The trough of 1982-83 suggests a MFP fall approaching four per cent. These are both very significant outliers that require detailed exploration.

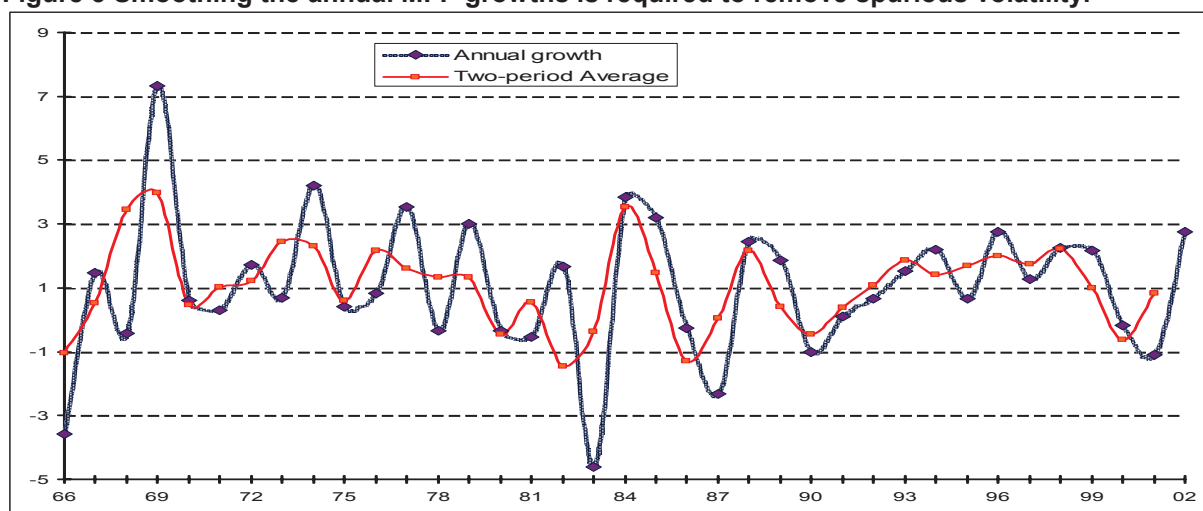
This sawtooth pattern in MFP growths might be taken as suggesting that the sequential local maxima and minima have some value in explaining how productivity responds to cyclical and long-run growth forces. This would be incorrect. It is more likely that the pattern reflects the sensitivity of the MFP residual to minor measurement error. Accuracy is difficult to achieve as nominal outputs and inputs must be adjusted for quality and price change. Spurious MFP peaks and troughs are generated when annual volatility in the output (or input) growth reflect disequilibrium adjustment rather than short-run equilibrium. It is to overcome such spurious non-equilibrium identities that Aspden uses cycle averages.²²

Figure 2 does not show the growth cycles. The annual growths in the Aspden trend MFP index (depicted by the dark blue wavy line) suggest a productivity slowdown in the 1980s. It is noteworthy that the Henderson X11 smoothing (figure 1) does not remove the influence of long cycles exceeding about 10 years. Such longer cycles are suggested by the Aspden trend growths, with different interpretations of cycle length possible according to whether the ill-defined cycles are measured peak to peak, trough to trough or mid-point to mid-point.

²² The BLS productivity data for the US shows similar volatility, but does not have the advantage of the Aspen methodology. However the US LP data is also provided on a quarterly basis.

The extent of the volatility is such that Dowrick (2001) used a three-term centred moving average to expose the underlying pattern. An alternative is the two-period non-centred smoothing presented in figure 3. It has some advantages over three period smoothing. The interaction of three-term averaging with the sequential clustering of local peaks and troughs (evident until the mid-1980s and around the mid 1990s) causes perverse effects. For example, with three-term moving averages, the peaks of 1968-69, 1980-81 and 1995-96 become local minima, and the 1977-78 and 1994-95 troughs becomes local maxima. Two-term averaging is a more intuitive approach to smoothing given this type of irregularity.

Figure 3 Smoothing the annual MFP growths is required to remove spurious volatility.



Moreover two-period averaging has an economic interpretation. The sequential ups and downs can be seen as form of mismeasurement associated with a systematic error in the timing of the underlying economic relationship—phase shifts that cause overestimation of MFP growth in one year leads to underestimation in the next, and so on. Finally, the two-period averaging has the advantage of centring the average MFP growth with the corresponding MFP index. Each MFP index value is accorded an MFP growth that is the average of the growths leading to it and from it.

5.5.2 Aspden averaging and residual cyclicity

The characteristics of the seven Aspden cycles are detailed in table 4. A measure of the cyclical influence on the difference in averages between the two 1990 cycles can be obtained by inspecting table 2 to compare the two ABS growth cycles of the 1990s. The trough in the late 1990s cycle is more than 1.6 percentage points higher than that of the early 1990s cycle (ie $+0.66 - -1.0 = +1.66$). Moreover the peak in the late 1990 cycle is more than half a percentage point higher than the peak in the early 1990s cycle (ie $2.74 - 2.2 = 0.52$). Taken at face value this would suggest that the bulk, if not all, of the apparent

acceleration between the two cycles is due to the cyclical factors, and in particular, to variation in capacity utilisation between very different cycles.

Table 4: Averages over the peak-to-peak cycle depend on the depth of the cyclical trough.

<i>Cycle ends</i>	<i>Cycle No.</i>	<i>Cycle Length (no. years)</i>	<i>Trough (Min growth) (% pa)</i>	<i>Average Growth over cycle (% pa)</i>	<i>Peak (Max growth) % pa</i>	<i>Standard Deviation</i>
Jun 1985	4 th	3	-4.60	0.82	(3.85, 3.21)*	4.70
Jun 1969	1 st	4	-3.58	1.20	7.33**	4.59
Jun 1989	5 th	4	-2.33	0.43	2.45	2.18
Jun 1994	6 th	5	-1.02	0.69	2.20	1.25
Jun 1982	3 rd	8	-0.54	1.03	3.54	1.57
Jun 1974	2 nd	5	0.31	1.51	4.21	1.60
Jun 1999	7 th	5	0.66	1.82	2.74	0.84

Source: Estimates from ABS MFP indexes published by the ABS (Zhao 2001 and ABS 2001)

*The peak here is a double one. For this cycle, the first observation is the deepest trough, but the next two form the double peak that includes two of the five highest peaks. For this cycle, the average reflects not only the depth of the trough, but also the presence this double peak.

** For this cycle, the presence of an abnormal peak of 7.3 (two standard deviations of 1.7 above the 3.9 mean for the single peaks) significantly influences average growth over the cycle.

Table 4 orders the cycles by ascending magnitude of the cycle average. Thus it can show whether the cycle averages are independent of cycle properties. In fact, it shows just the opposite: it shows how well the Aspden averages (unintentionally) capture cyclic irregularity and volatility. The shallower the cyclic trough, the higher is the Aspden average. This is a very strong relationship and fails only in the two most volatile cycles where exceptionally high peaks and exceptionally deep troughs make for less precise estimates of the cycle mean.

The table shows that averaging MFPG over the Aspden cycles does not control for cyclical variation. The cycle averages are strongly correlated with the depth of the MFPG trough. Based on the five observations, the correlation coefficient is 0.95 and the probability of no relationship is less than 1 in 100. The empirical reality is that while the Aspden average MFPGs are significantly better than the previously available annual estimates, they are not stripped of all cyclical variation.

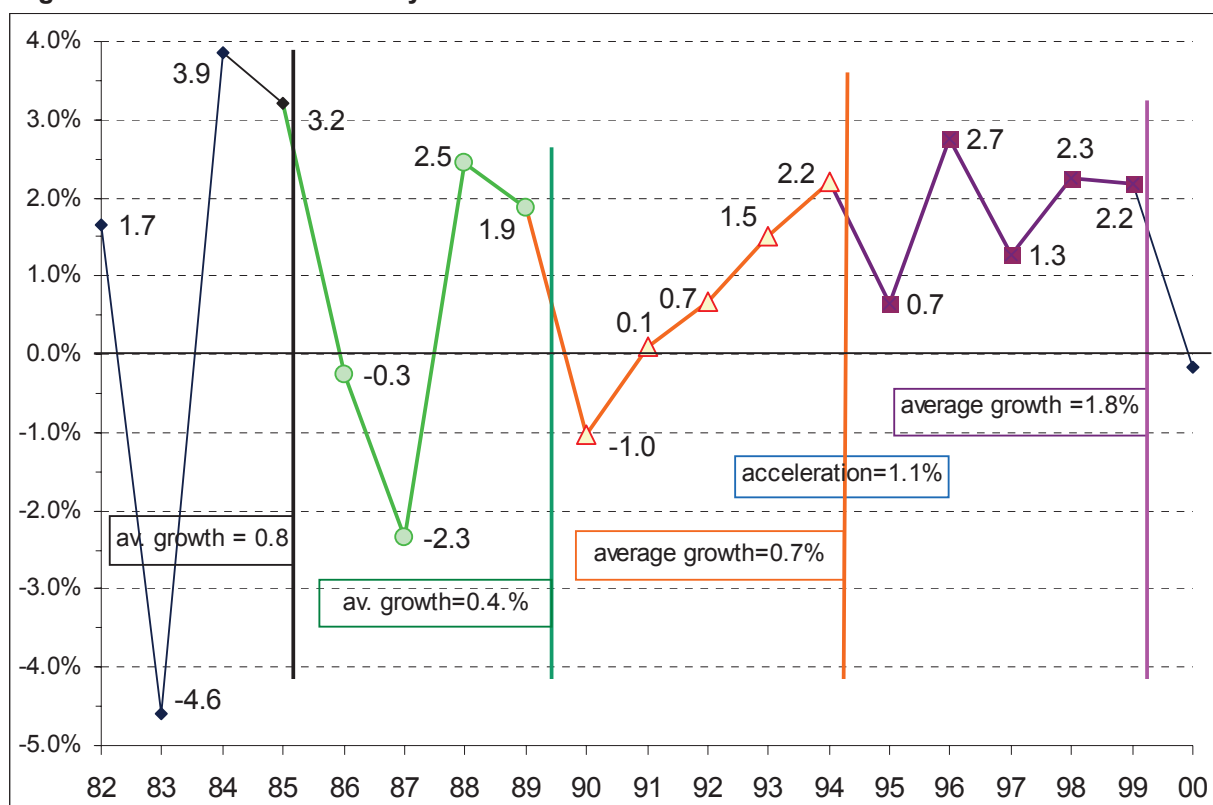
5.5.3 Acceleration between the growth cycles of the 1990s

The simple analysis of the growth cycles above questions whether microeconomic reform was in some underlying sense the fundamental driver and enabler of an Australian productivity acceleration in the 1990s. Figure 4 graphically depicts how the 1.1 percentage point revival between the early and late 1990 cycles arises. It suggests the change in MFP growth is cyclical and in consequence not a revival in trend productivity.

If we look at the performance of the economy since 1990, when the last period of negative productivity growth occurred, this latter period productivity growth is much higher than

that of previous periods simply because the latter periods did not have the large productivity shocks of the earlier periods. Hence it is not so much that trend productivity growth has picked up in the latter period that explains a good performance in the 1990s, but rather that Australia managed to avoid big recessions and the resulting negative shocks during the 1990s.

Figure 4 The Australian productivity revival of 1.1 percentage points between average MFP growths over the latest two cycles.



Source: ABS unpublished data - see Table 1.

Notes: The growth of 2.5% between 1986-87 and 1987-88 (labeled '88' on the x-axis) is the classic-cycle peak growth, whereas the (1.9%pa) growth-cycle peak that ends the cycle occurs the following year. Likewise, the '96' growth of 2.7%pa is a classic-cycle peak and not a growth-cycle peak.

The acceleration between growth-cycle peaks of 1988-89 and 1993-94 is 0.3 (ie 2.2 – 1.9). This corresponds to an annual average rate of acceleration of less than 0.1 per cent per annum between the peaks. The acceleration between the 1993-94 growth-cycle peak and 1988-89 growth-cycle peak is zero (ie 2.2-2.2).

5.5.4 ICTs contribution to MFP acceleration

This section examines whether the above findings require review of the existing estimates of the impact of ICT on productivity growth. We first review the existing estimates, before comparing those estimates to revised estimates of overall trend growth in MFP taking care to ensure valid comparisons.

The absolute extent of the contribution of ICT take-up in Australia to aggregate productivity growth was estimated in Gretton et al (2002). This research, with its

extensions, is one of the two sources of empirical data on ICT used in Parham (2004b) to explain the role of ICT in an Australian mid-1990s productivity revival. It uses an econometric analysis based on the ABS Business Longitudinal Survey for the four-year period from 1994-95 to 1997-98 which they saw as corresponding to a period of acceleration in national productivity growth.²³

The study reported that ‘businesses using computers had, on average, higher labour productivity than non-users and there was also a tendency for firms that had used computers longer to also have had higher labour productivity, on average.’ However, in respect to the sectoral impacts, the firm level data did not indicate the underlying reasons for the productivity differences or explain the substantial variability level of labour productivity across firms. These considerations suggest that it would be difficult to use sectoral averages and simple comparisons of performance to draw inferences about the influence of computer use on productivity.

In order to link firm performance, as measured by MFP, with use of computers, the researchers adopted an empirical model of economic growth. Simulations based on this model across eight industry sectors suggested that the use of computers had a positive effect on MFP growth in the mid-1990s but the effect varied across industries. Firms’ innovation experience interacted with the uptake of ICT to boost MFP growth. Overall, the uptake of computers was associated with a substantial reorganisation of industry and ways of working. These ICT-enabled transformations had raised the level of multifactor productivity amongst firms, thus increasing growth over the period 1994-95 to 1997-98 by 0.14 percentage points per year.

Computer use and Internet access alone is estimated to have raised MFP growth for the eight industry sectors (as a group) by over 0.11 percentage points per year over the period 1994-95 to 1997-98. Once the influence of associated skill, restructuring and organisational characteristics of firms is explicitly taken into account, MFP growth is estimated to have been raised by a further 0.03 points to make a total of 0.14 percentage points per year.

This finding, in itself, provides no indication of the relative importance of the ICT-enabled transformations to MFP acceleration. For that, the ICT contribution of 0.14 percentage points must be related to the total MFP acceleration over that period. At issue is the comparison of this estimated contribution to MFP acceleration over the four year survey period with the 1.1 percentage points difference in average market sector MFPGs between

²³ The researchers stated that whilst not primarily designed for this purpose, the BLS provides information on business use of computers and the duration of computer use obtained in the 1996-97 collection and, in less detail, in the 1997-98 collection. The 1996-97 information was sufficiently detailed to impute key computer use indicators for matched firms for the earlier survey years 1994-95 and 1995-96, and for 1997-98. The information about firm performance, computer use and other factors provided a basis for the analysis of the characteristics of firms using ICT and the implications of ICT use for productivity over the four year period 1994-95 to 1997-98.

the two 1990s MFP growth cycles, namely 1988-89 to 1993-94 and 1993-94 to 1998-99. The above researchers concluded :that the contribution from ICT use to Australia's aggregate MFP growth has been of importance, but not major — one or two tenths of a percentage point of annual average growth — as Australia's underlying annual average MFP growth reached 1.8 per cent in the 1990s.

The 1.8 percentage points is the average MFP growth over the late 1990s growth cycle (see figure 4 above), a period that includes the span of the econometric model. This comparison raises the question whether the 1.8 percentage points is to be interpreted not only as an MFP acceleration, but also as a component of the ongoing MFP growth. In the latter case, ICT-enabled MFP growth would represents only about 8 percent of the strong productivity growth located predominately in the Australian service sectors. This is implausible. Moreover, if this were the case then it would be apparent from case studies.

In any event the 0.14 of a percentage point has been typically interpreted as an acceleration. In this case, the appropriate comparison could be with the one percentage point difference between the average growths for the two Aspden cycles., an interpretation is suggested by Parham 2004c. The conclusion that ICT is not a major contributor to an Australian productivity revival comes when the 0.14 of a percentage point is compared to an claimed acceleration in Australia's annual average MFP growth of 1 percentage point over the 1990s. However, the economic estimate should be related to the MFP acceleration that occurred in the eight simulated sectors over the simulation period, ie 1994-95 to 1997-98. The researchers do not estimate this. However table 5 suggests that, for the market sector, there was little aggregate MFP acceleration over this period, just very strong MFP growth.

Table 5. Growth in market sector MFP during and around the 1994-95 to 1997-98 BLD study period, used in the Gretton *et al* econometric study.

<i>Period</i>	<i>Annual MFP growth</i>	<i>Annual MFP acceleration</i>	<i>1994-5 and 1997-98 averages</i>
1992-93 to 1993-94	2.2		
1993-94 to 1994-95	0.7	-1.5	
		+2.0	
1994-95 to 1995-96	2.7	-1.4	MFP growth = 2.1 MFP acceleration = minus 0.2 (ie. -1.4 + 1.0)/2
1995-96 to 1996-97	1.3		
1996-97 to 1997-98	2.3	+1.0	
1997-98 to 1998-99	2.2	-0.1	
1998-99 to 1999-00	-0.1	-2.3	

Source: Official ABS estimates when the report refereed in November 2004. The estimates were subsequently subjected to minor revision with the release of the 2003-04 annual accounts data.

Moreover, Breunig and Wong (2004) found little evidence of cyclical influence. Making this alternative comparison, the ICT generated contribution of 0.2 percentage points per annum on average relates to an overall acceleration of around zero over this period. On this basis, the research claim that for Australia, ICT did not make a major contribution seems unsubstantiated.

It remains at issue whether the claim might be justified though the use of the second source of the estimated 0.2 percentage point contribution of ICT to Australia's productivity revival. This second estimate involved the use of the US experience as a benchmark to suggest that the maximum MFP acceleration that could be attributed to ICTs is 0.3 of a percentage point, some of which must be attributed to ICT production leaving on balance 0.1 to 0.2 percentage points associated with ICT use. To convert this absolute estimate to a relative basis requires care to ensure comparison of like with like. Both the ICT contribution and the overall acceleration should ideally derive from the same analysis, ideally a formal model. If the estimated overall MFP growth between cycles is considered an overstatement of the underlying trend productivity, and adjusted downward, then so should also be the ICT contribution to that growth.

