THE MYSTERY OF TFP

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ABSTRACT

I analyse TFP growth at the sectoral and aggregate level, using data for 10 industry groups covering the market sector for 18 countries over the period 1970-2007 drawn from the EU KLEMS dataset. TFP growth displays persistence at the aggregate level but not at the industry level, suggesting industry outputs are measured with error. In all countries resources have been shifting away from industries with high TFP growth towards industries with low TFP growth. Nevertheless I find that structural change (as measured by changes in value added shares) has favoured growth in most countries. Errors in measuring capital or in measuring the elasticity of output with respect to capital are unlikely to substantially reduce the role of TFP in explaining growth. The pattern of growth in these 18 countries is more consistent with an underlying two-sector model than with the one-sector (Solow) model. Standard theory suggests that TFP growth induces capital accumulation, at least in the long run. This is not the case with the raw EU KLEMS data used here. But standard theory finds some support when the data are smoothed to remove cyclical effects.

1. Introduction[1]

It is generally agreed that increases in labour productivity are the only long run source of growth in living standards. And since Solow (1956) a wide though not universal consensus has existed that behind the growth of labour productivity stands the growth of Total Factor Productivity (TFP). Without continuing TFP growth there can be no continuing growth in labour productivity since capital accumulation by itself would be subject to diminishing returns. But what are the sources of TFP growth? The literature (surveyed by Hulten (2001)) suggests that *measured* TFP growth can arise in one or more of the following ways:

1. From technical and scientific progress (including improvements in management techniques). This does *not* include progress embodied in new or improved types of capital or which is purchased directly via for example consultancy. Only progress which comes for free is to be included here.
2. From learning effects, either learning by doing or learning from others, or more broadly from externalities and economies of scale.
3. By reallocation of inputs towards more (or less) productive uses, either at the firm or the industry level.
4. As an artefact of measurement error (as when increases in the quality of human or physical capital are wrongly ignored or output is mismeasured) or when some types of asset (such as intangibles) are wrongly omitted.

A particular concern in the literature has been the role of capital. In the past some at least of measured TFP growth would have been rightly attributed to the fact that indices of capital input were crude, e.g. horsepower. And some, including the originator of TFP as a theoretical concept and pioneer of its empirical measurement (Solow 1957), thought that price indices of capital goods did not allow for quality change. But nowadays it is accepted that they should and this principle is enshrined in the OECD Productivity and Capital Manuals (OECD 2001 and 2009). But the extent to which capital is well-measured in practice is still open to debate and will be discussed in what follows. The earlier growth accounting literature also paid a lot

[1] An earlier version benefited from the comments of participants at the IARIW Conference in Dresden, Germany, in August 2016, particularly of my discussant, Marcel Timmer. I also benefited from comments received when the paper was presented at the Philadelphia Fed, particularly from Leonard Nakamura. The current version has been greatly improved by the comments of Andrew Sharpe and two anonymous referees. An abridged version has appeared as Oulton (2016).

of attention to capital measurement (Griliches and Jorgenson 1967; Jorgenson et al. 1987); in particular it introduced the important distinction between capital stocks and capital services. The result of these pioneering efforts was to reduce but not eliminate the role of TFP.

This paper discusses some of the (non-exclusive) explanations of TFP growth listed above. A particular focus is the extent to which they are consistent with the pattern of TFP growth at the industry level. For example, it is not obvious how technical and scientific progress leads, year by year, to TFP growth in retailing. The factors which are important here are likely quite different to those which are important in (say) semiconductors. The fact that industry TFP growth rates differ suggests adding a fifth source of TFP growth at the aggregate level:

5. Shifts in the structure of output and demand leading to changes in the aggregate growth rate of TFP and hence of aggregate labour productivity. These shifts could be favourable or unfavourable to growth.

The paper therefore employs data from the EU KLEMS dataset to study the properties of TFP growth at the industry level. It seeks to quantify and assess the sources listed above as causes of TFP growth (except I shall have very little to say about the third source). I refer to the "mystery" of TFP since though almost everyone agrees it is fundamental to growth there is no consensus as to how much of measured TFP growth should be allocated to each of the five sources just listed. And as we shall see, the likelihood of significant measurement error bedevils further progress in understanding.

1.2 Plan of the paper

Section 2 describes the EU KLEMS dataset to be used in the empirical work and sets out some of its advantages by contrast with the micro data so popular nowadays. Section 3 uses this dataset to set out the broad facts about TFP growth and the allocation of resources to different industries in 18 countries over the years 1970-2007 (though not every country has data for all years). Section 4 asks a basic question about TFP growth: how persistent is it? This question relates to the first source of TFP growth, technical and scientific progress. The answer depends on whether we are looking at the industry level or at the aggregate level. Section 5 then turns to the issue of structural change (the fifth source of TFP growth) and whether it has tended to increase or reduce growth at the aggregate level. The motivation here

is that the industry to which resources have been shifting in every country is business services which has negative TFP growth in 17 out of the 18 countries. The possibility of measurement error (the fourth source) plays an important part here. The fourth source is studied again in Section 6, where I consider whether mismeasurement of capital, usually leading to understatement of capital growth, can account for an appreciable part of measured TFP growth . Such mismeasurement could take the form of understated quality change, missing assets (such as some intangibles), or failure to account for increases in the variety of capital goods available on the market. Section 7 analyses whether, even if capital is measured correctly, its impact on growth may not be. There might be externalities which make the elasticity of output with respect to capital greater than the value suggested by capital's share in the value of output (the standard measure in the growth accounting literature); this is the second source of TFP growth. Here I also consider whether the evidence is more consistent with a two-sector than a one-sector model. Section 8 concludes.

2. The EU KLEMS dataset

Much of the empirical analysis to follow uses data from the EU KLEMS dataset described in O'Mahony and Timmer (2009) which is freely available for download at www.euklems.net. More specifically, I use the March 2011 update of the November 2009 release (downloaded on 27th October 2015 as a file called all_countries_09I.txt). This file contains data on national accounts and growth accounting variables for 29 countries over 1970-2007. In particular it contains data on TFP growth (the value added concept), real and nominal value added, real and nominal gross output, labour services and capital services. Its estimates of labour input allow for labour quality and are on an hours worked basis. Its estimates of capital services distinguish between ICT and non-ICT assets and are estimated on a comparable basis across countries. However these data are not available for all countries and all years. Data on TFP are only available for a maximum of 18 countries (which includes three non-European countries: Australia, Japan and the US). So the following 11 countries which lacked TFP data were dropped: Cyprus, Estonia, Greece, Latvia, Korea, Lithuania, Luxembourg, Malta, Poland, Portugal and Slovakia. The maximum number of time series observations is 37 (Italy

and the UK) and the minimum number is 11 (Slovenia). The included countries, together with the years for which each has data for TFP growth, are in Table 1.[2]

The EU KLEMS dataset has two great strengths. First, it is consistent with the national accounts of the countries included. Second it goes beyond the national accounts by using a common methodology for estimating labour quality and capital services. Furthermore labour quality and capital services are estimated in a disaggregated manner: 18 types of labour (distinguished by educational attainment (3 types), sex (2) and age (3)) and 7 types of capital asset (3 in ICT and 4 in non-ICT assets[3]). Labour input is measured by hours worked not number of workers.

The EU KLEMS dataset therefore contrasts with micro (firm-level or establishment-level) data which are not usually consistent with the national accounts. Also in micro data firm- or establishment-level estimates of capital and labour are often crude. For example, for capital frequently only nominal book value (a stock not a flow measure) is available which then has to be deflated by some overall deflator. This is generally the case for all studies based on company accounts (e.g. Bartelsman et al. 2013; for India and China see Hsieh and Klenow 2009). Studies based on census data usually have to make do with investment, often aggregated over asset types, to which it is difficult to apply the Perpetual Inventory Model. Firm-level prices are usually not available so firm output has to be deflated by an industry deflator; on the rare occasions when firm-level prices can be observed there are substantial differences between them and the corresponding industry-level deflators (Foster et al. 2008). Labour input must frequently be measured by the number of employees. These criticisms are not meant to disparage micro-level studies, just to point out that the data on which they are based do not dominate empirically the data behind industry-level studies. So micro-level studies should be seen as complements to, not substitutes, for industry-level ones.[4]

The growth accounting variables in EU KLEMS are broken down by industry in accordance with Revision 1 of the NACE. There are (roughly) 21 2-digit industry groups — "roughly"

[2] The EU KLEMS database has previously been analysed by Timmer *et al.* (2010).
[3] ICT assets: computers, communication equipment, and software. Non-ICT assets: transport equipment, other machinery and equipment, non-residential structures, other. Residential structures are also in the EU KLEMS dataset but are not used in productivity analysis.
[4] See Syverson (2011) for a survey of work on productivity based on micro data. The focus of much of this work is on explaining why productivity levels differ across firms rather than on explaining differences in growth rates. He does not address the issue of data reliability.

because some groups are aggregates of underlying 2-digit groups — and 16 "1-letter" groups. Both the 2-digit and the 1-letter groups collectively add up to GDP. Most of the additional detail available at the 2-digit level comes from manufacturing. Since manufacturing has received arguably excessive emphasis in previous studies I decided to use the 1-letter level. The 16 1-letter groups, A-Q (A is actually combined with B), are set out in Table 2. The market sector is defined as the 10 industry groups A-K; note that the criterion for being part of the market sector is the nature of the industry, not ownership. Real estate (industry 70) is excluded from K ("Renting and business activities") since it mainly comprises the imputed rent of owner-occupiers; sector K is therefore renamed "Business services". The analysis to follow is confined to the market sector and its constituent industries for two reasons. First, the measurement of real output in the non-market industry groups is problematic and likely inconsistent across countries. Second, since much of it is publicly-owned the motivations of decision makers are probably not focused on cost minimization or profit maximization, thus calling into question the growth accounting methodology. On average, across all available years and countries for which TFP data is present in EU KLEMS, the market sector as defined here accounted for 71% of total value added and 75% of total hours worked (Table 2).

In summary, the results to be reported are for 18 countries and the 10 industry groups comprising the market sector over a maximum time span of 1970-2007. The EU KLEMS dataset is in the process of being extended to cover the period of the Great Recession and its aftermath. But at the time this research began it stopped in 2007. This means that the present paper can have nothing to say directly about the effects of the financial crisis on TFP which has led to at the very least a temporary slowdown in growth.[5]

3. TFP growth and the allocation of resources across sectors: an overview

3.1 TFP growth

Chart 1 shows TFP growth in the market sector in the 18 countries, both the actual growth rate and the growth of TFP after smoothing by the Hodrick-Prescott (HP) filter. Most

[5] See now on this Oulton and Sebastiá-Barriel (2016) who discuss whether the crisis will affect not just the level but also the future growth rate of labour productivity and TFP.

countries show little sign of either accelerating or decelerating growth.[6] Five countries were clearly above their own long run average at the end of our period: Austria, Finland, Netherlands and the UK. And five were by then below their own long run average: Australia, Spain, Ireland, Italy, and Japan, though in the case of Japan and Italy the HP trend is more encouraging. For five others, the data period was too short to allow a conclusion (Czech Republic, Germany, Hungary, Slovenia and Sweden). Much more striking is the difference between countries in their mean growth rate (Chart 2). Bottom of the class is Spain at 0.23% p.a. and top is Hungary at 2.55% p.a. (though over a short period). Other strong performers were Austria, Finland, Ireland and Japan.

Chart 3 shows mean TFP growth rates in each of the 10 sectors within the market sector. The highest rates are found in Agriculture (A&B) where the unweighted cross-country mean is 2.86% p.a. and in Manufacturing (D) where it is 2.15% p.a. The lowest are in Construction (F), Hotels and restaurants (H), and Business services (K) where the cross-country means are minus 0.18, minus 1.16 and minus 1.17 respectively. It is worrying that there are a considerable number of negative rates. For example, 8 out of 18 countries show negative TFP growth in Mining & quarrying (C), 5 in Electricity, gas and water (E), 9 in Construction (F), 12 in Hotels & restaurants (H), 5 in Finance (J) and no less than 17 in Business services (K).

Negative TFP growth suggests firms in these industries are becoming less efficient over time or that technical knowledge is being forgotten, which seems highly implausible in peaceful conditions. Negative growth may be explicable in some cases. For instance in Mining & quarrying deposits may be becoming harder to extract as they are progressively worked out. In Electricity, gas and water an increasing burden of environmental regulation might be the cause: the costs of meeting the regulations are measured but the benefits in terms of lower emissions are not included in output. These explanations do not seem to apply to Construction or Hotels & restaurants and still less to Business services which as we shall see is one of the sectors to which resources are shifting in all these countries. Hence one must suspect measurement error as already noted by Timmer et al. (2010) in the case of business services. If measurement error is present the first place to look is errors in output measurement. It is well known that price indices for private services are poorly developed by

[6] This contrasts with labour productivity at the whole economy level where there are signs of a pervasive slowdown commencing prior to the global financial crisis, at least in large economies (Cette et al. 2016; OECD 2016, chapter 5). For the US Byrne et al. (2016) document slowing TFP and labour productivity growth since 2004.

contrast to those of the industrial sector (though even those are not beyond reproach as discussed below); see Bean (2016, chapter 2) for UK evidence on this. It is quite plausible that the relative prices of sophisticated services like legal and advertising services or software are falling but that this is not picked up by the deflators actually used (often the GDP deflator or the CPI).

3.2 Value added shares

The pattern of resource allocation, as measured by the value added share of each sector in market sector GDP, has been changing in all our countries. In general in most countries, the share of agriculture and manufacturing has been declining while that of finance and business services has been rising (Chart 4). Chart 4a shows the agriculture share. It is falling in all countries except perhaps the US. The share of manufacturing has been falling in 11 countries (including even Germany) and flat in 6: Austria, Czech Republic, Finland, Hungary, Slovenia and Sweden, though in some of these the data period is short. It has been rising only in Ireland (Chart 4b). In construction the picture is different. In most countries the share is flat but rising in Spain and Ireland, particularly from around 1990 (Chart 4c). The share of wholesale and retail trade shows little change (Chart 4d). The share of hotels and restaurants is flat except in Spain and to a lesser extent Italy and the UK (Chart 4e). Finance displays a rising trend in 9 countries though in some the rise is in the first half of our period, e.g. France. The sharpest rise occurred in Ireland, the UK and the US. In Belgium, Denmark and Italy the share is flat. In Austria and Sweden it is hump-shaped, centred around the early 1990s (Chart 4f). The clearest pattern is seen in business services (K, exc. 70) whose share has been rising in every country (Chart 4g). This means that in most countries resources have been shifting away from agriculture and manufacturing where TFP growth is apparently at its most rapid towards in particular business services where TFP growth is measured as negative. The implications of this (on the face of it) puzzling fact will be pursued in section 5.

4. Persistence of TFP

If TFP growth is caused by underlying developments in science and technology then we would expect TFP growth to be persistent. The benefit arising from some scientific or

technological advance is not likely to be dissipated within a year; there is ample evidence that innovations (including improvements in managerial techniques) take time to diffuse across the firms within an industry.[7] We can test this proposition by running the following regression:

$$g_{ijt} = \beta g_{ij,t-1} + Controls + \varepsilon_{ijt} \quad (1)$$

where g_{ijt} is the growth rate of TFP in the *i*-th industry of the *j*-th country in year *t* and ε_{ijt} is an error term. The controls are industry, country and year dummies. We run the same regression for the market sector as a whole:

$$g_{it}^{MS} = \beta g_{i,t-1}^{MS} + Controls + \varepsilon_{it}^{MS} \quad (2)$$

Here g_{it}^{MS} is the TFP growth rate for the market sector as a whole, constructed as a weighted average of the industry-level growth rates (empirically, a Törnqvist index using value added weights). The results of running these regressions using the EU KLEMS dataset described above are in Table 3.