Unexplained cross-country divergences however seems to cast doubt on the assumption that since ICT is available globally, its contribution across economies should be uniform. In addition the underlying assumption that there cannot be spillovers across countries and over time needs to be empirically assessed. The work of Diewert and Lawrence and Carlaw reported earlier attempts such an empirical assessment. In turn this suggests a benchmarking methodology based on the US split of MFP acceleration into ICT and non ICT factors might be unreliable. The remainder of this chapter is therefore focused on improving evidence on the timing and extent of any MFP acceleration. For if the period of the 1990s was, for Australia, a period of solid persistent MFP growth in underlying MFP trends, with little MFP acceleration, then the attempt to determine ICT's contribution to Australia's productivity performance on the basis of an acceleration analysis could be of doubtful value.

The issue for the chapter is then to determine change in the underlying trend productivity, that is, to remove cyclical and transient components, a prerequisite to estimating the timing of any MFP acceleration. It is only after such an examination that the suggestion in the Gretton et al (2002) report to the OECD to the effect that ICT was not a major contributor to Australia's 1990s productivity performance can be properly assessed.

5.5.5 Alternative ways to use the annual MFP estimates

While the change in MFP index between Aspden peaks measures the average productivity growth between the peak years, the change in the height of the MFPG estimates at the peak years measures the acceleration between what are often peaks in the MFPG classic cycle.

As mentioned earlier, this measure of acceleration is not used by the ABS, possibly due to the high standard errors associated with any individual estimate. Nevertheless, it provides an alternative (complementary) measure of MFPA to compare with other estimates of the MFPA. This measure of MFPA is quite small, less than 0.4 percentage points in total and under 0.1 percent per year on average (see figure 4 footnotes). It questions the validity of a productivity revival in the mid-1990s.

This method could be extended and made more reliable by taking the difference between average heights of the MFPG ‘plateaus’ of adjacent cycles. This approach would reduce the RSE. Being independent of the path of the cycle (and so not relying on the less reliable estimates for decline, trough or initial recovery), such differences could indicate a fundamental change in the capacity of the economy to sustain long-run growth.²⁴

Trough-to-trough MFP growth cycles also provide another alternative to the peak-to-peak Aspden measures. Acceleration in averages over such troughs give results that can shed light on the robustness of the acceleration based on the increase in averages between adjacent peak to peak cycles. Growth cycle troughs occur at 1986-87, 1991-92 and 2000-01. The averages over these cycles are 0.81 and 1.28 giving an acceleration of 0.5 between the late 1980s trough-to-trough cycle and the 1991-92 to 2001-02 trough-to-trough cycle. Note that the analysis would reject possible troughs at 1994-95 and 1996-97, as both fail the decision rule (absolute deviation greater than 3/4 of a standard deviation (see table 3)).²⁵

5.5.6 Conclusions, explanations and implications

The evidence presented above cautions against the use of the difference in the 1990 Aspden averages as the measure of change in trend productivity. The reality is that an interaction between year-to-year volatility in the labour and output growths can create spurious local maxima and maxima in the Aspden cycle. The year-to-year volatility in MFPGs between 1993-94 and 1997-98 obscures the cyclical pattern (figure 2). Neither is the cycle clear in the pattern of the detrended MFP index. (figure 1). The domination of transient over cyclical effects is particularly apparent in the MFPG series, which nonetheless show that average MFPG was much higher in the late 1990s than in early 1990s.

²⁴As mentioned earlier, data relating to sustained peak productivity growth could provide robust estimates of the long-run relationship between resource inputs and outputs, or equivalently between labour productivity, capital deepening and MFP. Such estimates have not been made here. This expansion approach to estimating ‘speed limits’ to growth has been supported by the RBA (see Stevens 2000). It captures only dynamic efficiency effects, and not the effects of reduced volatility.

²⁵ It is possible that ABS may have had one eye on the labour-productivity cycle in deciding that 1993-94 was a peak. The labour productivity series makes a stronger case for a peak in 1993-94, with 1996-97 as the corresponding trough.

It was likely that ABS would declare the start of a new MFP cycle in the early to mid-1990s as many economic series in Australia have a four to five year periodicity.²⁶ The mid 1990s peak was not only expected, but made almost inevitable by the way the data evolved in the late 1990s. The changes were noted in ABS (1997) '1994-95, previously identified as a provisional growth cycle peak, has been provisionally replaced, in this issue, by 1995-96.' The cause was that new benchmark data for manufacturing gross product caused a big revision to the constant price estimates for 1994-95. The next announcement came in 1999, when after the one-off once-in-a-lifetime introduction of a new methodology including SNA93, this peak was revised to 1993-94 (ABS 1999a), as what was once MFP became capital deepening.

The decline that followed the 1993-94 peak might be seen as a pause in the long 1990s expansion. There was a similar pause during Australia's long 1980s expansion. Opinions differ as to whether such pauses mark a cyclical trough that separates business cycles. The marked pause in the 1980s expansion from the 1981-82 trough (associated in part with a severe drought) was characterised by the RBA as the 'pause that refreshes'. In contrast, the MFP growth series shows the pause as a very sharp deep trough separating two extreme peaks. However, such a central pause was harder to detect between the 1990s expansions, in both productivity and business cycle data, and most commentators treat the 1990s as a single long business cycle.

At issue is the relationship between the MFP growth cycle and the business cycle. The evidence suggests that any MFP cycle is a poor proxy for the business cycle and that the MFP cycle average cannot compensate for varying capacity utilisation over the phases of the longer business expansion.²⁷ If two productivity cycles correspond to one RBSA based expansion at issue is whether they reflect different phases in the broader business cycle.

Nonetheless, whatever the expansionary pattern, there is room for a fairly regular publication of productivity growth averages. We agree with the Aspden approach of using annual MFP data to determine the timing of the MFP averages.

The extent of the cyclical acceleration between the two halves of the 1990s can be roughly estimated. First, table 4 shows how cycle average is related to the depth of the cycle trough. It suggests the bulk of the acceleration is due to cyclical effects. Second, the trend MFP growths deriving from the Henderson X11 smoothing can be used. These X11 growths are

²⁶ Until the last few years, there had been consensus that Australia's cycles were well understood, and that the period was about 4 to five years. The termination of the experimental ABS leading coincident indicator of cyclical turning points in September 2003 is testament to the late awareness of change in cyclical behaviour, a change that may include a lengthening of the business cycle expansion phase and a moderation of the recessionary phase. See RBA Annual Conference 2005 for supporting evidence.

²⁷ While the labour productivity and MFP patterns are very similar, the research suggests (later, in figure 5 and table 6) that labour productivity data is somewhat less sensitive to year-to-year volatility and may be a sounder base for productivity analysis than MFP.

shown by the dark blue curvilinear line in figure 2. The X11 plot suggests a long cycle spanning shorter Aspden cycles. The difference between the average X11 growths over the two 1990 Aspden cycles is 0.8 percentage points. But figure 2 shows that the X11 growths rose from a trough in 1988-89 to peak in 1995-96. Thus early part of the X11 cycle fell in the early 1990s Aspden cycle, the peak falling the late 1990s Aspden cycle. Thus the longer X11 cycle could account for the bulk of the 0.8 percentage point difference in the X11 growths between the 1990 Aspden cycles.

Two conclusions come from this analysis. Firstly the inherent volatility suggests the average for each cycle can be sensitive to year-to-year volatility in annual MFP growths near the apparent end points, and differences between cycles are particularly sensitive. Secondly, the short Aspden cycles appear to cover different growth phases of longer periods of expansion, and hence their differences include these effects. In summary, a difference between the Aspden cycles, while a valuable indicator of short-to-medium changes in MFPG, is not a robust indicator of slowdown or revival in (long-run) trend productivity.

While this caution might appear to fly in the face of many analyses from around the world that compare productivity growth over the first half and second half of the 1990s decade, it in fact has strong support.

First, the macroeconomic issue of whether the 1990s represented one or two macroeconomic business cycles was fairly well resolved in favour of the former by 2001.²⁸ Quiggin (2001) comprehensively challenged the idea that the differences between MFP cycle averages could be taken as a measure of acceleration in trend MFP, arguing that two 1990s MFP cycles together comprised one peak-to-peak macroeconomic business cycle..

Second, the timing of the US productivity revival as dating from 1995 was based on a trend data series over many decades, using the same long term smoothing techniques that dated the US productivity slowdown as commencing in 1973 (eg Gordon 2003a). This provided strong support for US analysis that compared its first half and second half productivity experience—1995 was the year of the US productivity revival so it is appropriate to compare its performance around that year. The dominance of the US technology as a global source of productivity growth led other countries to compare their first half and second half productivity experiences, and compare the ‘acceleration’ with the US. In Australia, Parham *et al* (2001) was not the only paper to undertake such a comparison. Most notably, Simon

²⁸ For example, neither Stevens (2000) nor DiVenuto *et al* (2004) treat the mid-1980 local trough as a business cycle turning point. McTaggart *et al* (2004) use GDP growth to identify business cycles since 1980. Figure 20.2, page 391, uses annual data. Recessions are at 1982-83 (deep sharp single) and 1990-91 to 1991-92 (less deep, but wide and double). The deep trough at 1986-87 is labelled as such, but the shallow basin at 1996-97 is not treated as a trough. Figure 33.1, page 755, uses unsmoothed quarterly GDP series, not the headline annual estimates, and based on the ‘4 quarter’ estimates of growth rates. Perhaps controversially, it divides the 1990s by a very minor ‘trough’ of 1996-97. By selecting this trough, the periodicity of Australia’s business cycle is maintained at about 5 years.

and Wardrop (2002) of the RBA undertook an analysis to examine the role of ICT in Australia's productivity acceleration over the two halves of the 1990s. Such research does not examine the alternative that the business cycle may have dragged the early 1990s Aspiden average below trend and pushed the late 1990's cycle above trend.

In many applications, eg determining trends in MFP, the use of Aspiden cyclic averages is only one of a set of available methodologies, and arguably not the major one. As an aside, it is important to note that the validity of the annual MFP estimates is not questioned, although as noted later, recent ABS changes have improved the reliability of MFP time series data from 1990²⁹, and one gets the impression that the labour productivity time-series is more robust than the MFP series.³⁰ What is being questioned is the interpretation of growth cycle averages as robust measures of trend MFP growth.

5.6 Behind the MFP data

The MFP data that is input to Aspiden-peak-to-peak cycle averages is 'high level' data that results from the distillation of more basic input and output data. In analysing the MFP data, economists abstract from the individual disturbances that influence the basic series over time to expose the key underlying relationships and trends.

Rather than directly examine the MFP series, economists explore its properties indirectly by looking at how well variation in labour productivity (LP) is explained by variation in the capital labour ratio (K/L). In essence, MFP growth is the residual growth not explained by growth in capital intensity under the constant returns to scale assumption. This relationship between levels of labour productivity and capital output ratio is derived from the generalised production function. The growth form of the relationship was extended by Solow to develop the neoclassical model of steady state growth.

The key statistical characteristics of the productivity variables are shown in table 6. The extreme variation of the growth variables is suggested by the high standard deviation both absolute and relative to the mean. The base growth variables that feed into the calculation of the derived productivity variables were shown to be very volatile, with much due to year-to-year variation (see table 1 above). This suggests the variation in the derived growth variables might also be largely due to year-to-year volatility.

Capital productivity shows the greatest standard deviation (2.55), but this is less than the 2.95 for the corresponding output variable (table 1 above). Thus the variation in output growth is moderated by the influence of capital growth, but less so than the other variables.

²⁹ Thus for example, Zheng (2004) estimates of industry KLEMS-based MFP date from 1990.

³⁰ It is noteworthy that ABS has published LP estimates but not MFP estimates at the industry level. However, the Productivity Commission do use unpublished ABS data to calculate and publish the industry MFP estimates.

The standard deviation of 2.30 for labour productivity growth is higher than the 2.23 for MFP growth, suggesting higher volatility in an absolute sense. However, because of its higher mean, the relative volatility in LP growth (102%) is much lower than that for the capital productivity and MFP growth variables. Multifactor productivity is the weighted average of capital productivity and labour productivity. If we assume the relationship is unchanged over the full time period, the capital share needed to derive the index MFP from the capital and labour index is 15%. For the growth variables, the capital share is 65%. The gap between these and the expected 30-40 percent suggests instability in the relationship.

Table 6. Statistical characteristics of the derived variables (indexes and growths)

<i>Variable</i>	<i>N Obs</i>	<i>Mean</i>	<i>St Dev</i>	<i>Variance</i>	<i>Minimum</i>	<i>Maximum</i>	<i>RSD=</i> <i>St.Dev/Mean</i>
log (Index variable)							(%)
Labour Productivity	37	4.21	0.24	0.06	3.77	4.61	6
Capital Productivity	37	4.72	0.11	0.01	4.57	4.91	2
Multifactor Productivity	37	4.40	0.12	0.01	4.18	4.61	3
Capital intensity	37	4.09	0.35	0.12	3.48	4.64	9
Growth variable (%pa)							
Labour Productivity	36	2.26	2.30	5.31	-2.74	9.61	102
Capital Productivity	36	-0.95	2.55	6.52	-9.50	3.94	-270
Multifactor Productivity	36	1.05	2.23	4.96	-4.68	7.44	212
Capital intensity	36	3.21	1.86	3.45	-0.48	7.42	58

Source: ABS (2001) plus own calculations. As normal in macroeconomics, indexes are in natural logs, and the differences between adjacent index values are measures of the annual growth rates. Since growths are expressed as percent per annum, the variance of the growth variables is scaled up by 10,000 (ie 100 squared).

Table 7 presents the characteristics for the two-term average growth variables, in absolute terms and as a proportion of the un-averaged values. The difference in the averages is not significant—it is a technical factor associated with end point adjustment and the reduction in observations. The significant factors relate to the productivity growth variables, and are the reduction in the maximum (extreme) value by almost half, as expected, and the reduction in the standard deviation by about one third. This suggests that year-to-year volatility is a key source of variability in the productivity growth variables.

Analysis of labour productivity (LP) growth can be used to determine trends in MFP. The pattern of Australian LP growth is shown in figure 5. While it need not be the case, the figure confirms that in fact the Australian pattern of LP growth is very similar to that of MFP growth.

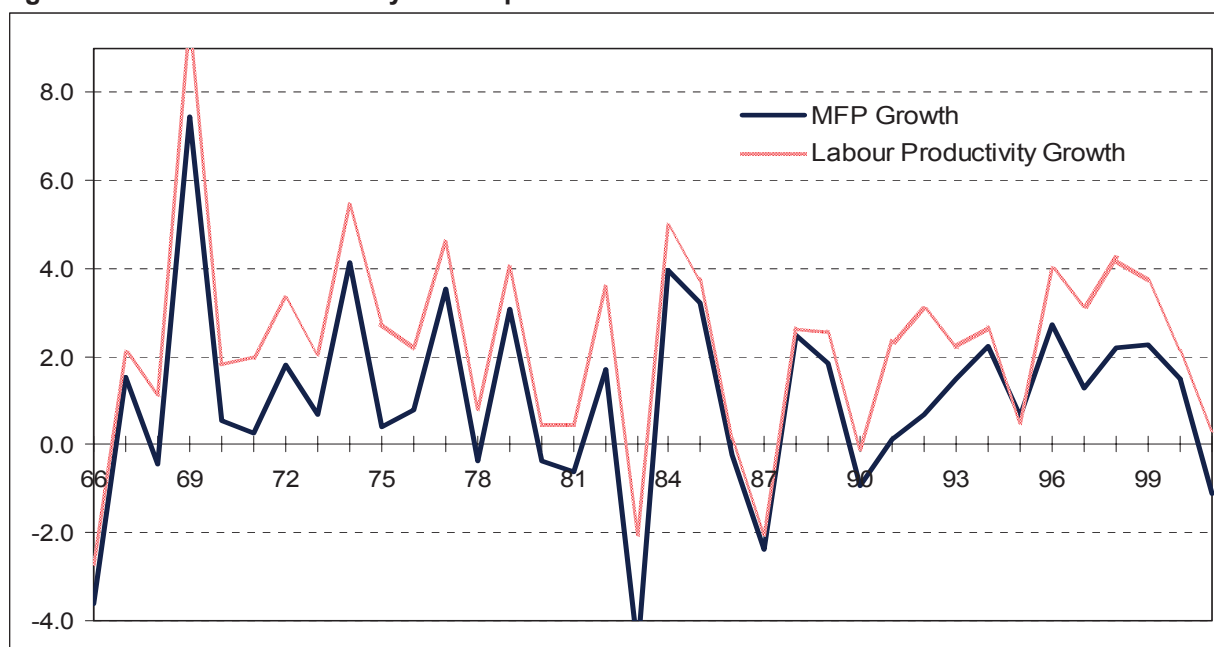
Table 7 Impact of two-term smoothing on productivity growth variables

<i>Variable</i>	<i>Mean</i>	<i>St Dev</i>	<i>Variance</i>	<i>Minimum</i>	<i>Maximum</i>	<i>RSD=</i> <i>St.Dev/Mean</i>
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The value of averaged growth variable						
Labour Productivity	2.36	1.46	0.02	-0.96	5.71	62%
Capital Productivity	-0.86	1.65	0.03	-5.76	2.11	-192%
Multifactor Productivity	1.15	1.31	0.02	-1.49	4.00	114%
Capital intensity	3.22	1.59	0.03	0.24	6.49	49%
Percent of the un-averaged variable						
Labour Productivity	104%	63%	40%	35%	59%	61%
Capital Productivity	91%	65%	42%	61%	53%	71%
Multifactor Productivity	109%	59%	35%	32%	54%	54%
Capital intensity	100%	85%	73%	-50%	87%	85%

Source: ABS (2001) plus own calculations. There are 35 averaged observations.

Figure 5 LP and MFP show very similar patterns



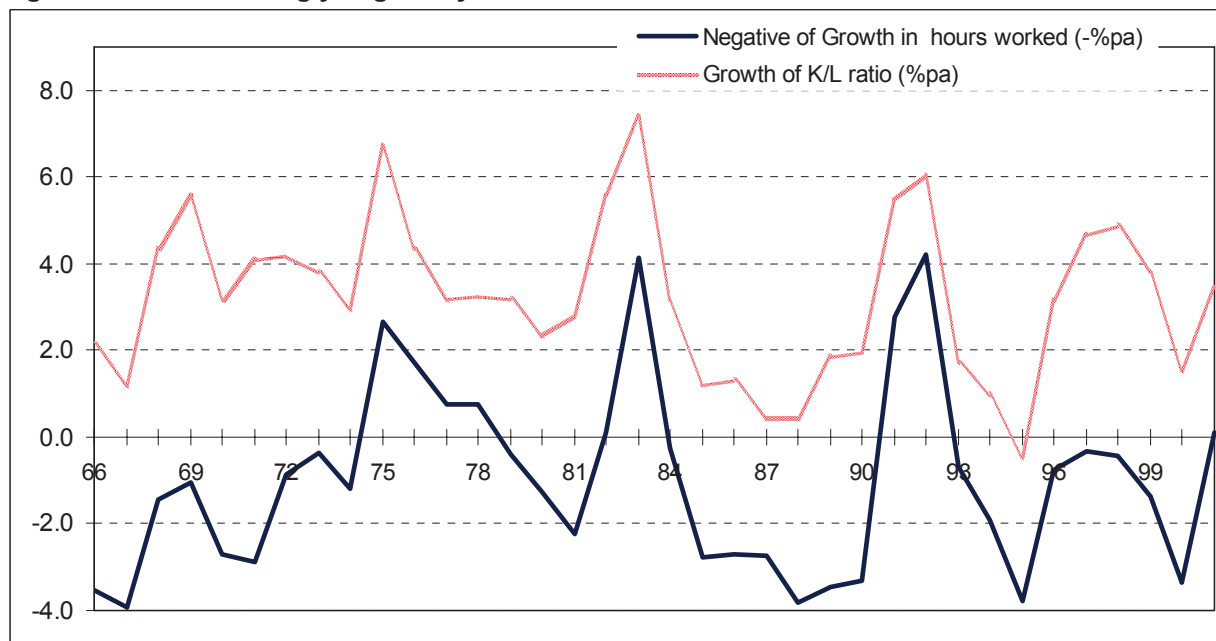
Source: Annual growths calculated from ABS MFP indexes published by the ABS (Zhao 2001 & ABS 2001)

Econometric investigation of the LP to K/L relationship has been used to estimate trend MFP. These studies are summarised below. Both Dowrick (2001) and Lattimore (2003b) have the acceleration in trend occurring before the recovery of the 1990s. Lattimore uses the 1988-89 MFP peak as the break. Dowrick uses the 1990-91 trough. The timing of the change in trend of these econometric studies do not support claimed stylised facts on timing (Parham, 2004a). Moreover the stochastic econometric analysis of Lattimore (2003b) points to a 1982-83 nadir in the MFP growth pattern, which marks a change from a decline to growth.

The growths in MFP and LP show a similar pattern because the difference is fairly stable. The difference is the capital deepening term of growth accounting, that is, the growth in capital intensity (ie K/L) weighted by the income share of capital. Both these are relatively stable. The move under SNA93 to replace capital stock with capital services has, somewhat

surprisingly, done little to increase the sensitivity of the capital input to output fluctuations. In contrast, the year-to-year jumps in the labour-hours series can at times exceed that of output. In fact, figure 6 shows that the growth in capital intensity is largely determined by the variation in the labour-hour series, with variation in capital services not sufficient to significantly affect the pattern.³¹

Figure 6 K/L ratio strongly negatively correlated with the volatile labour hour series.



Source: Annual growths calculated from ABS MFP indexes published by the ABS (Zhao 2001 & ABS 2001)

It will be shown that the year-to-year volatility is an issue for the econometric estimation as the ECM model interprets the volatility as impact of demand shocks.³² The chapter shows how the generalised least squares (GLS) econometric method allows the 2-term averaging transformation of the dependent variable, LPG, and the explanatory variable, capital intensity growth, that together comprise the short-run growth relationship. This transformation improves the econometric (ECM) estimation of trend productivity growth using co-integration. Thus, this form of volatility in the growth data is of concern for economic interpretation of productivity growth data in all methods (Aspden, ECM and X11 trend methods).

There may be a case to combine econometric methods with the more normal non-parametric methods early in the processing. Whether this work would be best done within or outside the ABS is less certain. Its effect may reduce the volatility and extreme values in

³¹ The affect of variation in the K/L ratio on MFP growth can be gauged from the difference between the MFP and labour productivity (LP) growths at the data points. The difference is fairly constant with some peaking and troughing. Further graphical analysis, not presented here, shows that at the common MFP and LP troughs of 1975 and 1983, the growth in the K/L ratio is a peak. In contrast, at the MFP, LP troughs of 1987 and 1994, growth in the K/L ratio troughs. This suggests some structural break in the relationship between 1983 and 1987. Support comes from comparison with the USA.

³² If the volatility is from year-to-year 'measurement error', then such interpretation might be misleading.

the MFP growth series. Volatility in the productivity data may have led to bias in the trend estimates.³³

Often there is no practical alternative to the indirect investigation of data through use of economic relationships between parameters. However sometimes the underlying data is both accessible and manageable, and approaching it directly can resolve issues associated with the impact of volatility on higher-level approaches. This is the case here. The data from which LP and K/L parameters are calculated are available for inspection. The data set is neither long nor complex. One can directly observe whether labour input growth and output growth shows the relationship expected over the business cycle. In fact, section 5.3.3 shows statistically that the sawtooth volatility in the productivity growths derives from the sawtooth volatility in the base variables (particularly the growths in output and labour)

5.6.1 Possible interpretations of the Aspden MFPG averages

The issue requiring consideration is how the two Aspden cycles that span the ten year interval between 1988-89 and 1998-99 should be interpreted in relation to the business cycle. At its heart, the issue is about the interpretation, not the validity of the Aspden averages for official use. Below, we list five possible interpretations that reflect different judgements about the Australian business cycle and its relationship to the Aspden cycle.

First, the Australian business cycle is regular in amplitude and periodicity, and is accurately tracked by the Aspden MFP cycle. This would mean that the Aspden MFPG averages necessarily strip out cyclicalities and can be taken as robust measures of trend productivity over the 1990s.

Second, the Australian business cycle is, or has become, quite irregular, in amplitude, with average capacity utilisation varying widely between adjacent cycles. In this case, the relationship between the Aspden and business cycles is not relevant — the Aspden averages do not strip out cyclicalities and do not measure an acceleration in trend productivity over the 1990s.

³³Other Australian economists have encountered surprising counter-intuitive findings with the productivity data, for example, Appendix E ‘Reverse Causal Flow’ of Bulman and Simon 2003. The relationship is so counter to what is expected that the authors found it necessary to raise the possibility of measurement error in their MFPG estimates, but unlike Diewert and Lawrence, 2004, quickly reject that possibility. ‘Given the odd relationship predominately appears in the multifactor productivity growth equations, a possible explanation may be the measurement issues with our multifactor productivity growth series. Measuring multifactor productivity growth as a residual of an output function means the series also captures the measurement error in capital—which is especially hard to measure accurately—and the aggregate hours and real and nominal GVA series. However, this explanation is unconvincing given multifactor productivity growth behaved similarly to labour productivity growth in the model observing price growth’s effect on productivity growth.’ p.38.

Third, the Australian business cycle has moderated along with other national business cycles, in part due to interaction of: (a) ICT-enabled leaner, less weighty, production; and (b) an improved ability of monetary authorities to moderate business cycles in an information age.³⁴ Here a close relationship between Aspden and business cycles would suggest the change in the Aspden average over the 1990s is a measure in the moderation of business cycles.

Fourth, the Australian and global business cycles have a complex periodicity, with for example a short to five year cycle resonating within a longer eight to thirteen year cycle. In this case, a close relationship between the Aspden and these more complex economic cycles would mean the simple comparison of Aspden averages is not a robust indicator of change in trend productivity over the 1990s. Rather, it would mean that the broader comparison between the 1980s and 1990s Aspden averages cycles may give a meaningful measure of change in trend productivity.

Fifth, the Aspden averages are not robust indicators of the business cycle, since the MFP estimates show as strong transient impacts any irregularity between the labour input and production output. Statistical processes available to date in reference to business cycles are inherently robust against aberrations that could grossly distort the Aspden averages. In this case, the Aspden averages should be taken as no more than a non-parametric estimate of short-to-medium change in productivity, and not inherently superior to other estimates, and certainly not as comprehensively tracking and stripping out the effects of business cycles.

In evaluating these five different interpretations, the next section first examines the two 1990s Aspden cycles, looking at the change in the underlying component time series that together form a reference business cycle and that feed into the calculation of the MFPG estimates.

5.6.2 The weak versus strong interpretation

Figure 7 shows the market sector GDP and the production inputs over the relevant Aspden cycles. The 1993-94 cyclical peak was formed by the decline that followed in 1994-95, a decline that ultimately resulted in 1994-95 becoming a local minimum. At issue is the cause of the large slowdown or de-acceleration in 1994-95.

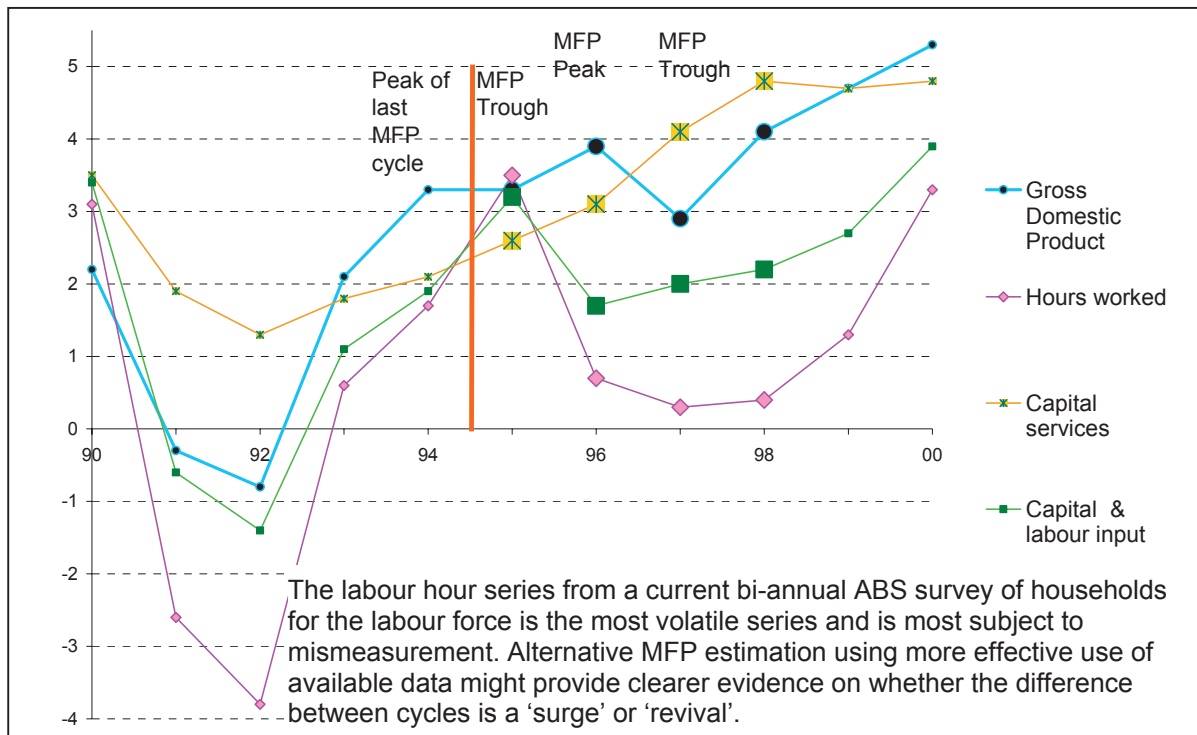
Figure 7 shows that this slowdown could not have been caused by slowdown in output growth (as output growth was sustained at the same level). It could not have been caused by acceleration in the use of capital services (as the acceleration was very slight, and in any event has a low one-third weight in the combined labour/capital input index.) Instead the

³⁴ See Baker (2003) for an analysis of new-found confidence by economists in the ability of monetary policy in an information age to smooth out the economically-harmful aspects of the business cycle. Dean Baker is Co-Director of the Center for Economic and Policy Research in Washington, D.C.

large fall in the residual between output and input growth is clearly due to a very large, but transient, acceleration in labour hours.

The claim that a transient aberration in the labour hour series explains the 1993-94 Aspden peak is supported by the examination of the associated mid-1990s trough. There are two candidates, local minima at 1994-95 and 1996-97. Lastly it is difficult to explain why the actual peak MFPG (the classic cycle peak) is separated by a trough from the growth cycle peak. Such considerations support the fifth of the five interpretations above.

Figure 7: The cause of the 1993-94 cyclical peak in MFP seems to be overshooting of labour market post the 1990-91 recession ‘guitar string’ resurgence.



Source: Annual growths calculated from ABS indexes published by the ABS (Zhao 2001 & ABS 2001)

The longer time series shows other instances where volatility in the measure of labour hours causes unexpected and non-equilibrium relationships between the production function variables. A similar finding could be made in respect to the two 1980s cycles. The issue is not so much as whether the ABS should declare a peak and new average, it is whether the adjacent cycles created by that peak are comparable. If not the Aspden averages will not control for differing degrees of capacity underutilisation in business cycle troughs.

In consequence, we see the evidence supportive of the fifth of the five interpretations, and rejecting the first. We also see some support for the third and fourth interpretation. (The fourth interpretation would reject the centrality of (microeconomic) reform as the central driver and enabler an Australian productivity revival, instead leaving the transformational

impacts of modern ICT to play a key role in a long run transition.) Overall, we see the Aspiden average as a means to expose the short-to-medium term movement of MFPG in the face of the volatility in the annual MFPG estimates. This ‘*weak*’ interpretation supports current statistical practice of providing a robust official estimate every three to six years.

However we see no guarantee that differences between the Aspiden averages for adjacent cycles give MFPG stripped of cyclical influence. That is, change in cycle averages may be necessary, but are certainly not sufficient, as evidence of change in trend productivity. Rejecting this ‘*strong*’ interpretation means the differences cannot be taken as evidence of a productivity slowdown and revival by productivity researchers without further supporting research along the lines indicated above.

In accepting the ‘*weak*’ interpretation, we conclude there is no need for substantial change in existing official productivity reporting, but care in its interpretation and use. Moreover, there is some scope to improve existing procedures to minimise the potential distorting effect of transient aberrations. For example, cycle averages could be estimated between troughs as well as peaks. This would provide more frequent observations in medium term trends in MFP growth. It may also help remove the misconception that averaging over the MFP growth cycle removes all cyclical effects. We would also like to see the cyclical pattern better exposed before making determinations of peaks and troughs. The analysis suggests that much of the variability in MFP growth is the result of year to year volatility. One way to better expose the underlying MFP cycle is to use the two-term moving average. A partial alternative might be to smooth the labour hours series.

5.6.3 A strong interpretation as a proxy for economic performance

The market sector productivity data need not be used as a macroeconomic performance indicator. It can be used as a reference when evaluating the performance of other industry sectors. The recent Productivity Commission (2003) research into the manufacturing sector carefully analysed the sectoral and market sector data in order to compare the productivity performance of this sector to that of other sectors and the market sector as a whole. Such research is of some value, even if its value is limited by less than full coverage.

Nevertheless, some experience suggests that working with sectoral National Accounts data is problematic—it is much safer to stick to aggregate level data where inter-industry flows of intermediates cause fewer measurement problems. Productivity researchers commonly ask statistical authorities to provide productivity data on property and business services, health and education, and generally for more and better data on the increasingly important service sectors.

However if, despite its various shortcomings,³⁵ market sector productivity is to be used to characterise the performance of the Australian economy as a whole, then there is a need to understand the relationship between the market sector MFP and the more conventional macroeconomic measures of performance. While the measured growth in the whole economy will be influenced by the treatment of, for example, government sectors,³⁶ it would be expected that it would broadly parallel that of the market sector in timing and extent. In this regard it should be noted that the current ABS market sector excludes around one-third of the economy. Greater confidence as a macroeconomic measure might result if market sector findings can be verified against the wider economy methodologies.

The Reserve Bank of Australia (Stevens 2000), using quarterly data, has compared recent complete business cycles, one each for the 1970s, 1980s and 1990s. The 1990s cycle showed the highest trend productivity growth, by 0.5 of a per cent on a GDP/head/year basis, and had the longest growth phase. Somewhat surprisingly, these three RBA business cycles correspond to the six productivity cycles of the ABS, the ABS cycles being half RBA cycles, a point made strongly by Quiggin (2001).