Whether we include one, two or three lags of the dependent variable, the lagged variables are never significant at the 5% level or better. Despite including industry, country and year dummies the degree of explanatory power as measured by R^2 is always low, less than 7% (columns 2-4). Including up to three lags does not raise R^2 appreciably relative to including none (compare column 1). Splitting the sample into two does not raise the significance of the lagged dependent variables (columns 5-8).[8] But aggregating over the 10 industries does (column 9). Now the coefficient on the lagged dependent variable is of non-negligible size (0.231) and highly significant. R^2 is also considerably higher at 0.325. That there is excessive year-to-year variation in TFP growth is suggested by column 10 where TFP growth in each industry and country has been averaged over time. Now the inclusion of industry and country dummies can "explain" about 47% of the variation in the dependent variable.

In summary, at the 10-sector level there appears to be no significant persistence in TFP growth. But for the market sector as a whole there is substantial and statistically significant persistence. A likely explanation is that there are offsetting errors in the industry-level TFP

[7] Persistence of TFP growth at the aggregate level is an important feature of RBC models such as the one in Kydland and Prescott (1982).

[8] I also tried running the regression for each industry separately (including country and year dummies) but this led to estimates of persistence that were significant at the 5% level in only two out of 10 cases: Agriculture where persistence was negative and Manufacturing where it was positive though low (0.145).

estimates arising most probably from errors in industry-level value added (see below). To justify this claim, consider first the effect of errors in industry-level TFP growth on estimates of the persistence parameter β. Suppose that the true relationship is

$$\tilde{g}_{ijt} = \beta \tilde{g}_{ijt-1} + Controls + \tilde{\varepsilon}_{ijt} \tag{3}$$

where $\tilde{g}_{ijt}$ is the true measure of TFP growth and $\tilde{\varepsilon}_{ijt}$ is assumed to be serially and spatially uncorrelated. The actual measure is related to the true one by

$$g_{ijt} = \tilde{g}_{ijt} + \eta_{ijt} \tag{4}$$

Here η_{ijt} is a random measurement error assumed uncorrelated over time and uncorrelated with the $\tilde{\varepsilon}_{ijt}$ but with the property that the errors cancel out within a given country in a given year:

$$\sum_{i=1}^{N} v_{ijt}\eta_{ijt} = 0 \tag{5}$$

where v_{ijt} is the share of the *j*-th industry in the *i*-th country's market sector value added in year *t*. Now substituting (3) and (4) into (1) we can see that the regression equation (1) now has the classic errors-in-variables form with measurement error in the independent variable:

$$g_{ijt} = \beta g_{ij,t-1} + Controls + [\eta_{ijt} - \beta\eta_{ij,t-1} + \varepsilon_{ijt}] \tag{6}$$

The independent variable $g_{ij,t-1}$ is correlated with the error term because of (4), hence the OLS estimate of β is biased towards zero: see e.g. Greene (2008), chapter 12, page 326. (There is also measurement error in the dependent variable but this affects only the standard error of β and does not cause bias).

Suppose instead we run the same regression at the market sector level, equation (2), taking market sector TFP growth to be a weighted average of the industry-level rates:

$$g_{it}^{MS} = \sum_{j=1}^{N} v_{ijt} g_{ijt} \tag{7}$$

So using (4) and (5):

$$\tilde{g}_{it}^{MS} = \sum_{j=1}^{N} v_{ijt} \tilde{g}_{ijt} \tag{8}$$

Using (3), (7) and (8) and ignoring for simplicity the controls we find that

$$\tilde{g}_{it}^{MS} = \sum_{i=1}^{N} v_{ijt} \tilde{g}_{ijt} = \beta \tilde{g}_{it}^{MS} + \sum_{i=1}^{N} (v_{ijt} - v_{ij,t-1}) \tilde{g}_{ij,t-1} + \sum_{i=1}^{N} v_{ijt} \tilde{\varepsilon}_{ijt} \tag{9}$$

Applying (4) and (5) we obtain

$$g_{it}^{MS} = \beta g_{i,t-1}^{MS} + \sum_{i=1}^{N} (v_{ijt} - v_{ij,t-1}) \tilde{g}_{ij,t-1} + \tilde{\varepsilon}_{it}^{MS} \tag{10}$$

putting $\tilde{\varepsilon}_{it}^{MS} = \sum_{i=1}^{N} v_{ijt}\tilde{\varepsilon}_{ijt}$. Now the error term $\tilde{\varepsilon}_{it}^{MS}$ is uncorrelated with the independent variable $g_{i,t-1}^{MS}$ so we there will be no attenuation, i.e. the OLS estimate of β is unbiased. It is true that there is now an additional term on the right hand side, $\sum_{i=1}^{N}(v_{ijt} - v_{ij,t-1})\tilde{g}_{ij,t-1}$, but this is likely to be small and uncorrelated with $g_{i,t-1}^{MS}$ so omitting it (as in the results discussed above) is unlikely to bias the estimate of β.

How are errors in the TFP growth series most likely to arise? Consider Table 4 which shows the standard deviations of TFP growth and its two main components, the growth of real value added per hour and the contribution of capital deepening (calculated as a residual). Real value added per hour is further broken down into its components: real value added, nominal value added, the price of value added and hours worked. Two striking features are apparent. First, the standard deviation of the capital deepening contribution is much lower than that of labour productivity (real value added per hour); this is surprising given that investment is usually considered to be one of the more volatile components of GDP. Second, after breaking labor productivity growth down into its components, the highest standard deviations of all are for nominal value added and the price of value added. The high standard deviation of nominal value added growth may arise from the national income balancing process carried out within the framework of supply and use tables, a practice common amongst National Statistical Institutes (NSIs). If the NSI adjusts gross output and value added at the industry level so that the sum across industries agrees with a control total then this could induce offsetting errors in nominal industry outputs. Balancing is typically done at a low level of aggregation (e.g. 60-100 or more industries). So this could also induce offsetting errors in the price deflators at the industry group level used here since the latter are weighted averages of price indices from a much lower level. So if the components of gross output in some industry group are distorted then the weights for the industry-group deflators are similarly distorted.[9]

Oulton and Rincon-Aznar (2013) found that the implied rates of return to capital were very implausible at the industry level in the EU KLEMS dataset, and were very volatile over time. One explanation for this is that gross operating surplus, part of value added, has been

[9] As a referee pointed out to me, the model of measurement error is hard to distinguish from an alternative where the error term in equation (4) η_{ijt} represents genuine random technology shocks. I feel that this interpretation is less likely given the evidence of Table 4 which shows the much higher variance of nominal value added and its price than of the other components of TFP.

misallocated across industries. This is consistent with the argument that nominal value added has been misallocated across industries.[10]

This discussion is not meant as a criticism of the EU KLEMS dataset which was necessarily dependent on the underlying national accounts data supplied by NSIs. It does however justify using averaging or other smoothing processes in the empirical work which follows.

I conclude that despite initial appearances TFP growth probably exhibits persistence at the 10 industry group level as well as at the market sector level. So these results are weakly consistent with the view that sees technical progress as the driving force behind TFP growth.

5. Structural change and increasing specialization

The first aim of this section is to show theoretically that aggregate TFP growth rises when resources (value added) are shifting towards industries supplying intermediate goods and services. This is the case even when these supplying industries themselves have low TFP growth (provided it is positive). The second aim is to quantify the size of these effects in our 18 countries.

5.1 Aggregate and industry-level TFP growth: theory

Let us begin with a brief review of TFP growth at the aggregate and industry level; see The Appendix for a more detailed exposition. Start by defining the aggregate growth rate of TFP (μ)), aka the Solow residual, as

$$\mu := \hat{V} - \alpha\hat{K} - (1-\alpha)\hat{L} \tag{11}$$

where V is real GDP, K is aggregate capital services, L is aggregate labour input, α is the capital (profit) share, and hats denote growth rates, e.g. $\hat{V} = d\ln V / dt$ where t is time; the symbol ":=" denotes a definition.

[10] Oulton and Rincon-Aznar (2013) also suggested that the allocation of investment by NSIs to different industries may be a problem. However for growth accounting purposes we are dealing with *growth rates* of capital so (consistent) errors in capital levels are not an issue here. Also, averaging of growth rates will tend to remove time-varying errors.

In Solow's original formulation (Solow 1957) equation (11) was justified as deriving from an aggregate production function

$$V = A(t) f(K, L) \tag{12}$$

under constant returns and perfect competition. The parameter $\mu (= \hat{A})$ can be interpreted as the rate of disembodied technical progress (manna from heaven), though Solow was well aware that TFP as measured by (11) could in practice arise from many other causes.

In fact, the assumption of a an aggregate production function is not needed. Assuming marginal cost pricing and that a given input receives the same price in all industries, the Solow residual can be given a deeper justification in a multi-industry setting as measuring the outward shift of the production possibility frontier made possible by technological change, with all inputs including intermediate ones held constant (Hulten 1978; Gabaix 2011, Appendix B). Then equation (11) can be justified as a way of measuring the important parameter μ using readily available data.

But the economy is made up of different industries and it seems plausible that technical progress occurs at different rates in different industries. So how is the aggregate rate of technical progress related to the rates in different industries? At the industry level there are two possible concepts of TFP growth, the value added one and the gross output one. The gross output concept is based on the existence of an industry production function:

$$Y_i = f_i(K_{i1,}..., K_{iC}; L_{i1}, ..., L_{iD}; M_{i1}, ..., M_{iN}; t) \tag{13}$$

Here Y_i is real (gross) output in the *i*-th industry ($i = 1,..., N$) and there are assumed to be *C* types of capital K_{ik}, *D* types of labour L_{il}, and *N* types of intermediate input M_{ij} (produced by the *N* industries but possibly also imported). Now define μ_i^{GO} as the gross output concept of TFP growth in the *i*-th industry:

$$\mu_i^{GO} := \frac{\partial \ln Y_i}{\partial t} \tag{14}$$

We can then readily find that

$$\mu_i^{GO} = \hat{Y}_i - \sum_{k=1}^{C} \alpha_{ik} \hat{K}_{ik} - \sum_{l=1}^{D} \beta_{il} \hat{L}_{il} - \sum_{j=1}^{N} m_{ij} \hat{M}_{ij} \tag{15}$$

where $\alpha_{ik}, \beta_{il}, m_{ij}$ are the elasticities of the capital, labour and intermediate inputs with respect to output. Assuming competitive conditions these elasticities can be equated empirically to the share of each input in the value of gross output (the input cost shares).

The value added concept of TFP growth is defined by:

$$\mu_i^{VA} := \hat{V}_i - \sum_{k=1}^{C} \alpha_{ik}^{VA} \hat{K}_{ik} - \sum_{l=1}^{D} \beta_{il}^{VA} \hat{L}_{il} \tag{16}$$

where V_i is real value added in the *i*-th industry and α_{ik}^{VA}, β_{il}^{VA} are the shares of the capital and labour inputs in value added. We then find that as a matter of algebra the relationship between the two concepts of TFP growth is:

$$\mu_i^{VA} = \left[\frac{GO_i}{VA_i} \right] \mu_i^{GO} \tag{17}$$

where GO_i is nominal gross output and VA_i is nominal value added. Hence $\mu_i^{VA} \geq \mu_i^{GO}$ with equality iff $GO_i = VA_i$. But note that this relationship holds by necessity only if value added is measured by double not single deflation (see the Appendix). If single deflation is employed then the relationship between the two concepts becomes an empirical question.[11]

Straightforward algebra shows that the aggregate TFP growth rate as defined by (11) is identically equal to the following aggregation scheme:

$$\mu = \sum_{i=1}^{N} d_i \mu_i^{GO} \tag{18}$$

Here d_i is the Domar (1961) weight for the *i*-th industry, defined as

$$d_i := \left[\frac{GO_i}{GDP} \right] \tag{19}$$

And using (17) we also have an alternative aggregation scheme based on the value added measure:

$$\mu = \sum_{i=1}^{N} v_i \mu_i^{VA} \tag{20}$$

For these equivalences to hold we just need to assume that a given input earns the same return wherever it is employed.[12] If this is not the case then the aggregate formulas become more complex with additional terms reflecting the shift of resources to or from industries where they are more highly valued (see Jorgenson et al. (1987), chapter 2, page 66). In what follows I ignore these complications which are not probably of great importance empirically

[11] Diewert (2015) derives discrete analogues for the continuous time formula of equation (17) in the Laspeyres, Paasche and Fisher cases.

[12] Equation (20) also requires that real value added by measured by double not single deflation. This is the case for most of our 18 countries though the UK is an exception. See equation (32) of the Appendix for the definition of double deflation.

in advanced economies (at least, Jorgenson et al. (1987) did not find them important for the US over 1948-79). [13]

The gross output concept of industry TFP growth is more fundamental than the value added one. The value added concept is derived from the gross output one under an additional, restrictive assumption: real gross output per unit of real intermediate input is determined entirely by input prices and can never be reduced by technical progress. Only under this condition does a value added production function exist (though whether or not it exists we can always *calculate* the value added concept of TFP using equation (16)). And we can always convert a value added measure into a gross output one using (17). So there would seem to be no need to consider the value added measure at all. However in practice value added measures are more readily available. So we cannot dispense completely with the value added measure of TFP.

5.2 Increasing specialization as an additional source of growth

Let us consider the aggregate rate of technical progress, as described by equation (18) relating aggregate and industry TFP growth rates, in more detail. First, it tells us that the aggregate TFP growth rate depends not just on technical progress in individual industries but also on the pattern of demand. Suppose a country loses comparative advantage in one of its export industries which happens to have a relatively fast rate of TFP growth. Then other things equal the aggregate rate will decline as resources shift towards less progressive industries. Another story leading to the same conclusion is the cost disease model of Baumol (1967). Suppose that over time consumer demand is shifting towards final demand services such as entertainment, health and education which have low productivity growth. In this case too resources will be shifting towards technologically unprogressive industries so the overall productivity rate will be declining.

But this is not the whole story. To see why consider the Domar weight in more detail. This can be decomposed as

[13] Note that under this approach there is no role for differences in the *level* of TFP across industries to affect the aggregate TFP growth rate, e.g. by shifts in labour and capital towards industries with a higher TFP level. This contrasts with the situation for labour productivity, on which see for example Reinsdorf (2015). The reason is that a given input is assumed to receive the same return in every industry, so there is no possibility for example of capital earning a higher return in some industries than in others. There is in any case competitive pressure to equalise TFP levels across different industries in a given country (Baumol and Wolff 1984).

$$d_i = \frac{GO_i}{GDP} = \frac{\text{Final sales by } i}{GDP} + \frac{\text{Intermediate sales by } i}{GDP} \qquad (21)$$

Consider for simplicity a closed economy. Then there are three points to note. First, the first ratio on the right hand side must necessarily be a fraction between 0 and 1 and the sum of these fractions is 1 since the sum of final sales equals GDP. Hence a rise in this fraction for one industry must necessarily be accompanied by a fall for one or more other industries. Second, the second ratio on the right hand side of (21) can in principle take any non-negative value. So the sum over industries of the Domar weights must be at least 1 (it is typically much greater, over 2, as we shall see), since the sum of final sales equals GDP. Third, it is possible for the sum of the Domar weights to rise over time if the degree of outsourcing is rising generally. Consequently the aggregate growth rate of TFP rises if all industry TFP growth rates are unchanged but the degree of outsourcing increases. This adds a new and different source of growth to those usually considered.