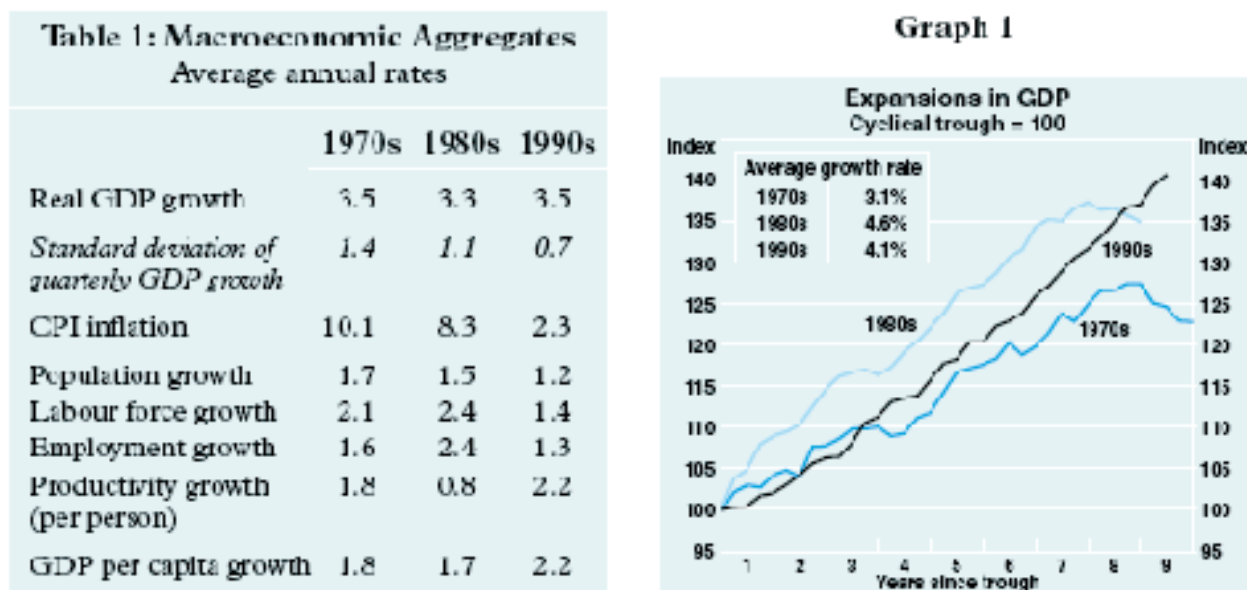
The RBA itself has in the past spoken of the expansion and intervention cycles, the later being when interest rate intervention is taken to reduce inflationary macroeconomic short-run gaps. Of course, such action affects the output composition of the economy, particularly in housing and construction activity, and hence may have influenced cross-industry productivity performance.

Paul Schreyer, author of the OECD productivity manual (OECD, 2001), has recently computed productivity based on the total economy level for Australia, the US, and France (table 8). This is work in progress, and Schreyer (2004) carefully documents the many steps in deriving the capital services index. Indeed the purpose of this work is to illustrate the effect of using capital services rather than capital stock, and to develop work-arounds for some of the conceptual/data issues, including the government-dominated sectors.

³⁵ These are well documented, but generally ignored. For general issues, see Schreyer OECD productivity manual. For Australia, additional issues are the exclusion of the PBS sector.

³⁶ Market sector can be regarded as a collection of industry sectors, in Australia, excluding private markets in property and business services, housing, health and education, and excludes at least some of the flows between the sectors through intermediate flows, use of natural resources, terms of trade effects, etc. Depending on the assumptions and treatment for the non-profit public sector, the whole-of-economy productivity estimates may or may not understate productivity growth.

Figure 8: A Reserve Bank of Australia comparison of expansion over three decades of cycle.



Source: RBA (2000).

Table 8: Draft whole economy estimates of annualised productivity growth (Schreyer 2004)

Measure	Period	Australia	United States	France
Output	1984-90	3.2	3.3	2.9
	1990-95	3.2	2.4	1.1
	1995-01	3.8	3.4	2.5
Capital services	1984-90	2.0	2.7	3.3
	1990-95	0.6	2.5	1.8
	1995-01	1.8	4.8	2.3
Net capital stock	1984-90	1.7	1.8	2.1
	1990-95	0.4	1.5	1.5
	1995-01	0.6	2.4	1.3
MFP based on capital services	1984-90	0.9	1.0	1.9
	1990-95	2.2	0.8	1.0
	1995-01	2.2	1.1	1.4
MFP based on net capital stock	1984-90	1.0	1.2	2.2
	1990-95	2.3	1.1	1.1
	1995-01	2.6	1.7	1.7

Although Schreyer's purpose for this draft work is not to show cross-country comparison, and it should not be taken as evidence in its own right, the findings ring true with a range of other studies.³⁷ Moreover, Schreyer's estimate of 1990s growth is consistent with that of figure 8 above.

³⁷ Schreyer notes the strong performance of the ABS against other National Statistical Bureaus, and its ability

- First, it highlights Australia's strong productivity growth in the 1990s relative to the US.
- Second, it suggests that the acceleration in Australia's productivity growth occurred at the turn of the decade, and is best seen as a 'between decades' effect rather than an effect of either the 1980s decade or the 1990s decade. The extent of the acceleration is quite high at about 1 percentage point.
- Third, the timing of Australia's productivity revival appears very different to that of the United States. The US acceleration occurred in the mid 1990s. Australia showed no acceleration in productivity at that time.

Schreyer (2005) extends the work above, to combine measures of productivity levels with measures of productivity growth. The study raises new issues for whole-of-economy cross-country comparisons, and points to the need for further work.

5.7 Towards more robust MFP cycles

MFPG is an important macroeconomic indicator. It is used to assess the performance of economies and policies. Forecasts of the medium to longer-term productivity outlook are used in forward government planning and policy development such as intergenerational issues associated with aging populations. Nevertheless, the evidence shows that in Australia, one of the world's leaders in application of statistical best practice to National Accounting, there are various issues and uncertainties associated with official measures of productivity.

The discussion points to where advances might be possible, while also pointing to the difficulty associated with coarse annual data series such as the input series to MFP estimates. The discussion on cycles and trends points to a range of issues which in turn leave open a broader set of approaches that might improve the data quality. Such approaches could include: using moving averages over the cycle, rather than just the peak to peak cycle; using classical cycles to determine a more comprehensive guide to how capacity utilisation might be varying than available with growth cycles; provide RBA style peak-to-peak estimates of 'speed-limit' for 'full-employment' productivity expansion; using outside series to date cycles, or alternatively placing more weight on more fine grained quarterly labour productivity series as a cyclical dating mechanism;³⁸ or using integrating parametric with non-parametric methods to better use relationships between hours worked and output series to remove the more extreme volatility; or using transformed

to keep abreast of global statistical developments.

³⁸ The US BLS last published the annual MFP series in 2001. However the quarterly labour productivity series is published to the June quarter 2004. Australia might consider greater emphasis on labour productivity growth given the issues with capital measurement. This is supported by the close correspondence between MFP and labour productivity growth (LP). Moreover the theoretical base for using a MFP cycle is less strong now than in 1990 when RBC theory was seen more favourable. It is appreciated that this might require surveys of hours worked to be undertaken more frequently than two per year, but at least for aggregate market sector, there may be alternatives. MFP could still be published on an annual basis.

series eg a smoothed labour hour series. There are, however, some concerns that the ABS should give priority to the provision of good raw data, leaving it to researchers to draw out the implications of that data.

The analysis shows that different measures of MFP acceleration provide information on different aspects of the acceleration. Changes in trends or the height of cycle plateau might indicate whether the long-run dynamic capacity of the economy for growth has changed, for example by technological advances (eg ICT) and structural and organisational innovation (including microeconomic reform). Changes in cycle averages capture how global cycles and one-off disturbances influence output and productivity after the moderating impacts of internal stabilisation and exchange rate management. Much of the explanation for generally reduced output volatility has been attributed to external rather than internal factors (Simon 2001).³⁹ This suggests some scope for wider use and interpretation of the data.

Nevertheless, less adventurous approaches may be pushed further. In particular, the greater exploration of base level productivity data by independent researchers exploring implications of the Information Age for growth accounting might clear the way to better understanding of the importance of productivity. The agreement by the ABS to allow Professor Erwin Diewert and Dr Denis Lawrence, amongst others, to access and explore the validity of the assumptions underlying the use of ICT, and to test alternatives is strongly supported as a very positive step. Further academic research should be equally beneficial.

5.8 Econometric estimation

It was shown above that the comparison of the Aspden MFPG averages may not be a robust indicator of change in Australia's trend productivity, because it does not remove, nor does it seek to remove, all cyclical productivity effects. At issue is therefore whether the Aspden methodology can be taken as stripping out cyclical effects to expose long-run trend in productivity. Resolving that issue was complicated by the volatility in the annual MFPG data.

This following sections explore whether the clouding effect of the year-to-year volatility in MFPG on robust estimation of trend MFP can be better addressed with an error correction model (ECM) framework. The work above suggests it might: it shows that the source of the volatilities in MFP growth stem from volatility in the underlying base growth variables,

³⁹ Simon (2001) finds there has been a large decline in the volatility of Australian output over the past 40 years. He finds 'part of the change have been substantial changes in the inventories cycle'. This would include 'Just In Time' organisational innovation of late married to ICT in the form of supply chain management. The other cause is 'a decline in the shocks hitting the economy rather than an increase in structural stability. Furthermore, the primary explanation seems to lie in a reduction in the volatility of supply or 'productivity' shocks. The ultimate source of these productivity shocks is left as an open question.' (Abstract)

namely output, capital and labour. But these are the same variables that go to make up the data-set on labour productivity and capital intensity. And the econometrics and short-run theory are designed to expose the underlying relationship in face of volatility.

The particular issue to be addressed is whether year-to-year volatility affects the accuracy or precision of the ECM estimators for trend MFP. The analysis first looks at the performance of the most recent research ECM research, noting the concerns expressed by the researchers. As a partial solution, it shows how treating year-to-year volatility as a complex form of ‘measurement error’ requires two changes to the ECM estimation procedure. First, the short-run growth part of the ECM is improved by Generalised Least Squares (GLS). Secondly, the co-integration of long and short run parts of the ECM is improved by centring the growth variables with the corresponding index variables. The new approach appears more robust and suggests previous estimates of acceleration in trend MFP were biased upwards.

It will be argued argues that the ECM and Aspden methods should be regarded as complements rather than substitutes. ECM may better decipher the data patterns to expose the underlying long-run trends. The Aspden averaging, or modifications thereof based on other cycles or intervals, whether applied to MFPG or LPG, generate measures of productivity that do not achieve the researcher’s objective of stripping out cyclical productivity change.

Thus insight into Australia’s 1990s trend productivity performance comes by linking the Aspden and ECM methods. The chapter shows that a lower ECM trend MFPG estimate for the 1990 is consistent with the difference between the Aspden 1990 averages being cyclical, with the recession and slow recovery of the early 1990s dragging average MFP growth below long-term trend in the early 1990s and the strong growth in the late 1990s pushing average MFP growth above trend.

5.8.1 Econometrics and volatility in productivity data

The Aspden methodology estimates the average annual MFP growth over a growth cycle. The annual MFP index is estimated directly by dividing the output index by the index of inputs. However it is not the absolute level of the MFP index at any time that is important, but rather in the MFP growth over time. The growth in MFP, $gMFP$, is related to growth in labour productivity, gLP , and growth in capital intensity

$$gKL. \quad gLP = f(gKL, gMFP)$$

The econometric approach parallels growth accounting. In growth accounting, the contribution of capital intensity growth to labour productivity growth is estimated from National Accounts data, and MFP growth is the residual. The econometric approach lets the

data decide the relationship between the growths in labour productivity, capital intensity and MFP. It thus has the potential to reduce the high relative standard errors (RSEs) in annual estimates of MFP that underlie the development of the Aspden growth-cycle methodology.

The pattern of LP growth is close to that of MFP for Australia (see Figure 5). Thus, the volatility reflects large RSEs in LP growth, because the capital use series is fairly stable over time. The short-term volatility in the MFP and LP growth estimates obscures longer-run patterns in these time series. The volatility often takes a year-to-year sawtooth pattern more characteristic of fine grained series than annual series. This pattern (of alternating annual peaks and troughs) is characteristic of a two-year cycle, and is not expected to be a dominant feature of a four to five year business cycle.

The factors that generate the variation in MFP growth also appear to influence the pattern of LP growth. At issue is the relationship between the econometric (ECM) and Aspden estimates.

5.8.2 The econometric methodology

The econometric analysis of Australian labour productivity has used the co-integration method for well over a decade. Lattimore and Dowrick were the earliest to explore this methodology (see Lattimore 2003b for references). The early focus was on the manufacturing sector where the quantity and quality of data is good. This appendix focuses only on the market sector, where both Dowrick and Lattimore have estimated trend MFP growth. Dowrick (2001) uses published ABS data (ABS 1999b). Lattimore (2003b) uses more recent but unpublished ABS data.

5.8.3 The error correction model

The co-integration method combines the long-run and short-run relationships in one estimating equation, assuming that part of the LP growth in any year is a response to a departure from the long-run equilibrium in the previous period. This response is proportional to the 'error'. For this reason, the method is termed the error correction model, the equilibrium correction model, or more simply, ECM.

Following Dowrick (2001)⁴⁰, the model can be written in algebraic form as

$$\Delta y_t = \{\theta_1 \Delta k_t - \theta_2 \lambda\} + \theta_3 \{\alpha k_{t-1} + (t-1)\lambda - y_{t-1}\} + \varepsilon_t \quad \dots \text{eq.1}$$

⁴⁰ The apparent simplicity of this ECM model disguises links between the two relationships being simultaneously estimated. The short term and long run models that together comprise the ECM can be written in the form of a set of equations and solved simultaneously with two or three stage regression models. The approach allows the identities that link the coefficients between equations to be specified and tested.

Labour productivity growth at time t is denoted by Δy_t . It is the sum of two explanatory terms and a residual ε_t . The first term captures the short-run impact on production from increased capital intensity and technological advance. With no technological change, labour productivity growth Δy_t is proportional to growth in capital intensity Δk_t , with coefficient, θ_1 , estimating the proportion. The unobserved long run rate of technological change, λ , contributes to Δy_t to an extent, θ_2 , in the short run. The value of θ_2 will depend, amongst other things, on cyclical and transient demand shocks. In the presence of fixed factors, and no technological change, θ_1 would decrease with increased capital intensity over the long run. However, technological change and replication can offset this effect, and for the purpose of modelling, θ_1 is assumed constant.

The apparent simplicity of the ECM regression technique disguises the two relationships being estimated. The short term and long run relationships can be written and solved as a set of two simultaneous equations. Separate equations allow structural features to be estimated, and identities that link the coefficients between equations to be explicitly specified. This section examines the ‘one-equation’ form of the ECM, where the long-run relationship is added to the short-run in the form of a disequilibrium correction.

The second term estimates the response of labour productivity Δy_t to the ‘disequilibrium’ gap of the previous period. The ECM term (in the squiggly brackets) captures the long run relationship between indexes of labour productivity, capital intensity and MFP. At time, $t-1$, the long run level is $\alpha k_{t-1} + (t-1)\lambda$. This differs from the actual level, y_{t-1} , because of past disturbances, ε_{t-j} . The parameter θ_3 is an estimate of the response generated by that gap.

The specification (eq.1) assumes a uniform rate of technological progress of λ per year. A productivity revival, or slowdown, would be reflected as a structural break in the rate of technological advance, the rate of productivity growth changing at the break point. To test for productivity slowdown and resurgence, Lattimore (2003b) and Dowrick (2001) add additional time trends to equation 1, the first to estimate the extent of any MFP slowdown, the second to estimate the extent of a revival.

The structural ECM model separates cyclical effects from the trend. The cyclical effects are taken as the short-run relationship, and captured by variation in the Δk_t term of eq.1. This suggests its coefficient should be significant and positive, reflecting the pro-cyclical nature of the MFP cycle.

The high year-to-year volatility in the LP data (see the first chapter) means the MFP trend estimates are sensitive to the determination of the break point. Structural breaks suggest a response to some significant enduring change in the macro economy. Such breaks could be the result of a major new oil resource coming on stream, or change in Australia’s external relationship with the world, or a new technology.

As a way of overcoming this and other issues with the structural approach, Lattimore (2003b) suggests a stochastic ECM process. The stochastic model informs on the nature of any productivity acceleration, ie it tests whether a productivity slowdown or revival occurs suddenly (a structural break) or as a gradual process. Rather than contributing a constant λ per year to LP growth over the long term (as in equation 1), the stochastic process treats λ as a variable. The econometrically determined properties of this variable describe how MFP growth varies over time, and so informs on whether the structural model is appropriate.

5.8.4 The findings of the ECMs

Some strong results emerge from this modelling (table 9), and these results are consistent with the earlier analysis. First, Australia's productivity revival does not appear to parallel that of the US. The US revival centred on the mid 1990s, whereas the Australian revival was well underway by then. The structural analyses have Australia's revival centred from the late 1980s. Lattimore's revival period starts in 1988-89, the year of a productivity peak, and Dowrick's starts in 1990-91 at the turn of the decade. The stochastic ECM modelling shows the turning point in Australia's productivity fortunes occurred in 1982-83 when the productivity growth reached as low of 0.3 percent per year after falling from 2.2 percent per year in 1966-67. The subsequent gradual 13 year acceleration to 1.8 per cent in 1995-96 was centred around 1989.

Secondly the size of the revival differs significantly between the models. The difference raises two issues. First, which estimates is best? Second, how robust is a methodology that generates this wide variation in trend estimates?

With the benefit of hindsight, it is clear that the Dowrick's estimate of 1.4%pa, while the best available at the time, significantly overstates Australia's recent trend productivity growth. This is because the official data used by Dowrick were subsequently revised by the ABS. These data revisions were significant. The data available to Dowrick indicated 1999-2000 was a peak. The subsequent data revision took the peak back to 1989, leaving 1999-2000 as a trough. The downward revisions to the late 1990s data by the ABS cause the Dowrick's estimate of 1.4% to overstate the true value. Moreover, Dowrick's choice of 1991-92 for the break in trend productivity may also contribute to an overestimation. The year 1991-92 was one of recovery from recession, and this break point could inflate the Dowrick estimate of 1.4%pa of a productivity acceleration, given our now better knowledge of the 1990s productivity cycles.

The extent of the overstatement is suggested by comparison with Lattimore. Lattimore had the advantage of longer-standing more robust data, and in addition, a longer data series than was available to Dowrick. Moreover, Lattimore states that given the extent of the volatility in LP growth, the trend estimates from the structural analysis can be biased by the selection

of break points. He chooses 1988-89 rather than 1991-92 as the break point, and the data series extend past the late 1990s trough. Lattimore's longer series (it starts earlier, and finishes later) makes it a more representative of a long-term trend than Dowrick's. Moreover his lower estimates for all trend variables are consistent with their end points occurring at similar points of the cycle. All in all, the robustness of the Lattimore estimate of 0.76%pa makes it credible gauge of the overstatement in the earlier estimate of Dowrick. Finally, the following research supports Lattimore, rejecting Dowrick's earlier estimate.

Table 9: Parametric estimation of Australia's productivity revival: market sector

<i>Variable</i>	<i>ECM</i>		<i>ECM</i>	<i>Simple long run</i>	
	<i>Structural Modelling</i>		<i>Stochastic M</i>		
	<i>Dowrick</i>	<i>Lattimore</i>	<i>Lattimore</i>	<i>Dowrick</i>	<i>Lattimore</i>
Δk	0.138 (0.8)	0.178 (0.8)	0.161 (0.9)		
Y_{-1}	-0.97 (5.9)	-0.822 (5.9)	-0.953 (6.1)	na	na
k_{-1}	0.27 (2.0)	0.328 (3.2)	0.313 (1.9)	0.27 (2.1)	4.7% (4.1)
$T64_{-1}$	2.3% (3.8)	1.7% (3.5)		2.4% (4.4)	1.8% (3.3)
$T74_{-1}$	-1.6% (5.6)	-1.4% (5.6)		-1.7% (6.5)	-1.6% (5.1)
$T88_{-1}$	na	0.76% (4.9)			7.2% (5.6)
$T90_{-1}$	1.4% (4.5)	na		1.4% (5.5)	
constant	-0.47 (2.8)	-0.320 (2.5)		na (~ -0.47)	-0.33 (2.3)
Irregular {variance}			na {2.15 E-4}		
Level {variance}			0.036 (2.8) {1.44 E-5}		
Slope {variance}			0.0131 (1.6) {1.076 E-5}		
N	34.	37		36	
R^2 adj	0.54	0.49	0.66	irrelevant	irrelevant

(1) Dowrick (2001 p.25) used data from ABS 5204.0 (1998-99) updated from 5206.0 of June 2000. (last data year 1999-2000) This data was subsequently significantly revised, with the 1999-2000 peak being replaced by a 1998-99 peak. Lattimore (2003) p.228 used unpublished ABS data.

The conclusion is that the Dowrick estimate should no longer be used, as is, to establish stylised facts of Australia's 1990s productivity performance. The credibility of research that uses it, without appropriate qualification, for such a purpose is open to question.

In respect of the issue of methodological robustness, a wider comparison of the two analyses suggests the ECM methodology is sound, once account is taken of data updates, revisions, additions and break-point sensitivity, as the two structural ECM models show quite similar estimates for the other coefficients and the test statistics, given an agreed 1974-75 break point.

5.8.5 Explaining the ECM coefficients

The coefficient on the $kt-1$ term is $\theta_3 \cdot \alpha$ and Table 9 shows that α is between 27% ($= 0.27/0.97$ for Dowrick) and 40% ($= 0.33/.822$ for Lattimore). The value α is an estimate of the capital share of income, known from non-parametric measures to range from about 30% to 40% for Australia. Thus these econometric estimates of α are consistent with non-parametric growth accounting.

These estimates can also be compared to those from the separate long run model. The long-run elasticity of output with respect to capital from the long-run model is 0.27 for Dowrick (identical to α) and 0.48 for Lattimore (somewhat higher than expected and perhaps less reliable than the co-integrated estimate for α of 0.40).

The estimates for θ_3 , (-0.97 and -0.82) imply that almost all of the adjustment needed to correct the 'error' takes place in the following year. With such a rapid response to disequilibrium, persistent departure from the long run relationship is not expected. However it depends on the nature of the shocks. Output disturbances could occur through demand shocks, or from technology shocks which influence the relationship through the θ_2 term of equation 1. The disturbance term, ϵ_t , may be a guide to the disturbances, although change in the predicted relationship will reflect the interaction of disturbances and the ECM response.

The relatively good econometric performance of the model to a series exhibiting strong year-to-year sawtooth volatility is shown, for example, by the adjusted R-squared of about 0.5. At issue is whether the performance of the ECM would improve if year-to-year volatility were removed. An indication that it might is suggested by the statistical insignificance of the short-run coefficient θ_1 , and the high estimate for the error correction coefficient θ_3 .

5.8.6 Understanding the econometric diagnostics

It is critical that the long-run relationship can be demonstrated as it is this relationship that drives the short-run correction following shocks. Both researchers separately estimate the long-run relationship (between the LP and K/L indices and time trends).

Lattimore uses a battery of econometric diagnostics on the long-run model. However he does not specify the R-squared measure of goodness of fit for the long-run model: 'Since the long run form is mis-specified (if the ECM is the 'correct' form of the model), no diagnostics are reported' (p.225). In other words, the long-run econometric model, unlike the ECM model, does not capture the effect of disturbances on the observed variation in labour productivity growth.

However, a particular econometric concern is that the ECM model can indicate a statistically significant relationship when it is known that there is none. Such false indications are known as ‘spurious’. A spurious regression may be revealed if the Durbin-Watson test on the long-run regression is very low.

The choice of regression variables is determined primarily by theory. Growth theory treats technological change and capital deepening as separate, each contributing to labour productivity growth. Technological change is the trend, taken as MFP growth. Therefore to be in accord with theory, the econometric estimation would normally include capital intensity and time trend(s) as explanatory variables. However the capital intensity index is a good proxy for the time trend. This condition, known as ‘multicollinearity’, does not affect goodness of fit, but does make for statistical imprecision of the trend coefficients that we are interested in.

The strength of the co-integration relationship can be econometrically tested using the LP and K/L index series. These should be non-stationary with a unit root of 1. In other words, the first difference of the indices (ie growth rates) should be stationary. The SHAZAM manual suggests a high R-squared and low Durban Watson on their regression is evidence of a co-integration relationship.

5.9 ‘Sawtooth’ volatility as measurement error

The above discussion points to a range of economic and econometric issues relevant to the ECM relationship. A particular focus is the pattern of productivity variation. The year-to-year volatility in the productivity growth variables is a significant feature of the data set used by the ECM. It shows as a sawtooth pattern in the growth graphs. The previous sections shows that this sawtooth form of volatility can be removed from the growth data by two-term averaging.

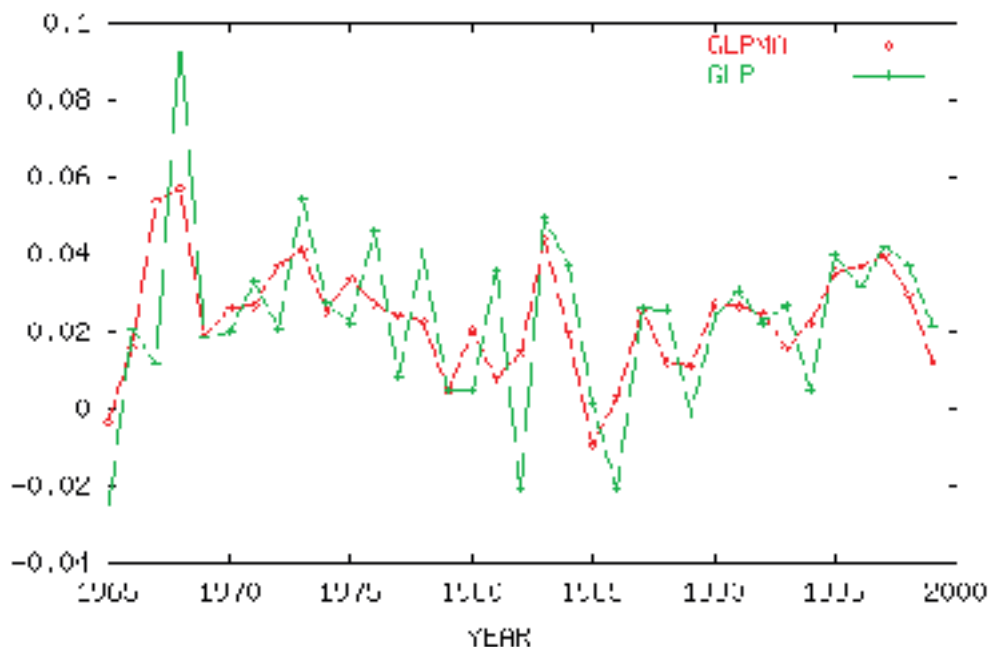
Two-term averaging not only exposes the underlying pattern, but reduces some of the more extreme values. Figure 3 above shows that the high 1968-69 peak and deep 1983-83 trough that are features of the original growth data are both reduced by two-term averaging.

Figure 4 above demonstrates the extreme sawtooth that created the 1982-83 trough (a minus 4.6 % pa fall in MFP). It was formed by a prior 6.3 percentage point drop and a following 8.5 percentage point acceleration to a growth peak of 3.9 %pa (figure 4 above). With two-term averaging, this extreme trough, especially prominent in the MFP growths (see figure 5 above) loses much of its significance. In contrast, the extreme 1968-69 peak remains a significant feature (figure 9).

Thus the issue is the extent to which unwanted year-to-year volatility in the growth series obscures and distorts the important underlying productivity relationship that links the

growths in output and input indexes. Section 5.4.3 shows the original sawtooth pattern has relatively little impact on the indexes, but a very significant impact on the growths. The relative standard deviation (RSD or standard deviation divided by the mean) is around 10% for index variables, but often over 200% for the growth variables.

Figure 9: The comparison of the conventional and centred growth estimates



Section 5.6 shows how year-to-year volatility in the derived growth variables (particularly LP and MFP) derives from the year-to-year volatility in two of the base growth variables (output and labour) and the imperfect correlation between the patterns due for example to slight variations in the phase relationship.⁴¹ Treating this year-to-year volatility in the LP growths as a form of measurement error might improve that short-run growth part of the ECM model, and so make for more robust MFP trend estimates.

The rationale for treating year-to-year volatility as measurement error is economic rather than econometric. A characteristic of economic models is their abstraction from one-off transient effects to focus on the key underlying relationships between economic factors. If year-to-year volatility is not something to be explained by a model, then there are grounds for ensuring such one-off effects do not confound the model. This is a possible outcome of using the original data, and can be avoided with two-term averaging.

As an example, consider the one-off output blip associated with the 2000–2001 Olympics. Much of the investment for the Olympics occurred in the 1999–2000 year. In productivity, the focus is not on the data correctly identifying the Olympic output blip in 2000–2001, and perhaps an investment blip in 1999–2000, but rather the input-output relationship which is distorted by the accurate data. There are many such blips, and two-term moving averaging

⁴¹ Our analysis does not seek to explain blips in LP growth associated with small phase shifts in the relationship between the volatile labour inputs and the volatile output.

is a general approach for moderating their effects. In a broad sense, two-term averaging can be justified on the same grounds ABS uses to justify the smoothing of its headline estimates for GDP in table 1 of the Australian National Accounts.

The approach depends on the source of the year-to-year volatility being unknown, and not necessarily representing the impact of shocks on the ‘true’ value of productivity growth. This appears unlikely. The frequency of change in MFP and LP growth is surprising. Most macroeconomic aggregates respond slowly—lags are common. If these changes are random, they obscure the real relationship and might be best treated as measurement error. While measurement error can arise from simple timing errors between adjacent periods, our concern is not the precision of the ABS estimates, but rather how data volatility that obscures underlying economic relationships should be treated.

It is important to recognise that the year-to-year volatility, that is the focus of this section, is not the only source of broadly-defined ‘measurement error’. The complexity of the growth process is hard to capture with simple non-parametric statistical methods. For example, a major new investment in Australia to develop mineral discoveries might well reduce the gross operating surplus (GOS) of the companies for a period, perhaps for a year or two, before the cash flow turns positive. The ABS survey would return volatile GOS estimates, and in turn, will influence the capital use estimation (see Diewert and Lawrence, 2004). However only some of this volatility is of the year-to-year sawtooth type. To address the general issue, however, would go beyond the limits of this .

We wish to assess the effect on the ECM model of treating year-to-year volatility as measurement error. This requires a base case. We use the replication of the structural ECM model used by Dowrick/Lattimore, using the most recently published ABS data, as the control. This replication ECM is estimated in the next section.

5.9.1 Replication

The results from replicating the ECM using SHAZAM are detailed in table 10. The coefficients and t-ratios are compared with those from Lattimore and Dowrick in table 11. Our goodness of fit (adjusted R-squared) and many of the coefficient values lie between those of the earlier research. In general, the replication is closer to Lattimore, reflecting the 1988-89 break point, and use of revised data. As expected, the slight differences in the data have had little impact on the estimates.

Figure 10 compares the actual growth rates with the predicted values. As expected from the regression results, the fit is quite good. But there are surprising features. Even though the ECM estimates higher MFP productivity growth in the 1990s, the fitted model shows short-run labour productivity growth has been slowing over the 1990s, perhaps due to demand shocks. This slowing in labour productivity growth in the predicted values does not sit well with other evidence, eg Aspden growth cycle evidence.

Table 10: Replicating the ECM model.

<i>Regression variable</i>	<i>Symbol for variable</i>	<i>Estimated coefficient</i>	<i>T-ratio 29 DF</i>	<i>Probability</i>	<i>Elasticity at means</i>
gKL	Δk	0.1411	0.8144	0.422	0.1999
ziLLPlag	y_{-1}	-0.84097	-5.754	0	-155.8825
ziKllag	k_{-1}	0.35958	2.571	0.016	64.7822
T65lag	$T65_{-1}$	1.64E-02	3.053	0.005	13.4079
T75lag	$T75_{-1}$	-1.42E-02	-4.714	0	-6.1256
T89lag	$T89_{-1}$	9.07E-03	4.19	0	0.8678
Constant		1.8962	4.086	0	83.7502

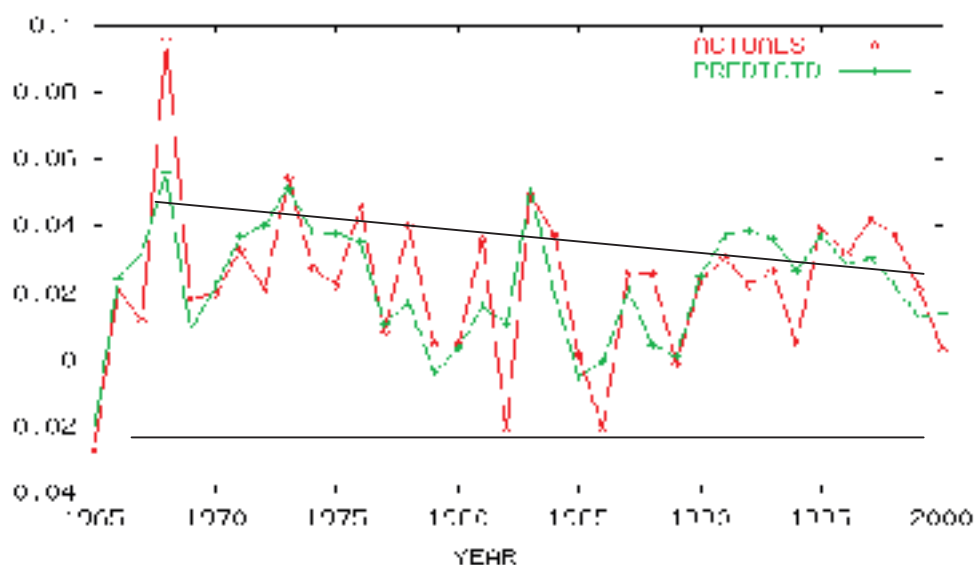
R-Square = 0.586 R-Square Adjusted = 0.499

Durbin-Watson = 2.026 Von Neumann Ratio = 2.084 Rho = -0.024

The trend variable T65 commences from year 1964-65. We follow the ABS convention of labelling financial years by the June end year as distinct from Lattimore and Dowrick.

Table 11: The comparison of the three structural models

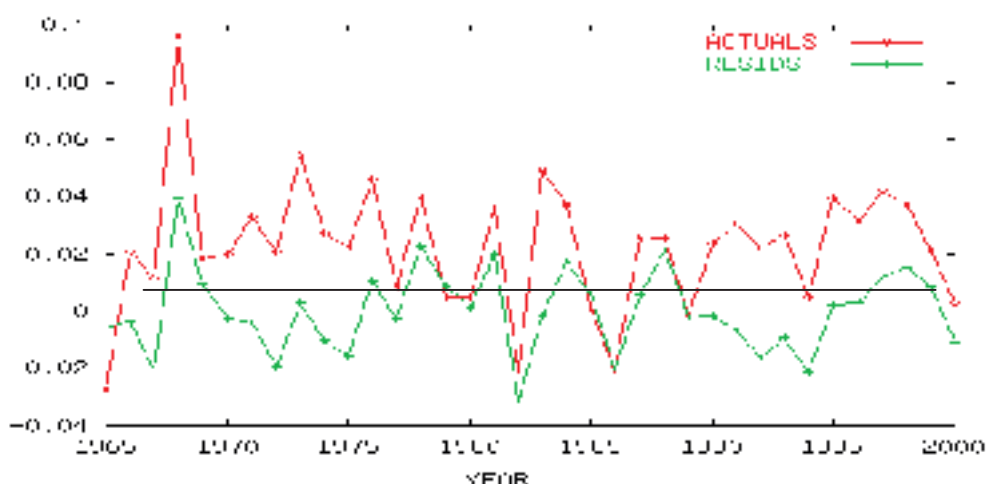
<i>Variable</i>	<i>ECM Structural Modelling</i>		
	<i>Dowrick</i>	<i>Lattimore</i>	<i>Replication</i>
Δk	0.138 (0.8)	0.178 (0.8)	0.141 (0.8)
y_{-1}	-0.97 (5.9)	-0.822 (5.9)	-0.841 (5.8)
k_{-1}	0.27 (2.0)	0.328 (3.2)	0.360 (2.6)
$T64_{-1}$	2.3% (3.8)	1.7% (3.5)	1.64% (3.1)
$T74_{-1}$	-1.6% (5.6)	-1.4% (5.6)	-1.4% (4.7)
$T88_{-1}$	na	0.76% (4.9)	0.91% (4.2)
$T90_{-1}$	1.4% (4.5)	na	
constant	-0.47 (2.8)	-0.320 (2.5)	1.89 (4.1)
N	na	37	36
R ² adj	0.54	0.49	0.50

Figure 10: The fitted and actual pattern—replication exercise

An interesting feature of the regression is that the 1990s trend of 0.91% in the replication is higher than Lattimore despite the end year being the MFP trough of 1999-2000. To check the influence of the trough ending, the regression was rerun ending in the 1998-99 MFP peak. This changed all the trend estimates. The base trend (for the late 60s to early 1970s) fell from 1.64%pa to 1.56%pa. The 1980s slowdown decreased (-1.42%pa to -1.39%), and the 1990s resurgence increased more significantly from 0.907%pa to 0.945%pa. The sensitivity of the estimates of the revival highlights the need for caution in making early predictions on the extent and timing in trend productivity.