This is most clearly seen if we consider an extreme case of an industry which sells only intermediate products. An example is business services in a closed economy (so there are no exports or imports of business services). Suppose that resources move towards this industry so that its sales rise faster than GDP, either because its products are cheaper than the same ones produced in-house or because it develops attractive new products. Then the aggregate TFP growth rate will increase without any change in the industry gross output TFP growth rates. Notice that this will still be the case even if the TFP growth rate is lower in business services than elsewhere (say in manufacturing). In other words, the aggregate TFP growth rate still rises even though resources are shifting towards a technologically unprogressive industry, so long as TFP growth in this industry is positive.[14]

So we have reached the paradoxical conclusion that the aggregate TFP growth rate can rise even if resources are shifting towards industries with lower productivity growth, provided these industries are selling intermediate not final products. The explanation for this paradox is

[14] This is a qualification to the cost-disease argument in Baumol (1967). The latter is still correct as long as it is understood to refer to industries producing final, not intermediate, products. All this is explained more fully in Oulton (2001). The basic point was generously acknowledged by Baumol in Krueger (2001, page 223), in Baumol (2002), pages 277-278, and further analysed in Baumol (2012), particularly chapters 9 and 10 (Wu 2012a and 2012b). Ngai and Pissarides (2007) subsequently showed that Baumol's original conclusion that the aggregate growth rate would decline need not follow in the long run: in a model with capital the equilibrium growth rate is constant even though employment shifts progressively to the stagnant sectors. However their model predicts that value added shares are constant in the long run and this is hard to square with the evidence presented above that these shares have been steadily changing over periods measured in decades.

that in this situation the industry-level value added TFP growth rate is misleading since it rises when the degree of outsourcing rises: see equation (17). In fact it is the shift in resources away from industries with higher productivity growth which makes them look even more progressive (on the value added measure) than they did before.

More formally, consider a closed economy with only two industries. The first industry ("cars") makes only final sales. It buys inputs from the second industry ("business services") which makes only intermediate sales. Then the Domar weights in the two industries are:

$$d_1 = \frac{GO_1}{GDP} = \frac{F_1}{GDP} = 1$$
$$d_2 = \frac{GO_2}{GDP} = \frac{M_{12}}{GDP} = \frac{GO_1 - VA_1}{GO_1} = 1 - \frac{VA_1}{GO_1} \tag{22}$$

Here F_1 is final sales by the car industry which by assumption are equal to GDP and M_{12} is intermediate sales by business services to the car industry (necessarily equal to the latter's intermediate purchases). Now if the degree of outsourcing by the car industry rises (the VA_1 / GO_1 ratio falls), then the Domar weight for business services rises while that for cars is constant. So for given gross output TFP growth rates in the two industries the aggregate TFP growth rate increases (by equation (18)).[15]

5.3 How much have the Domar weights changed in practice?

Another way to decompose the Domar weights is the following:

$$d_i = \frac{GO_i}{GDP} = \left[\frac{GO_i}{VA_i}\right]\left[\frac{VA_i}{GDP}\right] = u_i v_i \tag{23}$$

where

$$u_i := GO_i / VA_i$$

measures as we have said the degree of outsourcing in the *i*-th industry and

$$v_i := VA_i / GDP$$

[15] In this simplified case the sum of the Domar weights increases; the upper limit of the sum is 2. In general, if there were *N-k* industries selling final goods and *k* selling intermediate goods the limit of the Domar sum is again 2. In practice the Domar sum exceeds 2 (even in a closed economy) since all industries have some intermediate sales.

measures the importance of the industry in the economy. (In the simplified two-industry case just discussed these two ratios move in inverse proportion to each other in the car industry so that its Domar weight stays constant while that of the business services industry rises.) The sum of the Domar weights

$$\sum_{i=1}^{N} d_i = \sum_{i=1}^{N} \left[\frac{GO_i}{VA_i} \right] \left[\frac{VA_i}{GDP} \right] \tag{24}$$

now appears as an interesting statistic in its own right. It is the weighted average of the degree of outsourcing in the economy's industries, the weights being value added.

Chart 5 shows how the sum of the Domar weights (the Domar sum) has changed over time in each country. In every country the sum exceeds 2, in some such as Belgium or the Czech Republic substantially so. The Domar sum shows a clear upward trend in Austria, Belgium, Finland and Italy; there is a less pronounced upward trend in Sweden, France and Germany. It is flat in Australia, Japan, Netherlands, UK and US.

Charts 6a, 6b and 6c show the Domar weights over time for three important sectors: Manufacturing (D), Finance (J) and Business services (K, exc. 70). The weight for manufacturing is clearly declining in eight countries, flat in five, and clearly rising in only two. In Finance the Domar weight is rising in every country except Sweden, Czech Republic, Hungary and Slovenia. In Business service the weight is rising in all 18 countries.

A clearer picture emerges by collapsing the 10 sectors into three broad groups (Table 3). Sectors A-F constitute the goods-producing or "production" part of the economy. Sectors G and H (trade, hotels and restaurants) mainly provide consumer services, while Sectors I, J and K (exc. 70) (transport, communication, financial and business services) mainly provide services to other industries. The broad picture is that the Domar weight for the production part of the economy has declined in 13 of the 18 countries (the largest declines were in Japan and the UK). For consumer services the weight rose by a modest amount. The weight for finance and business services broadly defined (sections I, J and K) rose in all 18 countries and on average by more than the fall in the weight for production. In consequence there was a rise in the Domar sum in 13 out of the 18 countries.

5.4 Measuring the impact of structural change

We are now in a position to estimate the impact of structural change on aggregate TFP growth, making use of equation (18):

$$\mu = \sum_{i=1}^{N} d_i \mu_i^{GO}$$

We don't have gross output estimates of TFP growth but we can find them from the value added estimates in EU KLEMS using equation (17). Then treating these as parameters we can estimate the effect of different patterns of demand, both final and intermediate (the Domar weights), on the aggregate TFP growth rate. Two natural questions are first, what would the aggregate TFP growth rate have been if the pattern of demand in each country had remained that of the beginning of the period? And second, what would it have been if the pattern at the end of the period had prevailed throughout?

Table 4 shows the answers to these two questions. For reference, column 1 shows the mean TFP growth rate in the market sector that was actually observed (as already shown in Chart 2). A first shot at the answers appears in columns (2), (3) and (8). Column (2), headed "Initial structure", shows for each country the mean TFP growth rate with the pattern of demand (the d_i) set equal to the average of the first two years of the sample in each country in every year. Column 3, headed "Latest structure", shows a similar calculation but with the pattern of demand set equal to an average of the *last* two years of the sample in every year. In both columns (2) and (3) I use the actual TFP growth rates estimated for each industry. Column (8) shows the difference between columns (2) and (3): the growth rate under the latest structure *minus* the growth rate under the initial one.

The effect of structural change is seen to be predominantly negative. Only 5 out of the 18 countries show a positive effect: the Czech Republic, Denmark, Hungary, Ireland and Sweden. The unweighted cross-country mean of the change is minus 0.13 % p.a. Arithmetically, the reason for this is clear: in all countries resources have been shifting to Business services (sector K) but in this sector TFP growth is almost invariably estimated to be negative (Chart 2). So any shift of resources towards this sector will seemingly have reduced the aggregate growth rate (it will make an increasingly negative contribution to the Domar-weighted sum).

As noted above the negative TFP growth rate in Business services is very implausible. So in the next variant of the calculations I have set the TFP growth rate in this sector equal to the actual, observed market sector TFP growth rate in each country and each year. That is, I am assuming that the overall TFP growth rate is correct, but the measured rate in Business services is wrong. So there must be offsetting errors in the other sectors which need to be correspondingly adjusted to leave the aggregate rate unchanged. That is, from the value added formula for aggregate TFP growth (equation (20)) we have:

$$\mu = \sum_{i=1}^{N} v_i \mu_i^{VA} = \sum_{i=1}^{N} v_i \tilde{\mu}_i^{VA}$$

Here the $\tilde{\mu}_i^{VA}$ are the adjusted TFP growth rates which we need to find. Suppose that it is agreed that the growth rate of the *N*-th sector should be set equal to the aggregate growth rate μ, i.e. $\tilde{\mu}_N^{VA} = \mu$. Then we can derive the adjustments to the growth rates in the other sectors which will hold the overall average constant: see the Appendix for the details.

These adjusted value-added-based TFP growth rates $\tilde{\mu}_i^{VA}$ can be used to derive adjusted gross-output-based ones by solving (17):

$$\tilde{\mu}_i^{GO} = \left[\frac{VA_i}{GO_i} \right] \tilde{\mu}_i^{VA} \tag{25}$$

Finally, we can calculate what the aggregate TFP growth rate would have been under an alternative pattern of demand ($\tilde{d}_i$):

$$\tilde{\mu} = \sum_{i=1}^{N} \tilde{d}_i \tilde{\mu}_i^{GO} \tag{26}$$

An alternative, more radical assumption is to adjust the Business services rate upwards but to leave the rates in other sectors unchanged, thus raising the overall average. But this would be a dubious move for two reasons. First, insofar as business services are sold to other domestic sectors (rather than exported) an understatement of TFP growth in this sector (say because output is understated) means that TFP growth in the purchasing sectors is overstated. Second, that the aggregate rate is correct or at any rate more accurate than the sectoral rates can be justified by the way in which NSIs estimate real GDP. Typically this is from the expenditure side since expenditure-side price indices like the CPI are considered more accurate than PPIs or service industry price indices ; sectoral growth rates are then adjusted so that when

aggregated they conform to the estimated growth rate of GDP(E). Hence the more radical alternative should be rejected.

Columns (4), (5) and (9) show the results after the TFP growth rate in Business services is set equal to the market sector rate, with corresponding adjustments to the other sectors. Now a different picture emerges, with 11 countries showing a positive effect of structural change; the unweighted mean of this change is plus 0.03 % p.a.. Though the overall average effect is small, the effect is quite large for individual countries such as Austria, Denmark, Finland, Germany and Sweden which all received a boost to productivity growth from structural change on the order of 0.1 to 0.3 % p.a. For the 11 gainers there was an average boost to growth of 0.17% p.a. This can be compared to the average TFP growth rate in these countries of 1.4% p.a. So the effect is of an economically significant size.

There is a case for adjusting the TFP growth rate in Finance (sector J) too, because of the well-known difficulties of measuring output here. In Finance the TFP growth rate is usually positive but less than the aggregate rate (Chart 2). But adjusting the TFP growth rate of sector Finance as well as that of Business services does not make much difference compared with just adjusting Business services. 10 countries now show a positive effect and the unweighted mean of the change is plus 0.04 % p.a.: see columns (6), (7) and 10.

How sensitive is the finding that most countries have gained from structural change to the assumption that TFP growth in Business services, correctly measured, equals that of the market sector as a whole? We can test this by setting TFP growth in Business services equal to half that of the market sector in each year and each country: see column 11 of Table 4. Naturally this reduces the effect of structural change; the cross-country mean increase in TFP growth due to structural change is now -0.05 rather than +0.03. But the pattern of gainers and losers is very similar: 10 countries are net gainers and 8 are net losers with the winners gaining on average 0.15% p.a. and the losers losing 0.21% p.a.

Table 5 digs a bit deeper by showing the contribution of each sector to the change in overall TFP growth stemming from structural change. (Here as in column (9) of the previous Table 4 I set the TFP growth rate in Business services equal to that of the market sector). The contribution of Business services (K, exc. 70) to the overall change is positive in all countries, ranging from 0.01% p.a. to 0.16% p.a.; it averaged 0.08% per year. But in some

countries, notably Japan, the United Kingdom and the United States, this was more than offset by a negative contribution from Manufacturing (D), so that the overall effect of structural change is negative. In other words in these countries deindustrialisation has apparently gone so far as to impact negatively on overall growth. [16]

6. Mismeasurement of capital

6.1 Mismeasurement of quality change

It is entirely plausible that capital is mismeasured and indeed understated due to understated quality change, i.e. overstated investment goods price indices (Gordon 1990). But how much does this affect TFP measurement? The traditional argument (Jorgenson 1966) is that any errors in measuring capital show up on the output side as well as the input side. If the growth rate of capital services is underestimated due to measurement error this will tend to overestimate TFP growth. But there is an offsetting factor: the growth of GDP will be understated as well. This is because the growth of GDP is a weighted average of the growth rates of the expenditure components, one of which is investment. So the overall error depends on the size of the weights given to investment on the output side (the investment share in GDP) and to capital on the input side (the profit share). In the Golden Rule case the two shares are equal and the errors cancel out exactly.

More formally, divide output (Y) into consumer goods (Y_C) and investment goods (Y_I). Then in a closed economy , the growth of GDP from the expenditure side is

$$\hat{Y} = w_C \hat{Y}_C + w_I \hat{Y}_I$$

where w_C (w_I) are the shares in final expenditure of consumption (investment). Aggregate TFP growth is defined as

$$\mu := w_C \hat{Y}_C + w_I \hat{Y}_I - \alpha \hat{K} - (1-\alpha)\hat{L}$$

[16] The UK saw the second largest positive effect from Business services but the largest negative effect from Manufacturing. However a substantial fraction of the UK's business services output is exported. So for the UK there is a case for revising up the growth rate of market sector TFP if indeed the growth of business services output is understated by conventional price indices. If so, the UK might finish up as a net gainer from structural change.

where α is the capital share. Now suppose there is an error e in measuring capital growth: $e = \hat{\tilde{K}} - \hat{K}$ where $\hat{\tilde{K}}$ denotes the true growth rate. Also assume a steady state in which the growth of investment equals the growth of capital services ($\hat{Y}_I = \hat{K}$). Then the error in measuring TFP growth is

$$\text{TFP error} = (w_I - \alpha)e$$

The error in TFP is smaller than the error in capital since $w_I - \alpha$ is a fraction. Indeed in the Golden Rule case $(w_I = \alpha)$ the errors cancel out and the TFP error is zero.

Next, suppose capital growth is understated so that $e > 0$. Then TFP growth will be overstated if $\alpha > w_I$. This condition is likely satisfied for large, advanced economies like the United States (which because of its size is not very open) where the investment share is quite a bit less than the capital share.

However, these results are for a closed economy. Consider by contrast an economy which imports all its capital goods. Such an economy is likely to be small and poor. Then there is no error in real GDP since investment is balanced by capital goods imports of equal size. So any error in real investment is canceled out by an equal error in real imports. But capital input is still understated. So in this case there is no offset and the error in capital measurement translates directly into TFP. In this case the TFP error is the profit share times the capital input error $(-\alpha e)$. For example, if there is a 1% p.a. understatement of the growth of capital and the capital share is 0.35 then TFP growth will be overstated by 0.35% p.a. The significance of this can be judged by noting that the cross-country mean TFP growth rate in our countries was 1.16% p.a. (Table 8). In general the TFP error is likely to be larger in small, poor countries than in bigger, richer ones. But errors in measuring capital growth do not seem likely to eliminate TFP as a source of growth. According to Table 8, capital per hour is growing at 3-4% p.a. So a 1% understatement of capital growth would be a large error but would reduce TFP growth by only about 0.35 % and that is before allowing for any countervailing error on the output side.