The low t-ratio for the capital intensity coefficient suggests the model is weak in explaining the cyclical variation in productivity over the business cycle. It does not capture the recessions of the early and mid 1990s. Figure 11 shows residuals are negative during the major productivity troughs of the early and mid 1980s and positive during the major peak of the late 1960s. This is as expected but raises the issue of whether estimated MFP trends may be influenced by these more extreme values.

Figure 11: The residual pattern—replication exercise



5.9.2 The econometrics of measurement error.

Measurement error is well known in econometrics. The explanatory variables are not fixed by design, but stochastic, and treated as observations on true value. Stochastic regressors become an issue when the standard estimators (OLS and MLE) for the coefficients mean is biased, that is when a stochastic regressor correlate with the equation error term.

The approach is to assume gLP^* and gKL^* are the true but unobserved growth rates in the underlying level variables at a given time. However the (proxy) variables used in the estimating equation are measured with error, and that error is correlated with regressor variable.

The true short-run relationship is shown below where ε is the equation error:

$$gLP^* = \alpha gKL^* + \gamma \lambda^* + \varepsilon$$

Instead we use the variables (gLP and gKL) that not only have random sampling errors (ε_{lp} and ε_{kl}) but also have measurement errors (u and v). The properties of the measurement errors determine the appropriate econometric estimators of the coefficients, in this case α and γ .

$$gLP = (gLP^* + v) + \varepsilon_{lp}$$

$$gKL = (gKL^* + u) + \varepsilon_{kl}$$

The result is that estimating equation for the short-run estimating equation is:

$$gLP - v - \varepsilon_{lp} = \alpha (gKL - u - \varepsilon_{kl}) + \varepsilon$$

$$gLP = \alpha gKL + (v - \alpha u) + (\varepsilon_{lp} + \varepsilon_{kl} + \varepsilon).$$

The issue is whether the measurement errors v and u are correlated with regressor gKL

If so, the OLS estimator for α will be biased (asymptotically). The OLS estimator is not "consistent"

If there were only measurement error in gKL , then the instrumental variable approach could allow combining the two-term averaged values of gLP along with the actual values in the estimator. However the common source of the measurement error (taken as the unwanted year-to-year volatility) comes from volatility in output and labour growth. These have been shown to be imperfectly correlated. Thus we conclude that the two measurement errors in the estimating equation are not only correlated themselves, but also correlated with the regressors. The error covariance matrix will not be the desired $\sigma^2 I$, but rather $\sigma^2 \Omega$.

This means if we use the untransformed variables, the estimators will not be unbiased or efficient.⁴² Transforming the variables changes the estimator from the ordinary least squares (OLS) type to the Generalised Least Squares (GLS) type. Here the necessary transformation is the two-term averaging of the short run growth variables (gLP and gKL). This transformation reduces the unwanted year-to-year sawtooth-type volatility in the growth variables. The transformation matrix, P , has 0.5 in the main and lower diagonals. This generates an omega matrix in which the values in alternate rows and column vary in sign, expected given the sawtooth in growth that is taken as unwanted measurement.

⁴² With a sample set at 2 to 18, the OLS regression of the residuals from the short-run model against the capital intensity regressor suggests a possible relationship for the conventional model but none with two-term averaging. For the conventional growths, the t-ratio was 1.3, signifying a statistical relationship 3 times in 4 (probability=0.24). With averaged growths, the t-ratio was 0.34 signifying 1 chance in four of such a relationship. Thus, at least for the early observations, the use of a two-term averaging transformation would appear to address a real econometric issue associated with the use of untransformed variables.

It should be noted that GLS procedures are common. In fact, for autocorrelation models and pooled (cross-section and time series) models, the transformation matrices are built into the standard packages.

5.9.3 Measurement error and co-integration

Using the two-term averaging transformation on the short-run growth model improves the relationship, but applying it to the full ECM only marginally improved the goodness of fit (adjusted R-squared rose from 0.50 to 0.56). Realising the benefit of the GLS transformation requires that the growth variables be centred on the corresponding index variables. This is achieved by transforming the growth variables, but not the index variables.

In fact, there are three growth rates that one could associate with the index $\{Z_t\}$ at time 't'. The traditional one is based on growth from the past year. Denote this growth as gZ_t . An alternative is to use the next, rather than the previous observation. Denote this 'future' based growth as gZF_t . Alternatively the growth can be centred. Denote this centred growth as gZC_t .

The formulae in algebraic terms are⁴³

$$\text{Past growth (normal): } gZ_t = Z_t - Z_{t-1}$$

$$\text{Future growth: } gZF_t = Z_{t+1} - Z_t$$

$$\text{Centred growth: } gZC_t = (Z_{t+1} - Z_{t-1})/2$$

It is readily seen that the centred growth formula for $\{gZC_t\}$ is equivalent to the 2-term moving average formula — denoted as $\{gZMt\}$ — on single period growths.

$$gZMt = (gZ_t + gZ_{t+1}) / 2 = [(Z_t - Z_{t-1}) + (Z_{t+1} - Z_t)] / 2 = gZC_t$$

In fact, two-term moving average is just another way of calculating growth from an index series, a method widely used in economic modelling where curvilinear relationships are approximated by a series of linear stages. In geometric terms, we replace the arc by the chord, using the slope of the chord to approximate the slope of the arc at the mid-point of the interval.

Nevertheless, the 'conventional' ECM model uses conventional (or 'past') growth estimates readily calculated as a first difference between adjacent indexes. It is used by

⁴³ The base of the estimation is the index series $\{Z_t\}$. Because this is a macroeconomic estimation, Z is in the logs of the indexes rather than the index value themselves. This is just equivalent to using levels against a logarithmic scale (with the advantage that constant growth shows as straight lines). The advantage of expressing index in log form is that the difference between two annual index values is then the measure of annual growth between these years

Dowrick and Lattimore. A ‘centred’ model calculates growths as half the difference between once removed values of the index series, and so reduces sawtooth type volatility.

The improved within-sample performance from centring comes from better information only available in the real world if there is perfect one-period foresight. At time t , we know not only the past growth but also the following growth. The future growth is added to the past growth to obtain an estimate of the centred growth rate that is more appropriate to the index Z_t than the past growth. This could be expected to make the regression error in the short-run growth model more independent of the value of the lagged index variables in the long-run model.

The advantage of the centred growth of LP regressand in the co-integration exercise is not that it is the growth rate that exactly corresponds to index of the LP, but that it is the best approximation of the growth rate immediately preceding that LP value. It might be expected that for discrete change, the coarser is the data, the weaker may be the strength of the co-integration. The more the data resembles that for an infinitely small change, the better may be the model.

Nevertheless, the smoothing of growth rates suggests that some year-to-year smoothing of the index series may be optimal. Year-to-year volatility in the index series is not a significant source of its variability. In a sense, the chain linking of the growth automatically smoothes the index series.⁴⁴

The advantage of the centred ECM approach is that it reduces unwanted sawtooth volatility associated with possible timing or phase ‘mismeasurement’ with the minimum level of additional transformation and change. There are many other ways to reduce unwanted sawtooth, but other methods have the disadvantage of either requiring a new index series or else reducing the length of the ECM data. The centred ECM appears the simplest alternative to the conventional ECM.

5.9.4 The performance of centred ECM

Table 12 provides the standard goodness of fit diagnostics for the centred ECM. As expected the fit is better. More importantly, the centred ECM reduces the variability in the data, and strengthens the power of the model to rejecting the null hypotheses.

To this extent, it may be an alternative way to deal with Lattimore’s concern that statistical noise associated with volatile growth series makes the MFP trend estimates overly sensitive to choice of structural break. It might be a structural alternative to Lattimore’s stochastic ECM.

⁴⁴ If smoothing were used, it might be a three-term weighted smoothing with weights of 2.5%, 95% and 2.5%.

Table 12: Conventional diagnostics on the ECM with conventional and centred growths

<i>Diagnostics</i>	<i>Conventional growth</i>	<i>Centred growth</i>
R2	0.585	0.756
R2Adj	0.500	0.704
DW	2.026	1.949
Von Neuman	2.084	2.006
Rho	-0.024	0.014

Table 13 presents the comparison of the parameter estimates and figure 12 compares the two sets of predictions. The centred growth version of the ECM provides more reasonable parameter estimates. The short term relationship with capital intensity is now statistically significant at the 5% level. By contrast, in the conventional model there is a 42% probability of the null hypothesis (no relationship) being statistically accepted. Moreover the estimate coefficient of 0.25 for the capital intensity variable is close to the 30-40 percent expected from non-parametric analysis.

Table 13: Parameter estimation for the conventional and centred growths

<i>Coefficients</i>	<i>Estimates</i>		<i>T-ratios</i>		<i>Null Probability</i>	
	<i>Conventional</i>	<i>Centred</i>	<i>Conventional</i>	<i>Centred</i>	<i>Conventional</i>	<i>Centred</i>
gKL	0.142	0.250	0.82	2.08	42.1%	4.7%
ziLPlag	-0.841	-0.538	-5.75	-7.4	0.0%	0.0%
ziKllag	0.360	0.212	2.57	2.72	1.6%	1.1%
T65lag	1.60%	1.00%	3.05	3.4	0.5%	0.2%
T75lag	-1.40%	-0.80%	-4.71	-5.39	0.0%	0.0%
T89lag	0.90%	0.60%	4.19	5.62	0.0%	0.0%
Constant	1.896	1.285	4.09	5.05	0.0%	0.0%

Shortening the series to end on a peak, rather than trough, increases the T89lag term from 0.60%pa to 0.64%pa

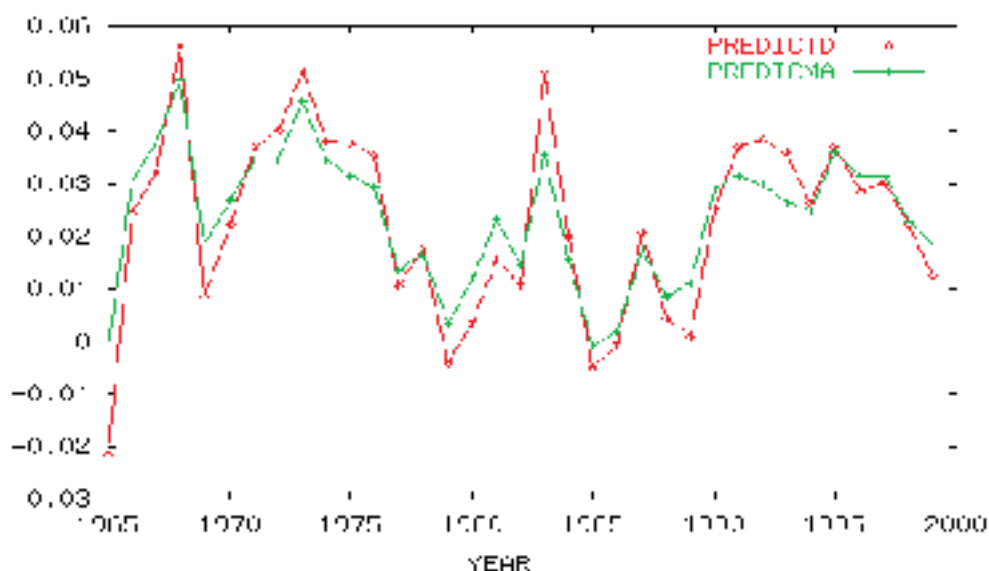
The responsiveness of labour productivity to capital intensity to the longer term α is calculated by dividing the coefficient on the lagged capital intensity index, ie $\alpha \cdot \theta_3$, by the ECM coefficient, θ_3 . For the conventional model, this is 43% (.36/.84). For the centred growth model, it is 39% (ie, .212/.538). This latter estimate would be preferred as closer to the capital share of income. Moreover the coefficient on the lagged capital intensity coefficient is now on the border of the 1% statistical significance. Lastly, the reduced responsiveness to as gap in the preceding year, as shown by the ECM coefficient of 54% seems more reasonable than the 84% of the conventional model.

The predicted values from the centred ECM are highly correlated with those from the conventional ECM. Statistically correlation is confirmed by an adjusted R-squared of 0.90 with the OLS regression of the centred ECM predictions against conventional ECM predictions, and coefficient of 0.68 for this regression with t-ratio of 17. However, OLS

regression is not efficient due to autocorrelation shown by a DW of 0.5 and a high autocorrelation diagnostic, rho, of 0.72. When regressed with AUTO, the t-ratio on the coefficient of 0.65 increased to 25 and R-squared adjusted to 0.95. This result suggests that one-third of the volatility in the data might not be the demand shock assumed by the conventional ECM but rather the assumed ‘measurement’ error.

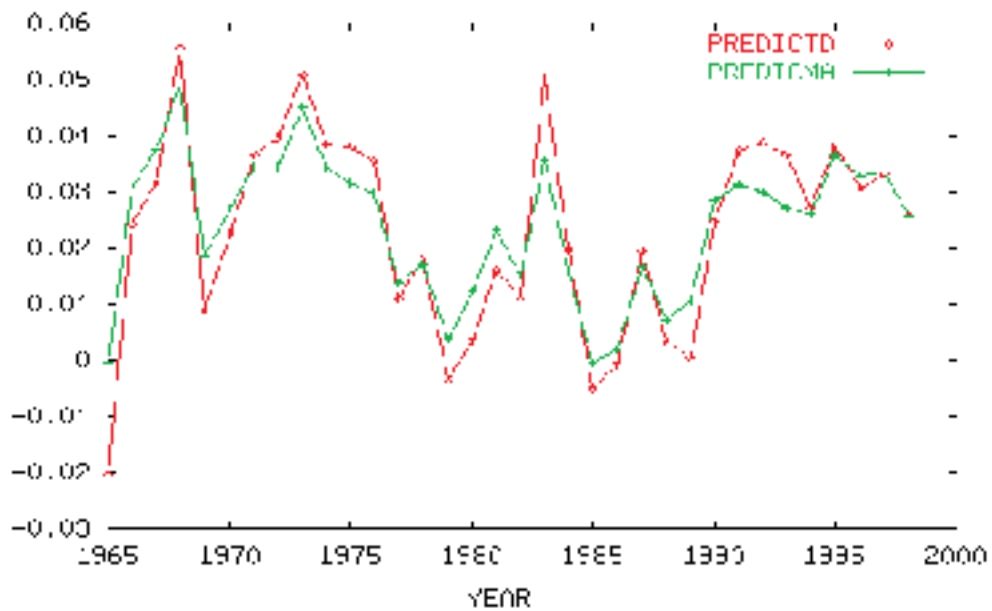
The comparison of the predicted values in figure 12 confirms that the predicted patterns of the centred and conventional models are almost identical, apart from the lower variability of the centred ECM. Demand shocks have the same pattern but are less extreme. Moreover, the centred model seems to better fit Australian facts. For example, the conventional ECM shows LP growth slowing over the 1990s, whereas until the slowdown at the turn of the century, labour productivity growth was accelerating. This is clearer in figure 13 below where the last observation is omitted so the series ends at a growth peak rather than trough. The centred ECM is superior in this aspect.

Figure 12: Comparing predicted values from the conventional and centred ECM models



Note: The red prediction is from the conventional model and the green is from the centred model.

This has implications for the best available estimates of the acceleration in trend MFP growth, the coefficient of the lagged T89 term. Using the estimates adjusted for the end-peak, the conventional model suggests an acceleration of about 0.94 percent centred just before the turn of the decade. The centred model suggests that the acceleration was only 0.64 per cent. This is close to what Quiggin (2001) suggested after analysing the effect of the business cycle. It casts doubt whether the stylised fact that the extent of Australia’s productivity revival was as much as 1 percent. This issue can be resolved better when the latest revisions are available, and a new growth peak is formed.

Figure 13: Prediction of conventional and centred ECM models with peak end.

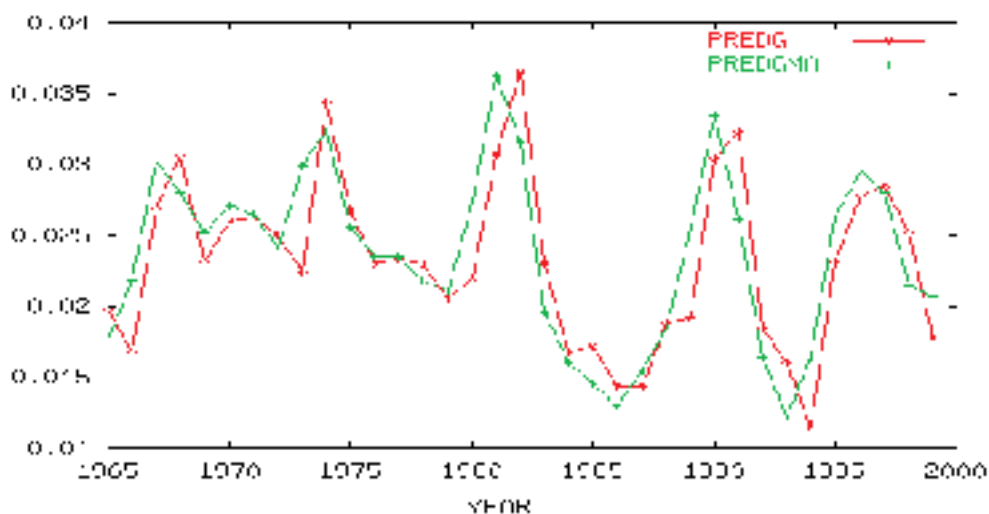
Note: The dark red prediction is from the conventional model and the green is from the centred model.