All this is for the aggregate economy. But the errors in TFP measurement are likely to be larger at the industry level. The reason is that most industries are users but not producers of capital goods. So there are no offsetting errors on the output side to at least partially cancel

out the input side error and so reduce the TFP error. This means that TFP growth in capital-goods -producing industries is likely to be understated and in other industries overstated.

6.2 Missing capital

It is possible that whole classes of capital assets have been omitted from the growth accounting calculations because they have been misclassified as intermediate inputs. This argument was first raised in regard to software and R&D. In this case the argument was accepted and expenditures on software and R&D are now recognized as forms of investment in the System of National Accounts (SNA); software but not R&D appears as an investment in EU KLEMS. It has also been argued that there is a whole range of other expenditures, dubbed intangible investment, which should also be reclassified as investment. These include expenditures on building organizational capital, in-house training, and design and marketing: see Corrado et al. (2005) and (2009) for the US, Dal Borgo et al. (2013) for the UK and Corrado et al. (2013) for a comparison covering the US, Japan and Europe. These expenditures have not yet been accepted as investment in the SNA but changing the latter is a lengthy process and it is quite possible that some or all of them will be in a future revision.

The effect on TFP calculations is quite complicated. The level of GDP rises since there are new forms of investment to include. But whether the growth rate of GDP changes depends on whether the new forms of investment are growing faster or slower than the old ones. A similar point applies to the growth rate of capital on the input side. In fact the analysis is very similar to the case just considered of mismeasured quality change, except that in addition the various weights involved in the calculation also change. The net effect is that TFP is still an important factor in the growth process. Corrado et al. (2013) find that TFP accounted for 26% of labour productivity growth in the EU (unweighted average), for 22% in Japan and for 39% in the US over 1995-2007 (their Table 2). These figures are not so different from those derivable from Table 8 which to repeat include software but not R&D or the other intangibles. For example according to EU KLEMS TFP accounted for 35% of labour productivity growth in the United States over 1978-2007. While a fuller accounting for the inputs behind the growth process is clearly desirable, on the evidence so far it does not seem likely to eliminate TFP as a factor or even to change its importance in a growth accounting sense.

6.3 Increasing variety and the Romer model

In Romer's (1986) and (1990) model of economic growth there is a goods sector with a production function of the following form:

$$Y = L_Y^{1-\alpha} \int_0^A x_j^{\alpha} dj$$

Here a composite good (Y) is produced with the aid of labour (L_Y) and (a continuum of) A types of capital good ($x_1, x_2, ..., x_A$). The composite good can be either consumed or invested.. Each type of capital can be hired at the real rental price p_j. By symmetry, in equilibrium each of the A types of capital will be used at the same level of intensity (x) and will bear the same real rental price (p):

$$x_j = x, \text{ all } j; \; p_j = p, \text{ all } j$$

Hence in equilibrium the production function can be re-written as:

$$Y = L_Y^{1-\alpha} x^{\alpha} \int_0^A dj = L_Y^{1-\alpha} A x^{\alpha}$$

Since all types of capital have the same rental price, we can "add them up" to get total capital services K:

$$K = \int_0^A x_j dj = x \int_0^A dj = Ax \;\Rightarrow\; x = K / A$$

Substituting this into the equilibrium production function:

$$Y = K^{\alpha} (AL_Y)^{1-\alpha}$$

This is identical to a common or garden Cobb-Douglas aggregate production function. Clearly capital (K) is subject to diminishing returns so the only long run source of growth is the factor A, the number of types of capital good, which acts here like labour-augmenting technical progress. If we apply conventional growth accounting to the goods sector under the usual assumptions we find that TFP growth is given by

$$\mu := \hat{Y} - \alpha \hat{K} - (1-\alpha) \hat{L}_Y = (1-\alpha) \hat{A}$$

where $(1-\alpha)$ can be measured by the labour share (Barro 1999). So TFP growth should now be interpreted as the growth in capital variety weighted by the labour share.

In Romer's model there is also a research sector where new types of capital are created by entrepreneurs who expect to profit by patenting their inventions. A full growth accounting analysis would have to cover the research sector too, taking into account that the latter is

subject to monopolistic competition. But this is not the focus here. Nor do we necessarily have to accept the Romer vision that all useful research is carried out by profit-seeking entrepreneurs rather than by non-profit organisations such as universities or government-owned research labs. The point is this: suppose we apply the Romer production function to the EU KLEMS sectors studied here. How then should we interpret conventionally-measured TFP growth? After all, the latter may reflect conventional notions of TFP such as increasing efficiency or manna from heaven technical progress as well as increasing variety. We could in fact trivially expand the Romer production function to incorporate "conventional" TFP as well as increasing variety:

$$Y = BK^{\alpha}(AL_Y)^{1-\alpha},\ B > 0$$

where B is conventional TFP, assumed to grow exogenously. Now the ordinary measure of TFP becomes

$$\mu = \hat{B} + (1-\alpha)\hat{A}$$

But how then do we decide how much of measured TFP growth should be attributed to increasing variety and how much to the other sources?

One response is that we should revise the measure of capital to take explicit account of the increasing (or for that matter decreasing) variety of capital types, whether human or physical. After all, the proximate source of productivity growth in the Romer model is more capital though not more of the *same* capital. And it is now generally accepted by NSIs that investment and capital should allow for increasing quality. So why not also for increasing variety? This is the approach suggested by Feenstra and Markusen (1992). Working with a discrete CES model they derive a formula for what is in effect a revised index of capital or more generally of all inputs. Define a quantity λ_t as the ratio of cost-minimising expenditure on the range of inputs available in period t to the cost-minimising expenditure on the range of inputs available in period t-1, both evaluated at a common set of prices and a given level of output. They then show that the growth of output can be decomposed into two factors: a CES quantity index assuming the same range of inputs is available in both periods multiplied by $\lambda_t^{\sigma/(\sigma-1)}$ where σ is the (common) elasticity of substitution between inputs ($\lambda \geq 1,\ \sigma > 1$). This latter factor measures the variety effect. Note that the CES index can be calculated from prices and quantities alone without any knowledge of the parameters of the production function. But it is necessary to know the range of inputs in both periods and the expenditures on each. It is also necessary to know (or estimate) the elasticity of substitution σ. At the

moment this makes the approach impractical on a large scale.[17] But in principle it could be used to allocate measured TFP growth between increased variety and other sources.

7. Capital externalities and the relationship between TFP and capital accumulation

7.1 Externalities, economies of scale, and learning-by-doing: an upper limit

The previous section considered whether capital services are generally mismeasured and if so what is the likely size of the resulting error in TFP growth. Another possibility is that even if capital is correctly measured its impact may not be. In other words, the elasticity of output with respect to capital may exceed capital's share. This could be because of economies of scale. But at the industry level these seem likely to be important in only a few industries where a square-cube law prevails, such as pipelines or electricity generation. A more plausible reason is network externality effects as a new technology such as the Internet is deployed. Another is learning by doing arising from capital investment, either within the firm or by follower firms learning from early adopters.

If the elasticity of output with respect to capital (the capital elasticity) has been understated by the capital share, then how large would it have to be to eliminate TFP entirely as a source of growth? Suppose our model is

$$y_t = Ak^{\gamma}h_0e^{\lambda t} \tag{27}$$

where y is output per hour, k is capital per hour, h is human capital per hour worked (labour quality), λ is the growth rate of labour quality, and γ is the capital elasticity which is now not necessarily equal to the capital share. Assume that TFP (A) is constant over time (though not necessarily across countries). Then the growth of output between time 0 and time t is given by

$$\ln(y_t / y_0) = \gamma \ln(k_t / k_0) + \lambda t$$

[17] Feenstra and Markusen (1992) state that their approach can be extended to the case where old varieties are disappearing as well as new ones appearing. In the Romer model old varieties never do disappear. However, in the real world some types of capital, e.g. Jacquard looms, disappear due to obsolescence (they are dominated by newer varieties) or because they are specialised on the production of things that nobody now wants to buy (newspaper printing presses may be headed this way). It seems necessary to use a quality ladders model to cover this aspect of reality (Aghion and Howitt 1992).

from which we can solve for γ:

$$\gamma = \frac{\ln(y_t / y_0) - \lambda t}{\ln(k_t / k_0)} \tag{28}$$

The parameter γ is therefore the hypothetical capital elasticity which would reduce TFP growth to zero. Columns (2)-(5) of Table 6 show the data necessary for calculating this parameter. Column (10) shows the resulting estimates while Column (9) shows the actual capital share for comparison. On average the hypothetical elasticity is more than twice as large as the actual share. This seems far too large a difference to attribute to network effects or learning-by-doing. An apparent exception is Belgium and Spain where the hypothetical elasticity is only about 12% larger than their actual capital shares. But this is because both countries had exceptionally low TFP growth (Column (2)).[18]

We can also test the hypothesis that the capital elasticity exceeds capital's share econometrically. We can regress the growth of output per hour on the growth of capital per hour and check whether the coefficient on capital differs significantly from capital's share. This approach runs into well-known econometric difficulties since capital growth is likely correlated with the error term which includes TFP. Nevertheless I estimated a model in which the current growth of labour productivity in the market sector depends on its own lagged growth rate and on the growth rate of capital per hour plus country and year controls. Both lagged productivity growth and capital per hour growth were highly significant. When estimated by OLS the long run capital elasticity was 0.42 and it was 0.40 when using the Arellano-Bond method. This is higher than the actual capital shares shown in Table 8 but nothing like high enough to eliminate TFP as a source of growth.

7.2 TFP and the Solow model

In Solow's model the long run growth rate of both output per hour and capital per hour is the TFP growth rate divided by the labour share ($\mu/(1-\alpha)$) plus the growth rate of labour

[18] Hall and Jones (1999) and Caselli (2005) attribute most of the cross-country variation in levels of GDP per capita to TFP differences. Their measures of capital are cruder than the ones in EU KLEMS so the present finding can be taken as a useful confirmation of theirs. In fact, if the hypothetical capital elasticity which would reduce the cross-country differences in TFP *levels* to zero is estimated from the data in Hall and Jones (1999, Table 1), using the same model as above, its average value over all their 127 countries is 0.793. This compares with the value they assumed for the capital share, 1/3. The mean value of 0.793 is remarkably close to the mean value of 0.700 in Table 8.

quality.[19] In fact the actual labour productivity growth rate exceeds the rate predicted by the Solow model in 17 out of the 18 countries here; on average the actual rate is higher by 0.75% p.a. The sole exception is Hungary (column 7 of Table 8). Also the growth of capital per hour exceeds that of labour productivity by on average 0.96% p.a.; the only exceptions are Austria, Hungary, Ireland and Slovenia (column 8). Two explanations come to mind. First, during a catch-up phase capital and labour productivity will grow faster in emerging economies than their long run rate. Against this we find actual growth exceeding the Solow prediction in mature economies as well as emerging ones and even in the United States which is not catching up to anyone. Second, the relative price of capital goods, particularly of ICT assets, has been falling in recent decades. So a two-sector model where the first sector produces consumer goods and some types of investment goods (e.g. buildings) while the second sector produces high-tech investment goods may be more appropriate (Whelan 2001). In such a model the long run growth rate of capital exceeds that of output even though in value terms the capital-output ratio is constant. This is the case even for countries which import all their advanced capital equipment. Aggregate growth is still driven by TFP growth at home, but also by TFP growth abroad; the latter benefits capital-goods-importing countries via favourable changes in the terms of trade (Oulton 2012).

In summary, the two-sector model like the one-sector one still predicts that TFP growth, wherever it occurs, drives capital accumulation. The reason is that TFP growth increases the marginal product of capital, thus creating an incentive to invest. So we should still expect to see a positive association between the growth of TFP and the growth of capital per hour.

7.3 Does TFP induce capital accumulation?

According to the Solow model in the long run output growth is entirely driven by TFP growth, the latter taken to be exogenous. And the growth of capital is induced by the growth of TFP, i.e. capital growth is endogenous. This suggests testing a model of the following type:

$$\ln(K_{jt} / K_{j,t-1}) = \beta_0 + \beta_1 \ln(K_{j,t-1} / K_{j,t-2}) + \beta_2 \mu_{jt} + \beta_3 \mu_{j,t-1} + Controls + \varepsilon_{jt}$$

[19] This can be seen from equation (27) after setting $\gamma = \alpha$, the capital share, and requiring that in the long run the growth of capital should equal the growth of output.

where *j* indexes countries and *t* indexes time; the controls are dummies for country and year, and ε_{jt} is a random error. The lagged terms allows for the possibility of a lagged response of capital to TFP. The maintained hypothesis that TFP growth is exogenous implies that it is uncorrelated with the error term.

Because of the errors we have found in the industry-level TFP growth rates I ran this model at the market sector level. The upper panel of Table 9 shows the results of a panel regression of the growth of capital services per hour on the growth of TFP; there are 18 countries in the panel and a maximum time span covering 1971-2007 (37 years). Since only a few countries have TFP data for the full span the number of observation is 445 when the regression is fitted with no lags. The results are clear. Current TFP growth is not significant. Lagged TFP growth is significant but negative, contrary to expectation. (The year and country dummies are always highly significant and in fact provide nearly all the explanatory power). Very similar results are found using the Arellano-Bond estimation method (not shown). These results are at variance with any theory which sees TFP growth as the exogenous driver of capital growth, including both the one-sector Solow model and its extension to two sectors.

However, Basu et al. (2006) have argued that in the short run a negative effect of a technology shock (defined as TFP growth purged of utilization effects) on inputs is to be expected. In a New Keynesian macro model with sticky prices output doers not initially increase following a positive technology shock so inputs fall. In the long run a positive effect emerges. They find evidence for this pattern in annual US data over 1949-1996. Also, measured TFP is affected by the degree of utilization. This tends to make TFP growth procyclical which muddies the waters. To adjust all 18 countries for utilization is beyond the scope of this study. But a simpler way to proceed is to reduce the effect of cyclicality by estimating Hodrick-Prescott trends of capital per hour and TFP (with the λ parameter set to 6.25). The same regressions are estimated in the lower panel of Table 9, but with growth rates of the trends replacing actual growth rates. Now a different picture emerges. When TFP and lagged TFP growth are included on the right hand side current TFP growth is negative and significant while lagged TFP growth is positive and significant (columns 2 and 4), the same pattern found by Basu et al. (2006). Admittedly, the negative coefficient is numerically larger than the positive one, implying that the long run effect is negative. But the reverse is the case

if time and year dummies are omitted (though these are highly significant). All in all, the smoothed data are broadly consistent with the findings of Basu et al. (2006).

8. Concluding remarks

Based on an analysis of TFP growth in 10 industries within the market sector for 18 countries over 1970-2007, drawn from the EU KLEMS dataset, the main conclusions reached were as follows:

1. Any theory which sees progress in science and technology as the cause of TFP growth (at least when the latter is correctly measured) would expect TFP growth to be persistent (i.e. positively auto-correlated). This is because innovations take time to spread. But at the industry level there is no persistence in TFP. However persistence does appear when we aggregate industries to the level of the market sector as a whole. I have argued that this is due to errors in the measurement of real value added growth at the industry level, leading to excessive volatility in year-to-year growth rates. These errors cancel out after aggregation to the market sector level.

2. In all the countries considered here resources have been shifting out of agriculture and manufacturing, where TFP growth is high, and into finance and particularly business services where it is low. In fact, in business services TFP growth is measured to be on average negative in 17 out of the 18 countries studied. Despite this I conclude that structural change has probably been favourable to growth in most countries. The negative TFP growth in business services is very implausible. So I set this rate to the average rate in the market sector as a whole, with a corresponding downward adjustment in all other sectors to maintain the same aggregate rate. With this adjustment structural change is found to favour growth in 11 out of the 18 countries, and by an economically significant amount.

3. Underestimation of quality change in capital goods could cause the role of TFP growth to be overstated and the role of capital to be correspondingly understated. And such underestimation, due to the failure of price indices for capital goods to fully reflect quality change, is plausible. But the upper limit for the effects of this mismeasurement seems to be

fairly low, of the order of 0.35% p.a. At the aggregate level such an error is partially offset by a corresponding error in measuring the growth of output. However at the industry level there is usually no such offset so here the effect on TFP is larger. Also the overstatement of TFP growth is larger in countries which import most of their high-tech capital goods.

4. Capital's role could also be understated if expenditure on some inputs is wrongly classified as intermediate consumption rather than as investment. The SNA now admits both expenditures on software and in R&D as investment where previously they were classified as intermediate. The net could be cast wider to include other types of expenditure on intangibles. But the evidence to date is that this will not reduce the importance of TFP in the growth process. This is because treating more inputs as investment changes the measurement of output as well as of capital.

5. Capital's role in the growth process would be larger if the elasticity of output with respect to capital were higher than capital's share, the latter being the standard growth accounting measure. This could be due to economies of scale, network externalities or to learning-by-doing. But we found that the increase in the elasticity necessary to reduce the role of TFP to zero (approximately a doubling) was far too large to be plausible.

6. The pattern of growth in these 18 countries is not consistent with the predictions of the standard one-sector (Solow) model. The labour productivity growth rate exceeds the rate predicted by the Solow model in 17 out of the 18 countries; on average the actual rate is higher by 0.75% p.a. Also the growth of capital per hour exceeds that of labour productivity by on average 0.96% p.a. whereas in the Solow model these rates should be the same. These facts are more consistent with a two-sector model in which the relative prices of high-tech capital goods are continuously falling.

7. Finally, we found that one empirical property of the raw data for TFP is inconsistent with standard theory: capital accumulation does not respond positively to a rise in the TFP growth rate. This is at first puzzling since TFP growth raises the marginal product of capital, thus creating an incentive to invest. However when the data are smoothed to remove cyclical effects the expected pattern appears: an increase in the TFP growth rate does increase the growth rate of capital per hour in the long run, though reducing it in the short run. This is consistent with a new Keynesian model in which prices are sticky in the short run.

In summary, we have seen that any attempt to eliminate TFP from the growth story and replace it with some wider or better measure of capital seems unlikely to succeed. But we still have much to learn about TFP. Given the importance given to TFP by growth theory and current fears of a pervasive growth slowdown (e.g. Cowen 2011; Gordon 2016), it is depressing that so much of the discussion still needs to be about measurement error. This is not the fault of the data compilers who are doing their best with limited resources. But though policy-makers everywhere are concerned about these issues they are generally unwilling to devote the (quite limited) additional resources needed for improved measurement to advance understanding. Until this changes the mystery of TFP is likely to remain unresolved.

Appendix

A.1 Domar aggregation

This exposition follows Domar (1961), Hulten (1978), Jorgenson et al. (1987) and Gabaix (2011). Start with some basic accounting relationships in an *N*-industry economy which uses *C* types of capital and *D* types of labour. For each industry the value of output equals payments for inputs (including profit):

$$GO_i := P_i Y_i = \sum_{l=1}^{D} P_{lL} L_{il} + \sum_{k=1}^{C} P_{kK} K_{ik} + \sum_{j=1}^{N} P_j M_{ij} \tag{29}$$

Here GO_i is nominal gross output of the *i*-th industry, Y_i is real output, P_i is its price, K_{ik} is the quantity of the *k*-th type of capital used in industry *i*, L_{il} is the quantity of the *l*-th type of labour, M_{ij} is the quantity of the *j*-th type of intermediate input, and P_{kK}, P_{lL}, P_{jM} are the corresponding prices of capital, labour and intermediate input respectively; the symbol ":=" denotes a definition. Note that we are assuming that a given input is sold at a common price in all industries; if any intermediate inputs are imported then they are sold at the same price as their domestic counterparts. Nominal value added is defined as

$$VA_i := P_{iV} V_i := P_i Y_i - \sum_{j=1}^{N} P_j M_{ij} \tag{30}$$

where V_i is real value added and P_{iV} is the price of value added. These last two concepts are not directly observable but they become so by totally differentiating both sides of (30) with respect to time and collecting terms in prices and quantities:

$$\hat{P}_{iV} := \frac{GO_i}{VA_i}\left[\hat{P}_i - \sum_{j=1}^{N} m_{ij} \hat{P}_j\right] \tag{31}$$

and

$$\hat{V}_i := \frac{GO_i}{VA_i}\left[\hat{Y}_i - \sum_{j=1}^{N} m_{ij} \hat{M}_{ij}\right] \tag{32}$$

Here "hats" denote growth rates, e.g. $\hat{V}_i = d \ln V_i / dt$. As defined in the main text, m_{ij} is the share of intermediate input *j* in the total costs of industry *i*. Equation (32) defines double deflated real value added in continuous time and (31) defines the corresponding price index.

At the industry level there are two possible concepts of TFP growth, the value added one and the gross output one. The gross output concept is based on the existence of an industry production function:

$$Y_i = f_i(K_{i1,}...,K_{iC};L_{i1},...,L_{iD};M_{i1},...,M_{iN};t) \tag{33}$$

Now define μ_i^{GO} as the gross output concept of TFP growth in the *i*-th industry

$$\mu_i^{GO} := \frac{\partial \ln Y_i}{\partial t} \tag{34}$$

We can readily find that

$$\mu_i^{GO} = \hat{Y}_i - \sum_{k=1}^{C} \alpha_{ik}\hat{K}_{ik} - \sum_{l=1}^{D} \beta_{il}\hat{L}_{il} - \sum_{j=1}^{N} m_{ij}\hat{M}_{ij} \tag{35}$$

where $\alpha_{ik}, \beta_{il}, m_{ij}$ are the elasticities of output with respect to the capital, labour and intermediate inputs respectively. Assuming competitive conditions these elasticities can be equated to the share of each input in the value of gross output (the cost shares) so that:

$$\begin{aligned}
\beta_{il} &= \frac{P_{lL}L_{il}}{P_iY_i},\ l = 1,...,D \\
\alpha_{ik} &= \frac{P_{kK}K_{ik}}{P_iY_i},\ k = 1,...,C \\
m_{ij} &= \frac{P_jM_{ij}}{P_iY_i},\ j = 1,...,N
\end{aligned} \tag{36}$$

The cost shares sum to 1.

The value added concept of TFP growth is defined by:

$$\mu_i^{VA} := \hat{V}_i - \sum_{k=1}^{C} \alpha_{ik}^{VA}\hat{K}_{ik} - \sum_{l=1}^{D} \beta_{il}^{VA}\hat{L}_{il} \tag{37}$$

where α_{ik}^{VA}, β_{il}^{VA} are the shares of the capital and labour inputs in value added:

$$\begin{aligned}
\beta_{il}^{VA} &= \frac{P_{lL}L_{il}}{P_{iV}V_i} = \left[\frac{GO_i}{VA_i}\right]\beta_{il},\ l = 1,...,D \\
\alpha_{ik}^{VA} &= \frac{P_{kK}K_{ik}}{P_{iV}V_i} = \left[\frac{GO_i}{VA_i}\right]\alpha_{ik},\ k = 1,...,C
\end{aligned} \tag{38}$$

making use of (36). Now substitute (32) and (38) into (37) and use (35) to get

$$\mu_i^{VA} = \left[\frac{GO_i}{VA_i}\right]\mu_i^{GO} \tag{39}$$

Hence $\mu_i^{VA} \geq = \mu_i^{GO}$ with equality iff $GO_i = VA_i$.

Note that we have given a theoretical justification for the gross output concept of TFP growth by invoking the industry production function. We have given no such justification for the value added concept. It is possible to base the value added measure more directly on theory by assuming the existence of a value added function:

$$V_i = g_i(K_{i1,}...,K_{iC};L_{i1},...,L_{iD};t) \tag{40}$$

and by assuming that the production function is separable in value added and intermediate input:

$$Y_i = f_i(V_i, M_{i1},...,M_{iN})$$

But this would be a very restrictive assumption since it says that technical progress can never reduce the requirement for intermediate inputs per unit of gross output. Note that it is always possible to *calculate* the value added measure by using either the direct formula, equation (37), or indirectly from the gross output measure, equation (35), even if this restrictive assumption does not hold. But then the interpretation of the measure becomes problematic.

At the aggregate level nominal GDP is the sum of value added in all industries:

$$GDP = \sum_{i=1}^{N} P_{iV}V_i \tag{41}$$

The growth rate of real GDP (V) is, using the Divisia approach,

$$\hat{V} = \sum_{i=1}^{N} v_i V_i, \quad v_i := \frac{P_{iV}V_i}{GDP} \tag{42}$$

where the v_i are the value added shares of each industry in GDP.

Now define the aggregate growth rate of TFP (μ) as

$$\mu := \hat{V} - \alpha\hat{K} - (1-\alpha)\hat{L} \tag{43}$$

where K is aggregate capital services, L is aggregate labour input, α is the capital (profit) share. Under the competitive assumptions made here μ can be shown to measure the rate at which the social production possibility frontier is shifting outwards as a result of technological progress (Hulten 1978; Gabaix 2011, Appendix B). In turn aggregate capital and aggregate labour of each type can be found from summing over the industries:

$$K_k = \sum_{i=1}^{N} K_{ik}, \quad k = 1,...,C$$
$$L_l = \sum_{i=1}^{N} L_{il}, \quad l = 1,...,D \tag{44}$$

Divisia indices of aggregate capital and aggregate labour are then

$$\hat{K} = \sum_{k=1}^{C} \left[\frac{P_{kK} K_k}{\sum_{k=1}^{C} P_{kK} K_k} \right] \hat{K}_k$$
$$\hat{L} = \sum_{l=1}^{D} \left[\frac{P_{lL} L_l}{\sum_{l=1}^{D} P_{lL} L_l} \right] \hat{L}_l \tag{45}$$

These last two equations embody the assumption that a given capital or labour input earns the same return in any industry. Finally, the aggregate capital share is

$$\alpha = \frac{\sum_{k=1}^{C} P_{kK} K_k}{GDP} \tag{46}$$

and the labour share is $1-\alpha$.

Equation (43) is the top-down approach to measuring aggregate TFP. The latter can also be measured by aggregating over industry-level TFP growth rates, the bottom-up approach. Straightforward algebra shows that the aggregate TFP growth rate as defined by (43) is identically equal to the following aggregation scheme.

$$\mu = \sum_{i=1}^{N} d_i \mu_i^{GO} \tag{47}$$

Here d_i is the Domar (1961) weight for the *i*-th industry, defined as

$$d_i := \left[\frac{GO_i}{GDP} \right] \tag{48}$$

And using (39) we also have an alternative aggregation scheme based on the value added measure:

$$\mu = \sum_{i=1}^{N} v_i \mu_i^{VA} \tag{49}$$

For these equivalences to hold we just need to assume that a given input earns the same return wherever it is employed. If this is not the case then the aggregate formulas become more complex with additional terms reflecting the shift of resources to or from industries where they are more highly valued (see Jorgenson et al. (1987), chapter 2, page 66).

A.2 Adjusting sectoral TFP growth rates while maintaining the same aggregate rate

Here I wish to change one or more sectoral TFP growth rates to a predetermined value while maintaining the overall rate at its observed value. To see how to do this, start with the value added formula for aggregate TFP growth (equation (20)):

$$\mu = \sum_{i=1}^{N} v_i \mu_i^{VA} = \sum_{i=1}^{N} v_i \tilde{\mu}_i^{VA}$$

Here the $\tilde{\mu}_i^{VA}$ are the adjusted TFP growth rates which we need to find. Suppose that it is agreed that the growth rate of the *N*-th sector should be set equal to the aggregate growth rate μ, i.e. $\tilde{\mu}_N^{VA} = \mu$. (Similar formulas can be developed if we wish to set sector N's growth rate to some fraction of the aggregate rate.) Then we have

$$\begin{aligned}
\mu &= \sum_{i=1}^{N} v_i \mu_i^{VA} \\
&= \sum_{i=1}^{N-1} v_i \mu_i^{VA} + v_N \mu_N^{VA} \\
&= \sum_{i=1}^{N-1} v_i \mu_i^{VA} + (v_N \mu_N^{VA} - v_N \mu) + v_N \mu \quad \text{(adding and subtracting } v_N \mu\text{)} \\
&= \sum_{i=1}^{N-1} v_i \tilde{\mu}_i^{VA} + v_N \mu
\end{aligned}$$

So the adjusted growth rates are

$$\tilde{\mu}_i^{VA} = \mu_i^{VA} + \left(\frac{v_N}{1 - v_N} \right) (\mu_N^{VA} - \mu), \quad i = 1, ..., N-1 \tag{50}$$

If in addition we set the growth rate in sector *N*-1 equal to the aggregate rate, i.e. $\tilde{\mu}_{N-1}^{VA} = \mu$, then the adjusted growth rates in the other *N*-2 sectors are

$$\tilde{\mu}_i^{VA} = \mu_i^{VA} + \left(\frac{v_{N-1}}{1 - v_{N-1} - v_N} \right) (\mu_{N-1}^{VA} - \mu) + \left(\frac{v_N}{1 - v_{N-1} - v_N} \right) (\mu_N^{VA} - \mu), \quad i = 1, ..., N-2 \tag{51}$$

(Similar formulas can be developed if we wish to set sector N's growth rate to some fraction of the aggregate rate.)

TABLES

Table 1
The 18 countries in the EU KLEMS dataset for which TFP data are available

Code	*Country name*	*First year*	*Last year*	*Number of years*
AUS	Australia	1983	2007	25
AUT	Austria	1981	2007	27
BEL	Belgium	1981	2006	26
CZE	Czech Republic	1996	2007	12
DNK	Denmark	1981	2007	27
ESP	Spain	1981	2007	27
FIN	Finland	1971	2007	37
FRA	France	1981	2007	27
GER	Germany	1992	2007	16
HUN	Hungary	1996	2007	12
IRL	Ireland	1989	2007	19
ITA	Italy	1971	2007	37
JPN	Japan	1974	2006	33
NLD	Netherlands	1980	2007	28
SVN	Slovenia	1996	2006	11
SWE	Sweden	1994	2007	14
UK	United Kingdom	1971	2007	37
USA	United States	1978	2007	30

Source: EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note: The first and last years mark the period for which data on TFP growth are available for each country. TFP appears in EU KLEMS in level form so one year is lost in taking growth rates.