Australia's multifactor productivity growth certainly grew at a remarkable 1 per cent a year over the 1990s (1.1% ie $1.4 - 1.2 + 0.9$, under the conventional model, and 0.8% under the centred model, the estimates not sensitive to choice of end point). However, the issue of whether MFP accelerated over that time, or whether the MFP acceleration occurred at the turn of decade is a more contentious and open question. The more robust finding is Australia's strong showing in labour productivity growth. This should arguably be the focus of analysis, rather than any acceleration in MFP.

If a measure of acceleration is to be used, then the best estimate of the revival, based on the 1988-89 break, is about 0.7 per cent per year. In respect of Gretton, Gali and Parham (2002) estimated 0.2 of a percentage point MFP acceleration from ICT uptake, this would increase the relative contribution of ICT, in line with its contribution to LP growth. Moreover, the evidence of Lattimore suggests the 0.2 per cent estimate relates to a period of little acceleration. So in the absence of significant cyclical impact on MFP at that time, the impact of ICT could be more significant again. Nevertheless, recognising the complementarities in growth, the appropriate policy focus should probably be focused on getting the balance right, rather than singling out any particular cause.

5.9.5 How robust is the structural ECM?

The effect of the centring methodology on the short run relationship (as shown by regressing labour productivity growth on capital intensity growth) was examined by comparing the predicted values of labour productivity growth. Figure 14 shows very little difference except for the slight effect on timing of the centring process.

Figure 14: The short run predictions of LP with the conventional and centred growths

Note: The dark red prediction is from the conventional model and the green is from the centred model.

There are two concerns with trend estimates in the all important long-run relationship between the index series. First is the economic concern as to what effect a structural break might have on the relationship. Second is the econometric concern about the ability of the econometrics to robustly differentiate between added time trends from the implicit time trend in the capital intensity index.

The economic issue is about how a structural break influences the relationship between labour productivity, capital intensity and the MFP trend. Lattimore and Dowrick assume it affects the MFP time trend and not the underlying relationship of labour productivity with capital intensity. This may well be appropriate in the analysis of the manufacturing industry, a key concern of these researchers over time. However at the macroeconomic level, there are various reasons to think that the relationship between labour productivity and capital intensity might have changed. In fact, Parham (1999) made a case that it changed in 1993-94. Alternatively the break in the ECM trend at 1974-75 could be a possibility.

The importance of external factors on the Australian macro economy suggests the relationship might have changed as a result of the gradual replacement of the Bretton Woods agreement with a rules based exchange rate system, a change that ultimately lead to the floating of the Australian dollar in the early 1980s, and the subsequently exchange rate issues of the mid 1980s. This impact might have been greater for Australia than that of the first oil price shock of 1973 and the subsequent slowdown in the world economy. Australia's productivity experienced a much smaller downward shock than for example the USA in the mid-1970s, possibly in part due to the bringing on stream of the Bass Strait Oil and expanding coal exports.

Economic theory gives little guidance on the form a structural break can take. One approach is to use a stepwise OLS procedure to test between alternative explanations. The approach also tests the robustness of the time trends. Thus, in addition to the trends, we added three dummy variables to distinguish the three periods to 1981-82, the period from 1990-91, and the period from 1994-95. The latter two periods clearly overlap, and it is the data that decides between them.

Table 14 shows that a time trend is not needed if there are structural breaks. The capital intensity variable acts as a default trend. The table shows that the period from 1990-91 on is determined as significantly different rather than the period from 1994-95. The adjusted R-squared was 0.995. The DW was low at 1.4 with rho estimated as 2.8. Somewhat surprisingly when the regression was run in the more conventional manner, with logs of the labour productivity and capital intensity, D95 was preferred to the D91.

Table 14: A test of a time trend versus the capital intensity trend in presence of breaks in relationship between labour productivity and capital intensity using index values.

<i>Step No.</i>	<i>Variable</i>	<i>Status</i>	<i>F-Value</i>	<i>D.F.No</i>	<i>D.F.Den.</i>	<i>F-Probability</i>
<i>*_stepping sequence *</i>						
0	IXKL	Forced In	1597.2672	1	35	0.000000
1	D82	Stepped In	50.5709	1	34	0.000001
2	D91	Stepped In	10.5563	1	33	0.001301
<i>*summary for potential variables not entered into the reg. equation*</i>						
	D95	If Entered	4.0434	1	32	0.052835
	T65	If Entered	2.6644	1	32	0.112421
	T75	If Entered	0.0092	1	32	0.924195
	T89	If Entered	0.7704	1	32	0.386621

end of stepping sequence

The coefficients for that regression, shown in table 15, suggests that the capital intensity variable had a greater impact on labour productivity up to the 1980s and then from 1995. However, one cannot determine the extent to which the capital intensity variable was acting as a time trend over those periods. That determines how much higher MFP growth might have been during those periods.

Table 15: Parameter estimates for the long-run model

	<i>Coefficients</i>	<i>T-ratios</i>
KL ratio (as log)	0.76	41.4
D82	6.90%	6.1
D95	2.90%	3.2
Constant	1.06	13.4

These results suggest that the long-run conventional ECM model cannot clearly distinguish between the time trend and the capital intensity index. To test this we ran the long run regression model of Lattimore with the significance level set at 2.5% rather than 5%. Such a tightening was suggested by Lattimore for the full ECM model. The results, in table 16, show that the T65 trend was rejected. The other trends were statistically, significant, and of the expected sign, but much smaller than expected. Table 17 showed that when the time trend was forced into the regression, the capital intensity variable was forced out.

Table 16: Letting the data decide at the 2.5% significance level.

<i>Step No.</i>	<i>Variable</i>	<i>Status</i>	<i>F-Value</i>	<i>D.F.No</i>	<i>D.F.Den.</i>	<i>F-Probability</i>
<i>* stepping sequence *</i>						
0	ZIKL	Forced In	2920.0687	1	35	0.000000
1	T89	Stepped In	5.8212	1	34	0.021375
2	T75	Stepped In	17.2486	1	33	0.000217
<i>*summary for potential variables not entered into the reg. equation*</i>						
	T65	If Entered	4.3749	1	32	0.044495
<i>*end of stepping sequence*</i>						

Table 17: Forcing in the time trend, and letting the data decide at 2.5% significance.

<i>Step No.</i>	<i>Variable</i>	<i>Status</i>	<i>F-Value</i>	<i>D.F.No</i>	<i>D.F.Den.</i>	<i>F-Probability</i>
<i>* stepping sequence *</i>						
0	T65	Forced In	1603.9090	1	35	0.000000
1	T75	Stepped In	32.4644	1	34	0.000002
<i>*summary for potential variables not entered into the reg. equation*</i>						
	ZIKL	If Entered	5.4460	1	33	0.025853
	T89	If Entered	4.4512	1	33	0.042544
<i>*end of stepping sequence*</i>						

MFP trends in the long-term model are not robust. Consistent with Lattimore, the long-run model appears miss-specified, and the focus should be on the ECM model. In particular, these results suggest a range of long term model specifications would do equally well in the ECM modelling. In essence, the long term model cannot be specified separately from the ECM.

5.9.6 The centred ECM against the conventional ECM

The above analysis suggests that the determination of MFP trends by the structural ECM is sensitive to underlying assumptions. However there is often a call for the ‘best available’ estimate in face of the uncertainty. Some estimate is better than none. The evidence above

suggests that the centred ECM model is more robust than the conventional one. Thus we would argue that an estimate of 0.7 per cent for a productivity surge commencing in 1989 is to be preferred to the one per cent revival in the mid 1990s.

It could be argued that we have not demonstrated that the centred ECM model passes the necessary econometric tests, for example, the Dickey-Fuller tests for co-integration. The response is that if the conventional ECM is reasonable, then our centred ECM will be also.

The first reason is that the predicted values are highly correlated. Their graph against time show almost identical patterns. Statistically correlation is confirmed by a high adjusted R-squared of 0.95 after correction for autocorrelation and coefficient of 0.65 with t-ratio of 25.

The difference between the two sets of predictions is not the pattern but the extent of the variation. This is because the shocks are causing smaller departures from the long-run relationship. The smaller error is consistent with the slower adjustment more in keeping with expected behaviour of macroeconomic aggregates than almost full adjustment of the conventional model.

While the centred ECM shares the same long run relationship as the conventional ECM, the long run relationship implied by the modified growth variables implies a different long run relationship. We constructed and tested this implicit long-run relationship from the growth series in the normal manner (table 18a and 18b). The tests in table 18a and 18b suggest the growth smoothing may improve the long-run relationship.

The DF test regresses the first difference of the variable (ie growth) against its lagged value (the lagged index), with sufficient lagged dependent variable to ensure behaved residuals. The test focuses on the coefficient of the lagged index variable denoted by A(1) in the table. A(0) is the constant and A(2) is a single trend. If the co-efficient A(0) is significant, then the index series is stationary, denoted by S in the table. The asymptotic critical values for the test statistic are provided by SHAZAM. We require the level series to be non-stationary and the first difference to be stationary. We use the 10% critical level that is the SHAZAM default.

Table 18a: The long run of the conventional ECM at the 2.5% significance

<i>Step No.</i>	<i>Variable</i>	<i>Status</i>	<i>F-Value</i>	<i>D.F.No</i>	<i>D.F.Den.</i>	<i>F-Probability</i>
<i>* stepping sequence *</i>						
0	T65	Forced In	1603.9090	1	35	0.000000
1	T75	Stepped In	32.4644	1	34	0.000002
<i>*summary for potential variables not entered into the reg. equation*</i>						
	ZIKL	If Entered	5.4460	1	33	0.025853
	T89	If Entered	4.4512	1	33	0.042544

End Of Stepping Sequence**Table 18b: The long run implicit in the centered ECM at the 2.5% significance.**

Step No.	Variable	Status	F-Value	D.F.No	D.F.Den.	F-Probability
<i>* stepping sequence *</i>						
0	T65	Forced In	1597.2672	1	34	0.000000
1	T75	Stepped In	50.5709	1	33	0.000000
2	T89	Stepped In	10.5563	1	32	0.002722
3	MAZZKL	Stepped In	26.7294	1	31	0.000013
<i>*end of stepping sequence*</i>						

Table 19: Dickey Fuller tests of Co-integration for Stationarity with SHAZAM

Tests of indexes for nonstationary	The Conventional ECM			The Centred ECM		
	Test stat	10% signif	Result	Test stat	10% sign	Result
The labour productivity Index						
No of lags used in coint test	0			2		
A(1)=0 Z-TEST	-7.414	-18.2	NS OK	na		
A(1)=0 T-TEST	-1.960	-3.13	NS OK	-2.667	-3.13	NS OK
F-test unit root test-zero rift						
A(0)=A(1)=A(2)=0	13.499	4.03	Drift	10.327	4.03	Drift
F-test unit root test-non zero rift			NS with			NS with
A(1)=A(2)=0	1.9379	5.34	Drift	4.6792	5.34	Drift
The capital intensity index						
No of lags used in coint test	2			2		
A(1)=0 T-TEST	-2.091	-3.13	NS	-1.582	-3.13	NS
A(0)=A(1)=A(2)=0	8.9787	4.03	Drift	10.641	4.03	Drift
A(1)=A(2)=0	3.3534	5.34	NS withDrift	2.9872	5.34	NS with Drift
Tests on Residuals from regression						
R-SQUARE	Constant, trend = 0.9884 OK			Constant , no trend 0.9899 OK		
DURBIN-WATSON	= 0.7433 OK			0.3272 OK		
NO.LAGS	0 M = 2 info			0 M = 2 info		
Test of first differences						
Labour Productivity						
no. of lags	1			2		
A(1)=0 T-TEST	-4.7167	-3.13	S OK	-2.57	-3.13	Border
A(0)=A(1)=A(2)=0	7.5894	4.03	S no drift	2.257	4.03	No drift
A(1)=A(2)=0	11.382	5.34	Drift	3.340	5.34	S Drift
Capital intensity						
no. of lags	0			4		
A(1)=0 Z-TEST	-21.038	-18.2	S OK	na		
A(1)=0 T-TEST	-3.7521	-3.13	S OK	-2.42	-3.13	Outside
A(0)=A(1)=A(2)=0	4.7057	4.03	S withDrift	2.010	4.03	Outside
A(1)=A(2)=0	7.0503	5.34	S no drift	3.013	5.34	Outside

Table 19 shows the two versions of the ECM model performed fairly comparably. The centred ECM performed worst, reflecting the lower standard errors with reduced volatility. The level variables were non-stationary and the first differences were stationary for the conventional ECM, but the latter were outside the 10% level for the centred ECM. If the lower variation in the centred model is a basis for rejection, it would also have implications for the robustness of the conventional model. We conclude that the differences shown by the tests do not rule out the centred ECM model on simple econometric grounds. (That said, we repeat our earlier caution it may be better to apply the econometric techniques earlier in the non-parametric process used to generate the annual LP and MFP growth rates.)

On the available evidence, we prefer the centred structural ECM to the conventional one, and an estimate of 0.7%pa to a 1%pa estimate for a productivity revival.

5.10 Does LPG volatility affect trend estimates?

The hypothesis tested above was whether the extent and nature of the volatility common to the LP and MFP growth pattern affects the economic measure or interpretation of the trend. Our conclusion is that reducing the extent of extreme volatility by the 2-term moving average improves the performance of the structural ECM model

The approach may partially address the following concerns of Lattimore's about the structural ECM. First, distinct structural breaks in productivity growth are assumed and identified after inspecting the data. Secondly, some data series — such as a random walk with drift — may appear to have variable trends, when none are actually present. Good model fit achieved by including deterministic trends for any apparent shifts in growth patterns may be quite illusory, and the forecasting potential of the models may be quite poor. Thirdly, when shifting productivity trends reflect microeconomic reform or new technologies, they are often likely to change gradually, rather than rapidly. In this case, productivity trends or levels may slowly evolve over time. (Lattimore, 2003 pp.226-7)

An alternative, used by Lattimore, is the stochastic ECM modelling of Andrew Harvey. This econometric approach may also be controversial. Its theoretical basis in equilibrium theory appears to rest with recent work by Robert Hall (2004), and this remains somewhat contentious. One advantage is that the stochastic model does estimate the extent of noise relative to level and slope characteristics of the MFP variable. On the other hand, its estimates are not as easily understood as structural trends, particularly when it reveals complex MFP patterns.

It seems important to look more closely at the way the productivity estimates are calculated, in line with work by the OECD. Econometrics is an appropriate tool to cope with noisy data and it can be applied in different ways and different stages to improve

productivity data. It is not clear what and when is the best way, if any, for econometrics to assist non-parametric methodologies to better measure productivity. Some approaches that may provide better data include:

- To measure macro-level productivity, work down from the more robust GDP data rather than up from the industry data. An advantage is that the productivity estimates would be a better proxy for whole-of-the-economy performance.
- More reliance on traditional methods that yield quarterly observations at least to complement the annual data, and to improve the labour hour data.
(There is a case to better understand the impact of disturbances on the new SNA93 based measures of capital services inputs. For example, Why are these capital use estimates less sensitive to disturbances than labour use? How do productivity estimates based on capital services differ in practice from those based on capital stock? And if the differences can be large, what are the implications for drawing on past productivity research?)

The general conclusion to be drawn from this section is that the error correction model has shown the difficulty in successfully separating cycles from long-term trends, and in determining the timing and extent of any acceleration in productivity. The evidence tends to suggest that Australia's productivity surge should be dated from the mid 1980s rather than the mid 1990s.

5.11 A summing-up

Across the world the evolution of ICT and its economic impact has created serious conceptual and data challenges for the analysis of productivity and growth. The response to these challenges has been far from uniform involving a degree of academic debate. Nevertheless, there is widespread agreement that ICT is having a significant impact on productivity growth, with debate being focused on the extent of that influence and on the influence of other factors.

In examining these issues the Chapter focused on two particular issues;

- whether too much weight has been placed on MFP cycles averages as a robust indicator of trend productivity; and if so,
- whether there are better approaches to the measurement and interpretation of productivity growth including the error correction model.

The Chapter shows that the present ABS methodology may not provide a robust measure of the nature of change in Australia's trend productivity and that its use may not achieve the desired stripping out of cyclical influences. Consequently, the evidence presented in this

chapter suggests that Australia did not experience a productivity revival paralleling that of the mid-1990s United States. Instead Australia's productivity revival appears to have been centred between the 1980s and 1990s rather than within either.

This analysis points to a need for more research on the underlying conceptual and measurement issues, issues that have been exposed by the long sustained falls in the price of computing power, and the sustained investment by industry and society in learning how best to apply these evolving technologies.

Also at issue is the extent to which government encouragement of ICT diffusion might be warranted to maximise productivity potential. It has been suggested that tapping ICTs future productivity potential is predominantly in the hands of firms. But this conclusion does not follow from the above analysis. Rather it is an inference drawn from empirical results which are now subject to question. Nor can it be justified from a GPT perspective which recognises the presence of significant market failures in the application of knowledge. Realising the potential of ICT should not simply be left to firms, important though they may be. The innovation system is more complex than that.

The results of these studies gives support for a non-neutral policy stance. In particular, it can be argued that the economic neutrality argument is not valid for a transforming General Purpose Technology like ICT which has very wide social and economic impacts and whose rate of diffusion is subject to significant market failures. Moreover, its impacts are as much influenced by societal attitudes and conventions as economic ones.

Support of ICT take up is in no way comparable to picking a winner in a technology race. There are no rivals for ICT in its race. There are no other GPTs competing for economic and social transformation in the field of information and communication. Other emerging GPTs like biotechnology and nanotechnology are not technological competitors, but are enabled by ICT. It is the widespread use of user-specific applications, and its potential for further development that differentiates ICT from other technologies.