Table 2
Sectors of NACE, Revision 1

Sector code	*Sector description*	*Value added share of GDP, %*	*Share of total (whole economy) hours, %*
A & B	Agriculture, hunting and forestry. Fishing	4.3	8.3
C	Mining & quarrying	1.4	0.5
D	Manufacturing	22.1	21.1
E	Electricity, gas & water	2.4	0.9
F	Construction	6.6	8.0
G	Wholesale & retail trade; repair of motor vehicles, motorcycles, and personal and household goods	11.9	15.3
H	Hotels & restaurants	2.4	4.1
I	Transport, storage and communications	7.3	6.6
J	Financial intermediation	5.1	2.9
K (exc. 70)	Business services	7.1	7.0
L	Public administration & defence; compulsory social security	6.5	6.5
M	Education	5.0	5.3
N	Health & social work	6.1	7.8
O	Other community, social and personal services activities	3.3	4.0
P	Activities of private households as employers and undifferentiated production activities of private households	0.3	1.0
Q	Extraterritorial organisations and bodies	0.0	0.0
70	Real estate	8.2	0.9
A-K (exc. 70)	Market sector	70.6	74.6
A-Q	Whole economy (GDP)	100.0	100.0

Source EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note 10 sectors, A-K (exc. industry 70, real estate), make up my definition of the market sector. Shares of GDP and total hours worked are means across 18 countries and time (maximum span is 1970-2007). Official name of sector K (including real estate) is "Renting and business activities".

Table 3
Persistence of TFP growth (18 countries. 10 sectors within market sector, 1971-2007)
Dependent variable is growth of TFP (*TFPg*)

	(1) No lags	(2) One lag	(3) Two lags	(4) Three lags	(5) 1971-1990 One lag	(6) 1991-2007 One lag	(7) 1971-1990 Two lags	(8) 1991-2007 Two lags	(9) Market sector	(10) Time-averaged
Independent variables										
TFPg(-1)	—	0.0180	0.00546	-0.00169	0.0983*	-0.0394	0.0651	-0.0365	0.231***	—
		(0.0280)	(0.0275)	(0.0280)	(0.0572)	(0.0307)	(0.0612)	(0.0308)	(0.0549)	
TFPg(-2)	—	—	0.0259	0.0364	—	—	0.0406	0.00612	—	—
			(0.0318)	(0.0320)			(0.0635)	(0.0356)		
TFPg(-3)	—	—	—	0.0385*	—	—	—	—	—	—
				(0.0224)						
Observations	4,450	4,250	4,070	3,890	1,460	2,790	1,330	2,740	425	180
R-squared	0.057	0.059	0.062	0.065	0.101	0.055	0.106	0.054	0.325	0.473
F-test for industry dummies	30.61	23.45	19.16	16.61	8.413	16.63	7.29	14.52	—	23.07
Probability > F	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000
F-test for country dummies	1.827	1.812	1.43	1.22	1.670	2.37	0.82	2.01	1.83	1.76
Probability > F	0.0200	0.0215	0.1140	0.2397	0.0676	0.0013	0.6246	0.0084	0.0236	0.0388
F-test for year dummies	2.166	2.220	2.70	2.57	2.14	1.85	2.86	1.98	3.60	—
Probability > F	0.0000	0.0001	0.0000	0.0000	0.0037	0.0209	0.0001	0.0113	0.0000	

Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1.

Source EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note OLS estimates. Constant and dummies for country, industry and year included but not reported. Robust standard errors. Column 10, time-averaged: the time mean of TFP growth in each of 10 industries within the market sector is regressed on country and industry dummies, i.e. 10 observations for each of 18 countries.

Table 4
Standard deviations of TFP and its components

Variables (growth rates, % p.a.)	10 industry groups (*N*=4,450)	Market sector (*N*=445)
TFP	6.52	1.91
Real value added per hour	6.97	2.03
Capital deepening contribution	2.48	0.99
Nominal value added	9.01	4.61
Price of value added	7.85	4.18
Real value added	6.64	2.61
Hours worked	4.66	2.24

Source EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note Capital deepening contribution is calculated as labour productivity growth *less* TFP growth and includes human as well as physical capital (labour quality).

Table 5
Change in Domar weights between first year and last year

	Sections			
Countries	A-F	G,H	I,J,K	Sum
Australia	-0.255	0.151	0.227	0.123
Austria	-0.086	0.035	0.275	0.224
Belgium	-0.104	0.117	0.371	0.384
Czech Republic	0.179	0.005	0.124	0.308
Denmark	-0.308	-0.024	0.369	0.037
Spain	-0.525	0.050	0.192	-0.283
Finland	-0.022	0.050	0.272	0.300
France	-0.290	0.062	0.297	0.069
Germany	0.130	-0.008	0.177	0.299
Hungary	0.152	0.011	0.086	0.249
Ireland	-0.246	-0.027	0.306	0.033
Italy	0.003	0.182	0.369	0.554
Japan	-0.507	0.042	0.222	-0.243
Netherlands	-0.356	0.065	0.268	-0.023
Slovenia	-0.043	-0.017	0.090	0.030
Sweden	0.054	0.011	0.079	0.144
United Kingdom	-0.697	0.118	0.452	-0.127
United States	-0.458	0.003	0.300	-0.155
Mean	*-0.188*	*0.046*	*0.249*	*0.107*
No. negative	*13*	*4*	*0*	*5*

Note The first and last years for each country are given in Table 1.

Table 6
Effect of structural change on TFP growth in the market sector, % p.a.

		No TFP adjustments		Only sector K adjusted		Sectors J and K adjusted		Change in TFP growth due to structural change			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Country	Actual structure	Initial structure	Latest structure	Initial structure	Latest structure	Initial structure	Latest structure	No TFP adjust-ments	Only Sector K adjusted	Sectors J and K adjusted	Sector K adjusted to half MS rate
Australia	0.79	0.75	0.60	0.68	0.67	0.71	0.72	-0.15	-0.01	0.01	-0.03
Austria	1.58	1.80	1.69	1.66	1.79	1.61	1.79	-0.11	0.13	0.18	0.06
Belgium	0.40	0.55	0.39	0.50	0.45	0.54	0.47	-0.16	-0.05	-0.07	-0.08
Czech Republic	1.30	1.06	1.42	1.04	1.44	1.08	1.48	0.36	0.40	0.4	0.39
Denmark	0.68	0.76	0.95	0.68	0.99	0.73	0.97	0.19	0.31	0.24	0.28
Spain	0.23	0.33	-0.14	0.28	0.04	0.29	0.03	-0.47	-0.24	-0.26	-0.25
Finland	1.94	2.02	1.90	1.88	2.06	1.85	2.03	-0.12	0.18	0.18	0.10
France	1.07	1.17	1.02	1.08	1.16	1.06	1.17	-0.15	0.08	0.11	0.03
Germany	0.63	0.71	0.69	0.60	0.75	0.57	0.74	-0.02	0.15	0.17	0.14
Hungary	2.55	2.50	2.58	2.50	2.66	2.52	2.67	0.08	0.16	0.15	0.13
Ireland	1.96	1.70	1.72	1.79	1.92	2.04	1.95	0.02	0.13	-0.09	0.10
Italy	0.61	0.76	0.44	0.71	0.54	0.71	0.62	-0.32	-0.17	-0.09	-0.21
Japan	1.43	1.50	1.36	1.44	1.46	1.47	1.44	-0.14	0.02	-0.03	-0.04
Netherlands	0.81	0.83	0.72	0.75	0.83	0.74	0.86	-0.11	0.08	0.12	0.05
Slovenia	1.74	1.85	1.65	1.82	1.65	1.83	1.66	-0.20	-0.17	-0.17	-0.19
Sweden	1.50	1.45	1.54	1.38	1.63	1.42	1.59	0.09	0.25	0.17	0.19
United Kingdom	0.91	1.17	0.66	1.11	0.78	1.1	0.88	-0.51	-0.33	-0.22	-0.42
United States	0.72	1.07	0.49	0.94	0.57	0.86	0.71	-0.58	-0.37	-0.15	-0.42

Table 6, continued

Unweighted mean	1.16	1.22	1.09	1.16	1.19	1.17	1.21	-0.13	0.03	0.04	-0.05

Source EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note Column headed "Actual structure": annual TFP growth calculated using the actual, annually-changing weights. Columns headed "Initial structure": annual TFP growth calculated using the average of the Domar weights of the *first* two available years. Columns headed "Latest structure": annual TFP growth calculated using the average of the Domar weights of the *last* two available years. "Only sector K adjusted" (columns 4, 5 and 9): for each year and country, TFP growth rate of sector K (Business services) set equal to TFP growth rate in the market sector in that year and country; other sector growth rates adjusted to maintain the original market sector growth rate. "Sectors J and K adjusted" (columns 6, 7 and 10): for each year and country, TFP growth rate of both sector J (Financial intermediation) and sector K (Business services) set equal to TFP growth rate in the market sector in that year and country; other sector growth rates adjusted to maintain the original market sector growth rate. Column 11: for each year and country, TFP growth rate of sector K (Business services) set to *half* TFP growth rate in the market sector in that year and country; other sector growth rates adjusted to maintain the original market sector growth rate. "Change in TFP growth due to structural change": TFP growth with latest structure *minus* growth with initial structure. For each country, TFP growth averaged over the period for which TFP growth is available (see Table 1).

Table 7
Contribution of each sector to the effect of structural change on TFP growth, by country
(TFP growth in business services set equal to market sector rate)

Country	*Sectors*										
	A&B	C	D	E	F	G	H	I	J	K	*Total*
Australia	-0.09	0.00	-0.04	-0.01	0.00	0.04	-0.01	0.01	0.04	0.04	*-0.01*
Austria	-0.13	0.01	-0.03	0.04	0.01	0.01	0.00	0.06	0.00	0.15	*0.13*
Belgium	-0.04	0.01	0.00	-0.01	-0.01	-0.09	-0.01	0.02	0.04	0.05	*-0.05*
Czech Republic	-0.04	0.01	0.24	0.04	0.01	0.05	0.07	-0.02	0.02	0.03	*0.40*
Denmark	-0.15	0.25	0.00	0.00	0.00	-0.02	0.00	0.07	0.08	0.06	*0.31*
Spain	-0.15	0.00	-0.05	-0.01	-0.01	-0.02	-0.04	0.00	0.02	0.01	*-0.24*
Finland	-0.31	0.00	0.15	0.00	0.00	0.04	-0.01	0.06	0.06	0.18	*0.18*
France	-0.08	0.02	-0.06	0.02	0.00	0.04	-0.03	0.07	0.00	0.11	*0.08*
Germany	-0.02	-0.01	0.05	0.01	0.04	0.00	0.01	0.06	-0.01	0.04	*0.15*
Hungary	-0.21	-0.01	0.22	-0.01	0.00	0.01	0.00	0.04	0.04	0.07	*0.16*
Ireland	-0.18	0.01	-0.09	0.01	-0.05	-0.05	0.00	0.00	0.43	0.08	*0.13*
Italy	-0.27	0.00	0.04	-0.01	0.01	0.02	-0.05	0.09	-0.06	0.06	*-0.17*
Japan	-0.01	0.00	-0.23	0.02	0.04	0.05	-0.03	0.03	0.08	0.09	*0.02*
Netherlands	-0.06	0.06	-0.09	0.00	0.01	0.06	0.00	0.04	0.00	0.07	*0.08*
Slovenia	-0.10	-0.03	-0.03	-0.01	0.00	-0.01	0.00	-0.02	0.00	0.03	*-0.17*
Sweden	-0.04	-0.01	0.13	0.01	0.00	0.02	0.00	0.00	0.03	0.09	*0.25*
United Kingdom	-0.06	-0.03	-0.44	0.00	0.01	0.00	-0.01	0.07	-0.04	0.16	*-0.33*
United States	-0.06	0.00	-0.26	0.00	0.01	-0.01	0.00	0.00	-0.12	0.09	*-0.37*
Mean	*-0.11*	*0.02*	*-0.03*	*0.01*	*0.00*	*0.01*	*-0.01*	*0.03*	*0.03*	*0.08*	*0.03*

Source EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net) and own calculations.
Note See text and note to Table 6. The rightmost column here is the same as column (9) of Table 6.

Table 8
Mean growth rates of TFP, labour productivity (*LP*), labour quality (*LQ*) and capital per hour (*KH*) in the market sector, % p.a.

Country	*Period*	*TFP*	*LQ*	*LP*	*KH*	*LP_ Solow*	*(4) minus (6)*	*(5) minus (4)*	*Capital share*	*γ*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Australia	1983-2007	0.79	0.25	2.12	2.98	1.43	0.69	0.86	0.354	0.626
Austria	1981-2007	1.58	0.30	2.70	2.55	2.69	0.01	-0.15	0.332	0.938
Belgium	1981-2006	0.40	0.43	2.27	4.77	1.03	1.24	2.50	0.328	0.386
Czech Republic	1996-2007	1.30	0.45	3.92	5.57	2.61	1.31	1.65	0.408	0.623
Denmark	1981-2007	0.68	0.33	2.30	4.58	1.30	1.00	2.28	0.295	0.432
Spain	1981-2007	0.23	0.55	1.98	3.39	0.91	1.07	1.41	0.360	0.423
Finland	1971-2007	1.94	0.63	3.86	4.50	3.49	0.37	0.64	0.289	0.719
France	1981-2007	1.07	0.57	2.59	3.41	2.01	0.58	0.82	0.264	0.591
Germany	1992-2007	0.63	0.06	1.89	4.73	0.94	0.95	2.84	0.271	0.386
Hungary	1996-2007	2.55	0.71	3.93	1.82	4.85	-0.92	-2.11	0.391	1.770
Ireland	1989-2007	1.96	0.03	3.88	3.61	3.48	0.40	-0.27	0.447	1.066
Italy	1971-2007	0.61	0.12	2.07	3.98	0.92	1.15	1.91	0.260	0.489
Japan	1974-2006	1.43	0.56	3.48	4.25	2.70	0.78	0.77	0.343	0.688
Netherlands	1980-2007	0.81	0.37	1.78	2.24	1.58	0.20	0.46	0.315	0.631
Slovenia	1996-2006	1.74	0.74	5.24	3.46	2.90	2.34	-1.78	0.204	1.304
Sweden	1994-2007	1.50	0.40	3.48	4.94	2.62	0.86	1.46	0.323	0.624
United Kingdom	1971-2007	0.91	0.43	2.47	4.78	1.74	0.73	2.31	0.285	0.427
United States	1978-2007	0.72	0.33	2.07	3.67	1.40	0.67	1.60	0.315	0.475
Cross-country mean		1.16	0.40	2.89	3.85	2.14	0.75	0.96	0.321	0.700

Source EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).

Table 8, continued

Note LP: real value added per hour worked. LQ: labour quality (labour services per hour worked, LAB_QPH in EU KLEMS). LP_Solow: TFP growth divided by labour share (estimated as LAB/VA in terms of EU KLEMS variables) plus the growth of labour quality. For each country, growth rates are Törnqvist indices built up from sectoral growth rates and are averaged over the period for which TFP growth is available: see Table 1. Capital share (col. 9): 1 minus labour share. The parameter γ (col. 10) is the hypothetical elasticity of output with respect to capital which would reduce TFP growth to zero: see equation (28).

Table 9
Does the growth of capital deepening depend on the growth of TFP (*TFPg*)?
Dependent variable is the growth rate of capital services per hour (*KHg*)

A. Original growth rates

	(1)	(2)	(3)	(4)	(5)
Independent variables					
KHg(-1)	0.390***	0.337***	0.481***	0.478***	0.623***
	(0.144)	(0.0786)	(0.0433)	(0.0428)	(0.0413)
TFPg	-0.0563	0.0459	0.0767		
	(0.0748)	(0.0676)	(0.0670)		
TFPg(-1)		-0.285***	-0.250***	-0.232***	-0.176***
		(0.0489)	(0.0475)	(0.0465)	(0.0541)
TFPg(-2)			-0.0706	-0.0785	0.0807
			(0.0565)	(0.0583)	(0.0578)
Observations	434	425	407	407	407
R-squared	0.377	0.567	0.604	0.601	0.428
F-test for country dummies	1.193	2.641	3.385	3.611	–
Prob > F	0.267	0.000445	0	2.45e-06	
F-test for year dummies	2.612	3.589	4.110	4.361	–
Prob > F	4.27e-06	4.13e-10	8.51e-06	0	

B. Growth rates of HP trends

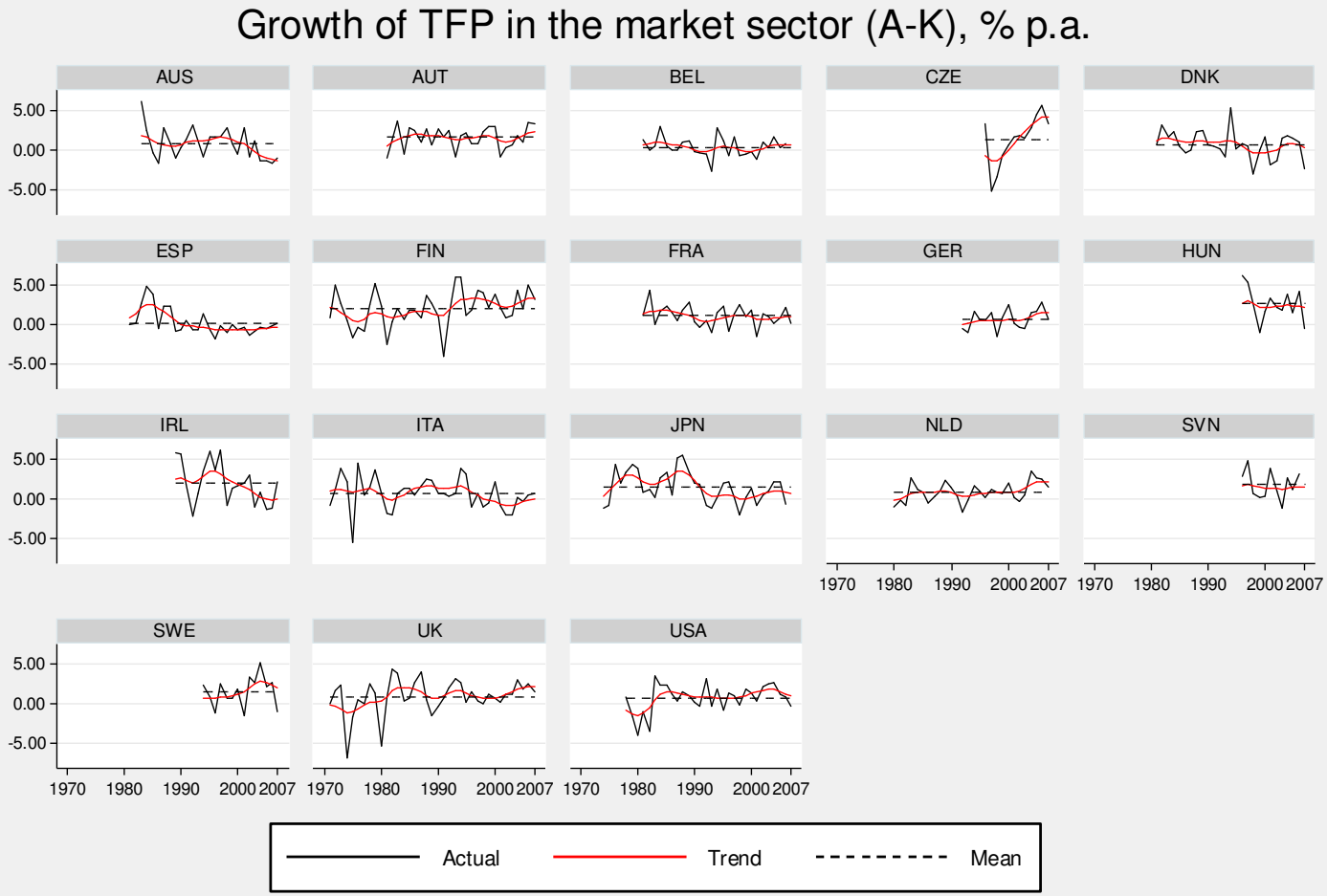
	(1)	(2)	(3)	(4)	(5)
Independent variables					
KHg(-1)	0.919***	0.919***	0.919***	0.919***	0.960***
	(0.0161)	(0.0161)	(0.0157)	(0.0157)	(0.0125)
TFPg	-0.0670**	-0.206**	0.121		
	(0.0263)	(0.0834)	(0.144)		
TFPg(-1)		0.146*	-0.520*	-0.317***	-0.481***
		(0.0800)	(0.266)	(0.0862)	(0.0854)
TFPg(-2)			0.384***	0.288***	0.526***
			(0.148)	(0.0840)	(0.0827)
Observations	412	412	412	412	412
R-squared	0.965	0.965	0.966	0.966	0.947
F-test for country dummies	5.496	4.661	4.671	4.498	–
Prob > F	5.50e-11	6.44e-09	0	1.62e-08	
F-test for year dummies	4.930	3.974	4.069	4.119	–
Prob > F	0	0	6.11e-09	0	

Source EU KLEMS, March 2011 update of the November 2009 release (www.euklems.net).
Note *KHg*: Growth rate of capital services per hour; *TFPg*: growth rate of TFP, both for the market sector. Growth rates of HP trends: growth rates of Hodrick-Prescott smoothed levels setting λ parameter to 6.25. Panel regression estimated by OLS with 18 countries over a maximum time span of 1971-2007. Constant and year and country dummies included but coefficients not reported. Robust standard errors in parentheses. *** p<0.01, ** p<0.05. * p<0.10.

CHARTS

Chart 1	Growth of TFP in the market sector, by country
Chart 2	Mean TFP growth rates in the market sector, by country
Chart 3	Mean TFP growth rates: 18 countries and 10 industry groups
Chart 4a	Value added share of sector A&B in market sector GDP, by country
Chart 4b	Value added share of sector D in market sector GDP, by country
Chart 4c	Value added share of sector F in market sector GDP, by country
Chart 4d	Value added share of sector G in market sector GDP, by country
Chart 4e	Value added share of sector H in market sector GDP, by country
Chart 4f	Value added share of sector J in market sector GDP, by country
Chart 4g	Value added share of sector K (exc. 70) in market sector GDP, by country
Chart 5	Sum of Domar weights, by country
Chart 6a	Domar weight for sector D, by country
Chart 6b	Domar weight for sector J, by country
Chart 6c	Domar weight for sector K (exc. 70)

Chart 1



Source: EU KLEMS.
Note: Trend growth rate is that of HP-smoothed TFP level. Dashed lines denote country means of actual TFP growth rate.

Chart 2
Mean TFP growth rates in the market sector , % p.a.

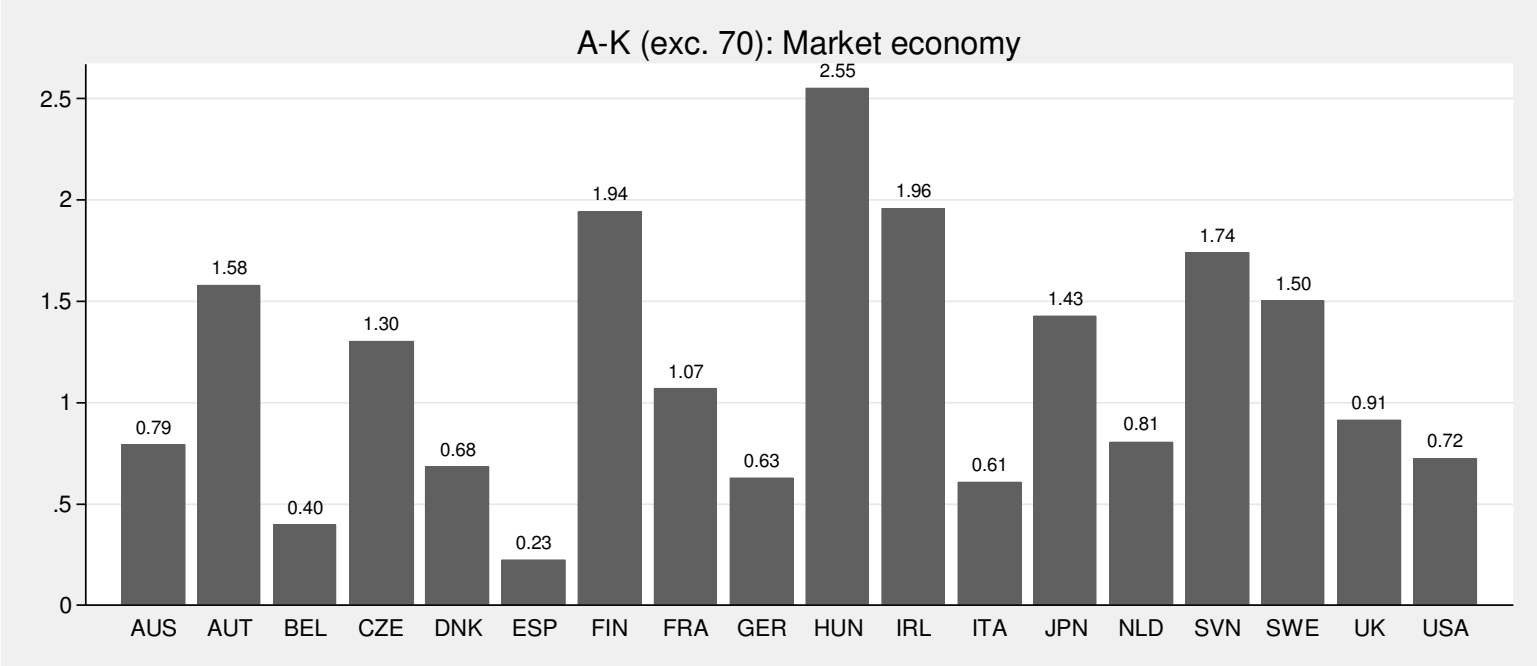


Chart 3

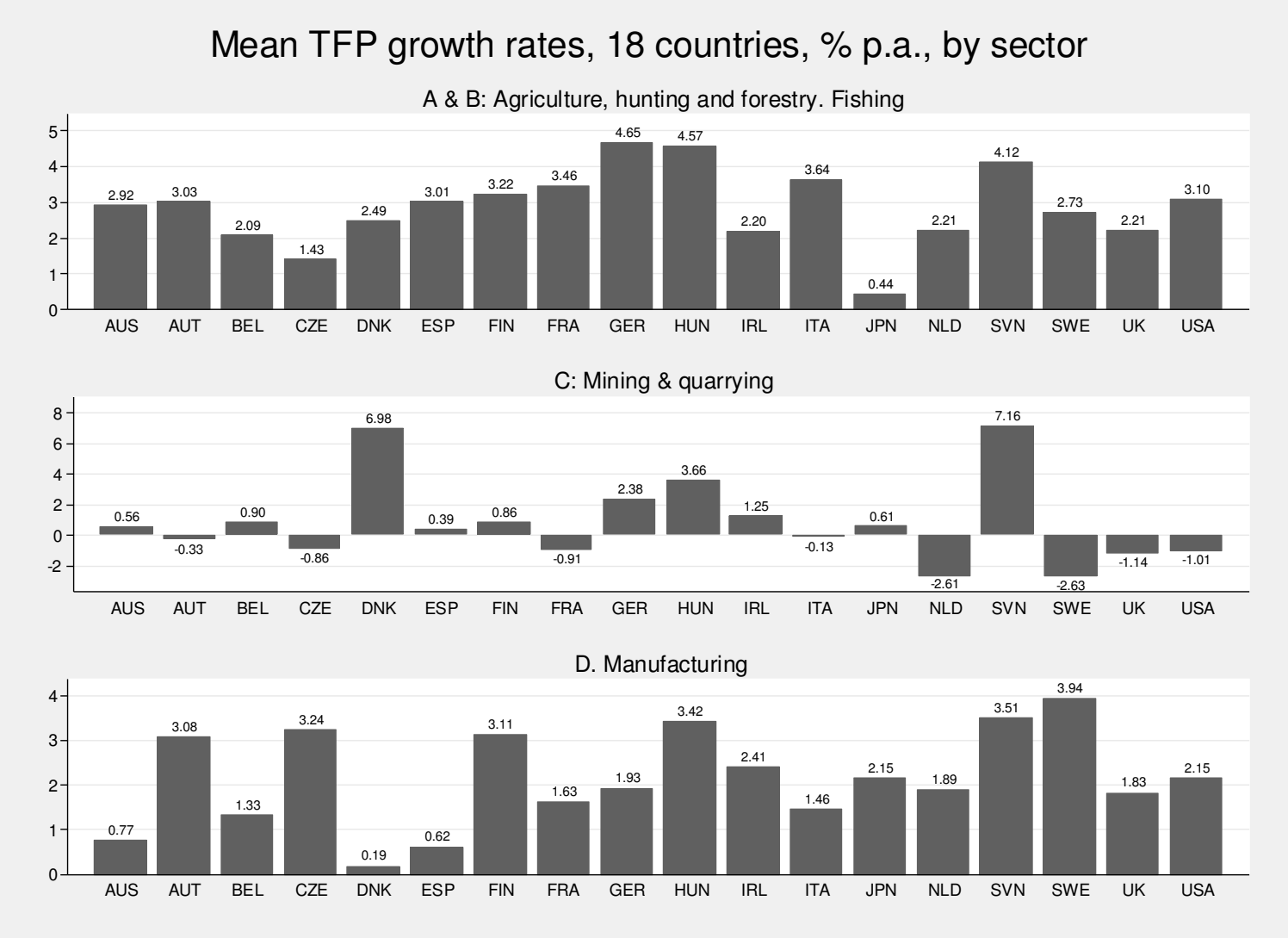

Mean TFP growth rates, 18 countries, % p.a., by sector
A & B: Agriculture, hunting and forestry. Fishing
2.92
3.03
2.09
1.43
2.49
3.01
3.22
3.46
4.65
4.57
2.20
3.64
0.44
2.21
4.12
2.73
2.21
3.10
AUS AUT BEL CZE DNK ESP FIN FRA GER HUN IRL ITA JPN NLD SVN SWE UK USA
C: Mining & quarrying
0.56
-0.33
0.90
-0.86
6.98
0.39
0.86
-0.91
2.38
3.66
1.25
-0.13
0.61
-2.61
7.16
-2.63
-1.14
-1.01
AUS AUT BEL CZE DNK ESP FIN FRA GER HUN IRL ITA JPN NLD SVN SWE UK USA
D. Manufacturing
0.77
3.08
1.33
3.24
0.19
0.62
3.11
1.63
1.93
3.42
2.41
1.46
2.15
1.89
3.51
3.94
1.83
2.15
AUS AUT BEL CZE DNK ESP FIN FRA GER HUN IRL ITA JPN NLD SVN SWE UK USA