References (chapter 5)

- ABS 1996 *Australian National Accounts: Multifactor Productivity, 1994–95* Catalogue 5234.
- ABS 1997 *Australian National Accounts: Multifactor Productivity, 1995–96* Catalogue 5234, 22 July.
- ABS 1999a ‘Upgrade of Capital Stock and Multifactor Productivity Estimates’ Feature Article pp.8–17 of *Australian System of National Accounts 1997–98*, Catalogue No. 5204, April
- ABS 1999b *Australian System of National Accounts 1998–99*, Catalogue No. 5204, November
- ABS 2001 *Australian System of National Accounts 2000–01*, Catalogue No. 5204, November
- Anas, Jacques, Monico Billio, Laurent Ferrara and Marco Lo Duca 2003 *Business cycle analysis with multifactor markov switching models*, mimeo, October 6
- Arora, Asish, Andrea Fosfuri and Alfonso Gambardella (2004) *Markets for Technology: The Economics of Innovation and Corporate Strategy*, MIT Press.
- Aspden, C 1989, *Development of Multifactor Productivity Estimates for Australia, 1974–75 to 1987–88*, Australian Bureau of Statistics, Information Paper, Catalogue No. 5229.0, Canberra, April
- Aspden, C 1990, *Estimates of Multifactor Productivity, Australia*, Australian Bureau of Statistics, Occasional Paper, Catalogue No. 5233.0, Canberra, August
- Baker, Dean (2003) ‘Macro Policy-Making in the New Economy’, in Derek Jones (2003).
- Basu, Susanto, John G. Fernald, Nicholas Oulton and Sylaja Srinivasan 2003 ‘The Case of the Missing Productivity Growth: Or, Does Information Technology Explain why Productivity Accelerated in the United States but not the United Kingdom?’ NBER Working Paper No. 10010, forthcoming in *NBER Macroeconomics Annual 2003* edited by Mark Gertler and Kenneth S Rogoff, MIT Press for National Bureau of Economic Research .
- Breunig, Robert and Marn-Heong Wong (2004) *Australia's Firm-level Productivity - a New Perspective* <http://ideas.repec.org/p/ecm/ausm04/177.html>
- Brynjolfsson, Erik and Lorin Hitt 2003 ‘Computing Productivity: Firm-Level Evidence’ *Review of Economics and Statistics* November at http://s.ssrn.com/sol3/s.cfm?abstract_id=290325
- Bulman, Tim and John Simon 2003 *Productivity and Inflation*, RDP 2003–10, Reserve Bank of Australia
- Carlaw, Kenneth 2004 *The Role of ICT in Australia's Economic Performance: Investigation of assumptions influencing the productivity estimates*, Paper presented in the Asia-Pacific Productivity Conference, University of Queensland, Brisbane.
- Carlaw, Kenneth and Stephen Kosempel 2004 ‘The Sources of Total Factor Productivity Growth: Evidence from Canadian Data’ *Econ. Innov. New Techn*, Vol. 13(4), June pp.299–309

- Carlaw, Kenneth I. and Lipsey, Richard G. (2002) 'Externalities, technological complementarities and sustained economic growth', *Research Policy*, 31 (8–9) pp.1305–15
- Carlaw, Kenneth I. and R. G. Lipsey 2003 'Productivity, Technology and Economic Growth: What is the relationship?' *Journal of Economic Surveys*, 17(3).
- Casserley, Dominic (2004) 'Helping Britons work smarter' *The McKinsey Quarterly*, No. 3, pp. 112–6 adapted from Casserley, Dominic (2004) 'How to achieve Wal-Mart productivity in the UK, *The Times* of London, 22nd March, and based on research undertaken with the Centre for Economic Performance of the London School of Economics.
- Colecchia, A. and Schreyer, P. 2001, *ICT Investment and Economic Growth in the 1990s: Is the United States a Unique Case? A Comparative Study of Nine OECD Countries*, OECD Science, Technology and Industry Directorate, Paris.
- Crafts, Nicholas (2002) *Productivity Growth In The Industrial Revolution: A New Growth Accounting Perspective*.
<http://www.frbsf.org/economics/conferences/0211/crafts.pdf>
- Crafts, Nicholas (2004) 'Steam as a general purpose technology: A growth accounting perspective', *The Economic Journal*, Volume 114 Issue 495 Page 338, April.
- David, Paul A. and Gavin Wright (1999) 'Early Twentieth Century Productivity Growth Dynamics: An Inquiry into the Economic History of 'Our Ignorance'', Paper to the Economic History Society Annual Conference, St. Catherine's College, Oxford, 26–28 March
- DCITA 2003 *Productivity Growth in Manufacturing Industries*, Department of Communications, Information Technology and the Arts, Canberra.
- DCITA 2005 Information Economy Division, *Productivity Growth in Service Industries*, Occasional Economic Paper, Department of Communications, Information Technology and the Arts, Canberra.
- Diewert, E. and Lawrence, D. 2004, *The Role of ICT in Australia's Economic Performance: Investigation of assumptions influencing the productivity estimates*, Paper presented in the Asia–Pacific Productivity Conference, University of Queensland, Brisbane.
- Diewert, Erwin and T.J. Wales (2004) 'A 'New' Approach to the Smoothing Problem' pp 104–144 in Belongia, M.T. and J. M. Binner (2004) (Eds) *Money, Measurement and Computation*, Palgrave, New York
- DiVenuto, Nicholas and Allan Layton 2004 'Do the phases of the business cycle die of old age', *ACE 2004*, 27–30 September, University of Sydney.
- Dorgan, Stephen J, and John Dowdy (2004) 'When IT lifts Productivity' *McKinsey Research Brief*, pp14–6 draws also on Dorgan, Stephen J, and John Dowdy (2002) 'How good management raises productivity' *The McKinsey Quarterly*, No. 4, pp9–11. and based on research undertaken with Nick Bloom and John van Reenan of the London School of Economics.
- Dowrick, S. 1994, 'Openness and Growth' in Lowe, P. and Dwyer, J. (eds.), *International Integration of the Australian Economy*, Conference Proceeding, Reserve Bank of Australia.

- Dowrick, Steve 2001 'Productivity Boom: Mirage or Miracle' in Niewenhuysen, J., Lloyd, P. and Mead, M. (eds), *Reshaping Australia's Economy: Growth with Equity and Sustainability*, Cambridge University Press, Cambridge, pp.19–32.
- Eliasson, Gunnar and Erol Taymaz (1992), 'The limits of policy making: an analysis of the consequences of boundedly rational government using the Swedish micro-to-macro model (MOSES), presented at the International Symposium on Economic Modelling, University of Gothenburg, August 18–20.
- Eliasson, Gunnar, Dan Johansson and Erol Taymaz (2002), *Simulating the New Economy*, Kungl Tekniska Högskolan, Stockholm. An early version of the study was presented to the DRUID summer conference on 'Industrial Dynamics of the Old and New Economy', Copenhagen/Elsinor 6–8 June 2002. The paper is part of a larger project 'The Macroeconomic Effects of Computer and Communications Technology'.
- Engle, Robert F. and João Victor Issler 1993 *Estimating Sectoral Cycles Using Cointegration and Common Features*, NBER Working Papers No 4529
- Fahy, John and Alan Smithee. 1999. 'Strategic Marketing and the Resource Based View of the Firm.' *Academy of Marketing Science Review* [Online] 1999 (10) Available: <http://www.amsreview.org/articles/fahy10-1999.pdf>
- Farrell, Diana, Heino Fassbender, Thomas Kneip, Stephan Kriesel and Eric Labaye (2003) 'Reviving French and German Productivity' *The McKinsey Quarterly*, No. 1 McKinsey and Company. This McKinsey Global Institute study contains three industry comparisons with the US, viz. (i) Bouvard, Francois and Stephan Kriesel 'French and German Trucking: IT for the long haul' (pp 53–5): and (ii) Kriesel, Stephen, Peter Leukert and Tidjame Thiam (2003) 'French and German Banking: Showing IT Strengths' (pp 50–2) and (iii) Telecom: Advantage France and Germany at <http://www.euractiv.com/Article?tcmuri=tcm:29-117644-16&type=Analysis>. The findings were published in Australia as Farrell, Diana (2004) : 'The real new economy' *Australian Financial Review* at <http://afr.com/articles/2004/01/27/1075088013804.html> drawn from the Harvard Business Review
- Fisher, Jonas D. M. 1999 'The New View on Growth and Business Cycles' *Economic Perspectives* (Q1), 35–56.
- Fisher, Jonas D. M. 2003b 'Technology shocks and the business cycle', *Chicago Fed Letter*, March.
- Gordon, Robert J 2003a 'Exploding Productivity Growth: Context, Causes and Implications', *Brookings Paper on Economic Activity (BPEA)* 2003:2 pp.207–98
- Gordon, Robert J. 2003b *Five Puzzles in the Behaviour of Productivity, Investment and Innovation*, draft chapter for World Economic Forum, Global Competitiveness Report 2003–04, at <http://faculty-web.at.northwestern.edu/economics/gordon/WEFTEXT.pdf>, September and reported in the *The Economist* of 13th September 2003
- Gregor, Shirley, W. Fernandez, D. Holtham, M Martin, S. Stern, M. Vitale and G. Pratt 2005 *Achieving value from ICT: key management strategies*, ICT Research Opticon Aust ANU, DCITA Occasional Paper

- Grenville, Stephen 1977 'The Reserve Bank and the Business Cycle' Talk by RBA Deputy Governor to Melbourne Institute Conference on 'Business Cycles: Policy and Analysis' on 5 September, published in Reserve Bank of Australia Bulletin, September, pp.1–12.
- Hall, Peter 1994 *Innovation, Economics and Evolution: Theoretical Perspectives on Changing Technology in Economic Systems*, Harvester Wheatsheaf, Sydney
- Hall, Robert E. 2004 *The Labour Market is the Key to Understanding the Business Cycle*, ACE 2004 , 27–30 September, University of Sydney.
- Hansen, Gary D. and Edward C. Prescott (1993): 'Did Technology Shocks Cause the 1990–91 Recession?' *American Economic Review Papers and Proceedings*, 83(2):280–86.
- Harding, Don and Adrian Pagan, u.d. ca2001, *Rejoinder to James Hamilton*, mimeo at <http://www1.ecom.unimelb.edu.au/iaesrwww/people/dharding/rhamilton.pdf>
- Harding, Don and Adrian. R. Pagan (2002), 'Dissecting the Cycle: A Methodological Investigation,' *Journal of Monetary Economics* 49(2), 365—381.
- Harding, Don and Adrian. R. Pagan (2003), 'Synchronisation of Cycles' ACE 2004 , 27–30 September, University of Sydney.
- Helpman, Elhanan (Ed) 1998 *General Purpose Technologies and Economic Growth*, MIT Press
- Henry, Ken 2004 *Enhancing Freedom, Generating Opportunities—Challenges for Governments*, Chances for Citizens, Address to Institute of Public Administration (Victorian Division) by the Secretary to The Treasury, 20 July, Melbourne.
- Kydland, Finn E., and Edward C. Prescott (1982): 'Time to Build and Aggregate Fluctuations.' *Econometrica*, 50:1345–1370.
- Lattimore, R. 2003a, 'Determining Productivity Peaks' Appendix G, pp. 209–10 from Productivity Commission 2003 *Trends in Australian Manufacturing* Commission Research Paper, AusInfo, Canberra
- Lattimore, R. 2003b, 'Modelling Productivity' Appendix I, pp.217–228 from Productivity Commission 2003 *Trends in Australian Manufacturing* Commission Research Paper, AusInfo, Canberra
- Madden Gary and G. Coble-Neal (2004) 'OECD Growth Blocs and the Role of ICT' Chapter 5 of Bohlin, E., S.L. Levin, N. Sung, and C.-H. Yoon, (2004) (eds) *Global Economy and Digital Society*, Elsevier
http://www.elsevier.com/wps/find/bookdescription.cws_home/672845/description
- Mankiw, N. Gregory (1989): 'Real Business Cycles: A New Keynesian Perspective.' *Journal of Economic Perspectives*, 3:79–90.
- McTaggart Douglas, Christopher Findlay and Michael Parkin (2004) *Economics: fourth edition*, Addison Wesley
- Melville, Nigel, Kenneth L. Kraemer and Vijay Gurbaxani (2004) 'Information Technology and Organisational Performance: An Integrative Model of IT Business Value' in *MIS Quarterly*, 28(2) at www.misq.org/archivist/vol/no28/Issue2/Melville.html

- Milgrom Paul and John Roberts 1990 'The Economics of Modern Manufacturing: Technology, Strategy and Organisation' *American Economic Review*, v80 pp511–28, June.
- Milgrom Paul, Yingyi Qian and John Roberts 1991 'Complementarities, Momentum and the Evolution of Modern Manufacturing' *American Economic Review*, v81(2) pp.84–88, May
- Murphy, Marian (2002) *Industry Issues: Organisational Change And Firm Performance*, STI Working Paper 2002/14, OECD, Paris at [http://www.oalis.oecd.org/olis/2002doc.nsf/linkto/dsti-doc\(2002\)14](http://www.oalis.oecd.org/olis/2002doc.nsf/linkto/dsti-doc(2002)14)
- National Office for the Information Economy (NOIE) 2004, *Productivity Growth in Australian Manufacturing*, NOIE Occasional Economic Paper, Canberra.
- Nelson, Richard and Stanley G Winter *An Evolutionary Theory of Economic Change*, Cambridge: Harvard University Press 1982
- Nelson, Richard R. 1995 *An Agenda for Formal Growth Theory*, IIASA Working Paper WP-94-085 International Institute for Applied System Analysis at <http://www.iiasa.ac.at>
- OECD 2004 *The Economic Impact of ICT: Measurement, Evidence and Implications*, OECD, Paris.
- Oliner, S. and Sichel, D. 2002, 'Information Technology: Where are we now and where are we going?' *Federal Reserve Bank of Atlanta Economic Review*, 87(3), pp. 15–44.
- Pakko, Michael R. 2002 'What Happens When the Technology Growth Trend Changes?: Transition Dynamics, Capital Growth and the 'New Economy'.' *Review of Economic Dynamics*, April 2002, 5(2), pp.376–407.
- Parham, D. 1999, *The New Economy? A Look at Australia's Productivity Performance*, Productivity Commission Staff Research Paper, AusInfo, Canberra.
- Parham, D. 2002a *Productivity Growth in Australia: Are we enjoying a miracle*. Melbourne Institute/The Australian conference, Towards Opportunity and Prosperity, Melbourne, 4–5 April 2002
- Parham, D. 2002b *Productivity Gains from Policy Reforms, ICTs and Structural Transformation*, to the IAOS Conference on the New Economy, London, 27–29 August
- Parham, D. 2004a, 'Sources of Australia's Productivity Revival', *The Economic Record*, Vol. 80, No. 249, pp. 239–257.
- Parham, D. 2004b, 'ICT: An engine or enabler of Australia's productivity growth', Paper presented in the Asia-Pacific Productivity Conference, University of Queensland, Brisbane.
- Parham, D. 2004c 'Productivity taking a breather' *Australian Financial Review*, 26 May 2004 p63
- Parham, D., Roberts, P. and Sun. H. 2001, *Information Technology and Australia's Productivity Surge*, Staff Research Paper, Canberra.
- Pilat, Dirk (2004) *The economic impacts of ICT: A European Perspective*, Paper prepared for conference on IT Innovation, Hitotsubashi University, Tokyo, 13–14 December 2004. <http://www.iir.hit-u.ac.jp/file/WP05-07pilat.pdf>

- Plosser, Charles (1989): 'Understanding Real Business Cycles.' *Journal of Economic Perspectives*, 3:51–78
- Prescott, Edward C. 1986 'Theory Ahead of Business Cycle Measurement.' *Federal Reserve Bank of Minneapolis Quarterly Review*, 10:23–27 (Fall). Reprinted in Preston J. Miller, ed., *The Rational Expectations Revolution. Readings from the Front Line*. Cambridge, MA: MIT Press (1994).
- Productivity Commission 2004b, *ICT Use and Productivity: A Synthesis from Studies of Australian Firms*, Commission Research Paper, Canberra
- Quiggin, John 2001, 'The Australian Productivity 'Miracle': A Sceptical View', *Agenda* 8(4), pp. 801–17.
- Schreyer, P. 2000, *The contribution of Information and Communication Technology to Output Growth: A Study of the G7 Countries*, OECD Directorate for Science, Technology and Industry, Paris.
- Schreyer, P. 2003 Capital Stocks, Capital Services and Multifactor Productivity Measures, OECD Statistics Directorate Draft, 3rd November
- Schreyer, Paul (2001), *OECD Productivity Manual: A Guide to the Measurement of Industry-Level and Aggregate Productivity Growth*, OECD, Paris at http://www.oecd.org/catch_404/?404; <http://www.oecd.org/subject/growth/prod-manual.pdf>.
- Schreyer, Paul 2005 International comparisons of levels of capital input and productivity, paper to OECD/Ivie/BBVA workshop on Productivity Measurement 17–19 October 2005, Madrid. <http://www.oecd.org/dataoecd/33/1/35446773.pdf>
- Simon, John 2001 *The Decline in Australian Output Volatility*, RDP 2001-01, Reserve Bank of Australia, March.
- Simon, John and Wardrop, S. 2002, *Australian Use of Information Technology and its Contribution to Growth*, Research Discussion Paper 2001–02, Economic Research Department, Reserve Bank of Australia.
- Solow, Robert M. 1987 and 2001 'Growth Theory and After', *R. M. Solow - Prize Lecture*, Nobel e-Museum Laureates at <http://www.nobel.se/economics/laureates/1987/solow-lecture.html>
- Stevens, G. R. 2000 'Speed limits' growth and monetary policy', Remarks to Symposium 31 May 2000, Canberra, in Reserve Bank of Australia Bulletin, pp.5–10, June.
- Zhao, Shiji 2001 'Further Developments in the Analysis of Productivity Growth in Australia' *Australian National Accounts ABS Catalogue 5206.0* September at <http://www.abs.gov.au/Ausstats/abs@.nsf/Lookup/79E72AF9D4B3095ECA256B18007D8978>
- Zheng, Simon 2004 'Estimating industry-level multifactor productivity for the market sector industries in Australia', Paper presented to the Australia Pacific Productivity Conference (APPC2004)