Chart 3, continued

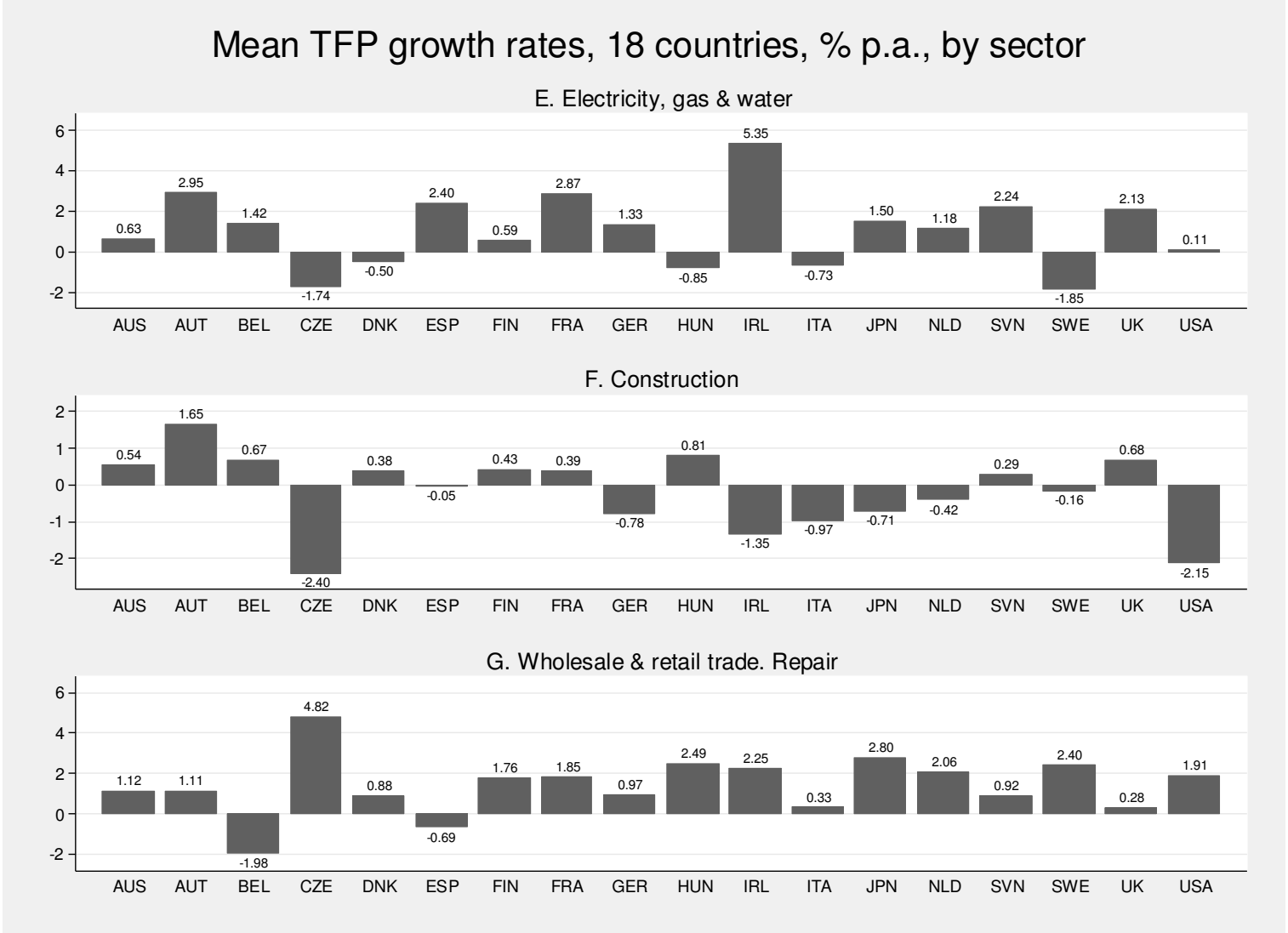


Chart 3, continued

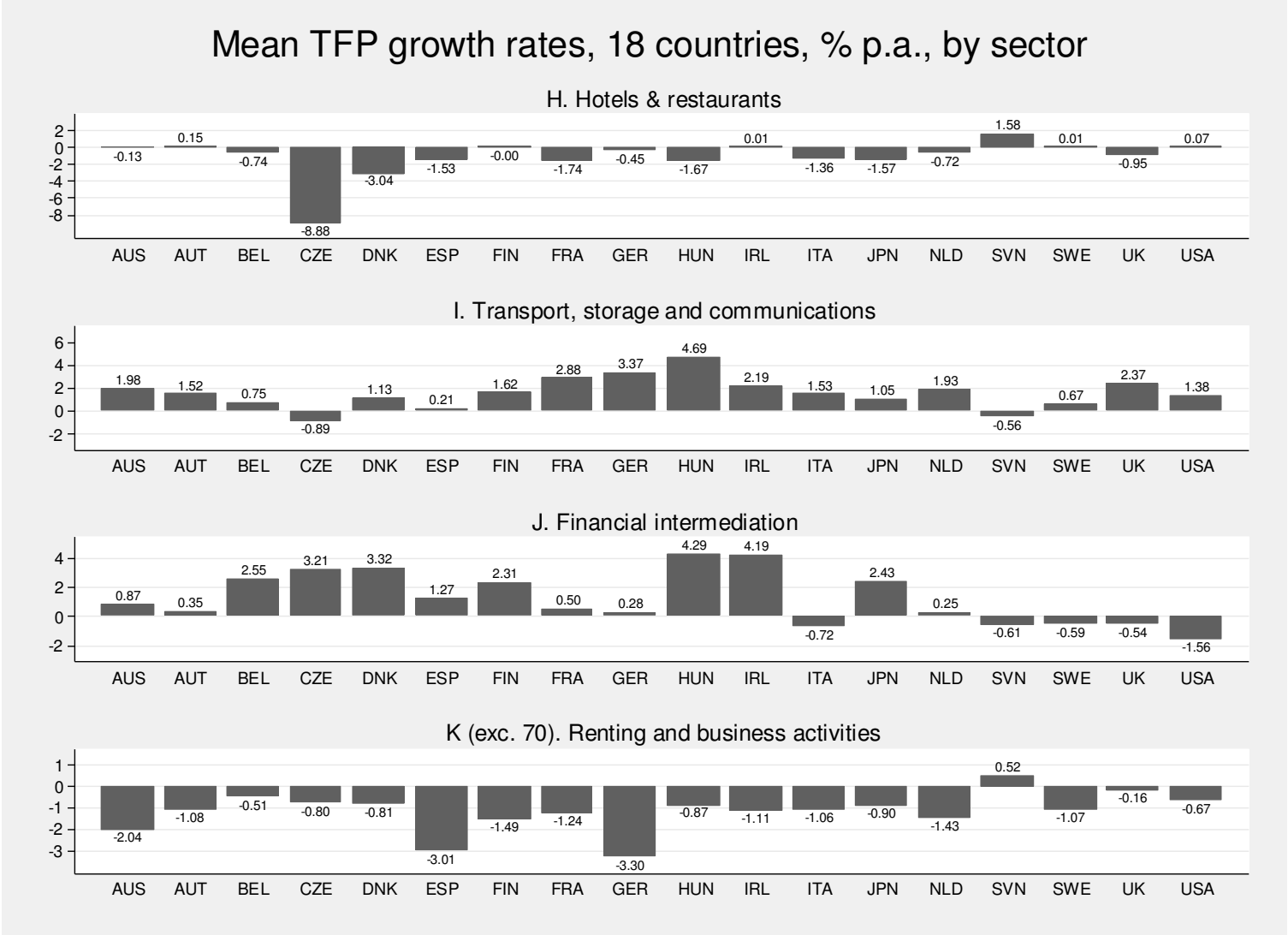
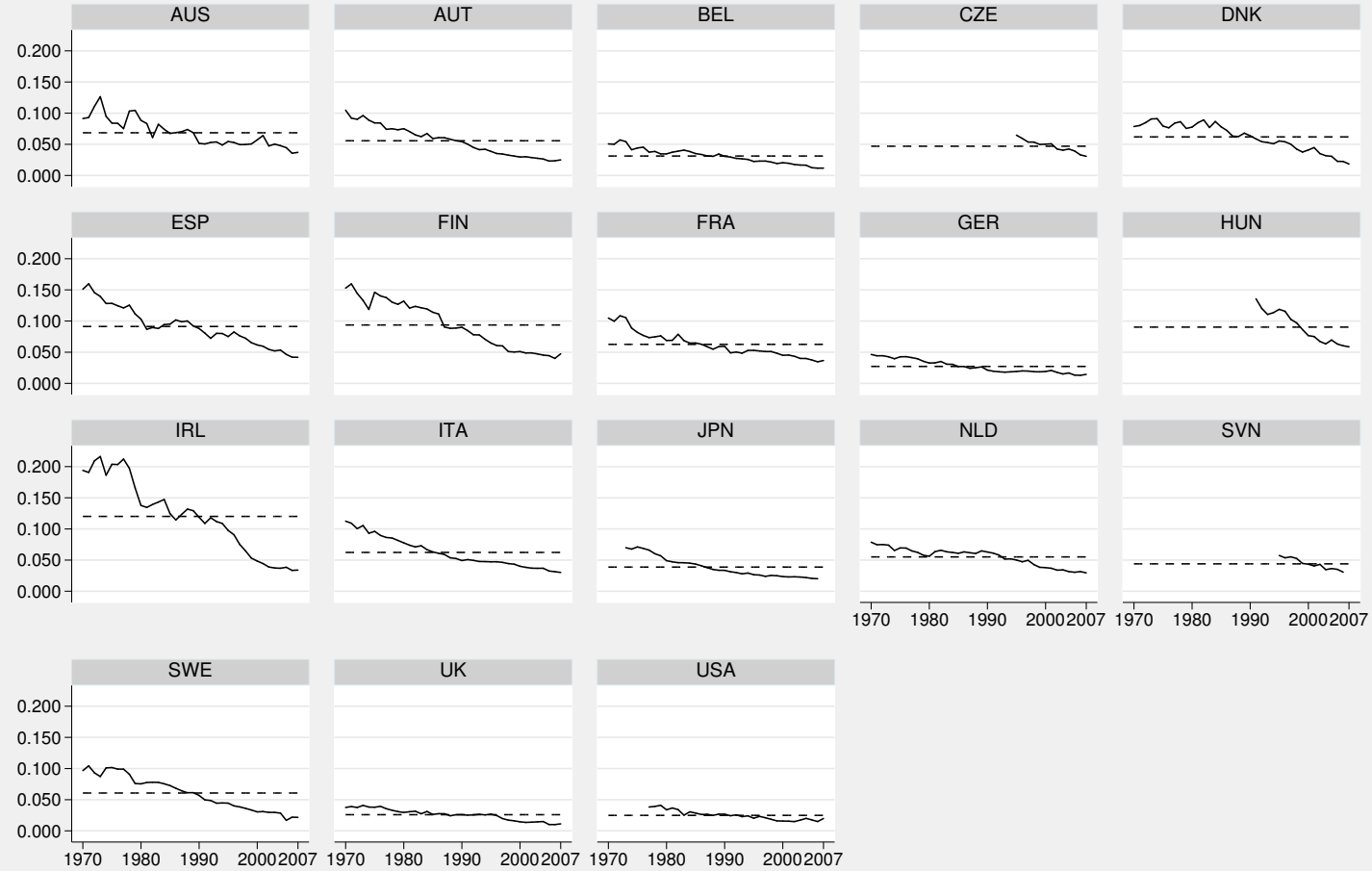
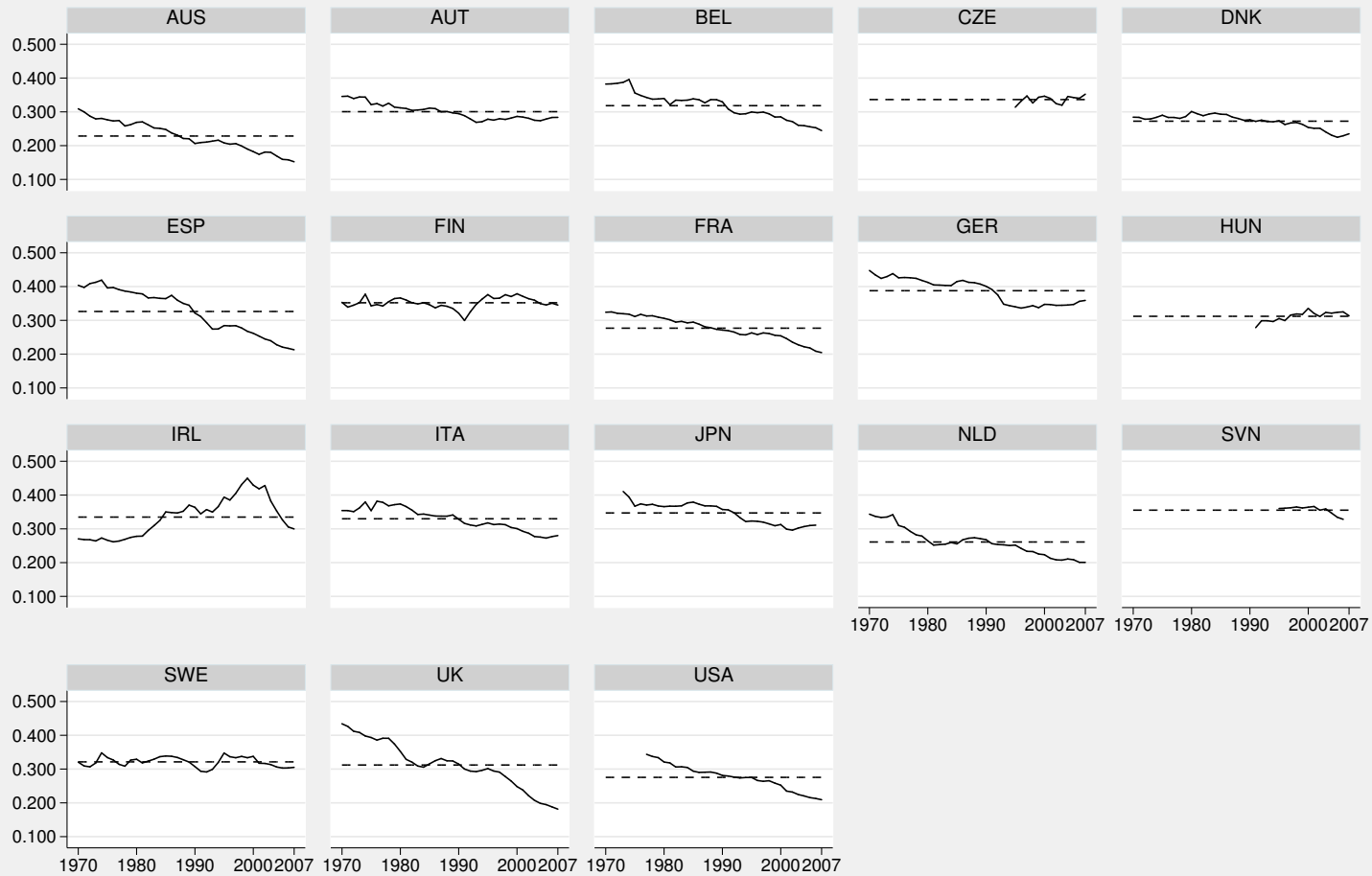


Chart 4a



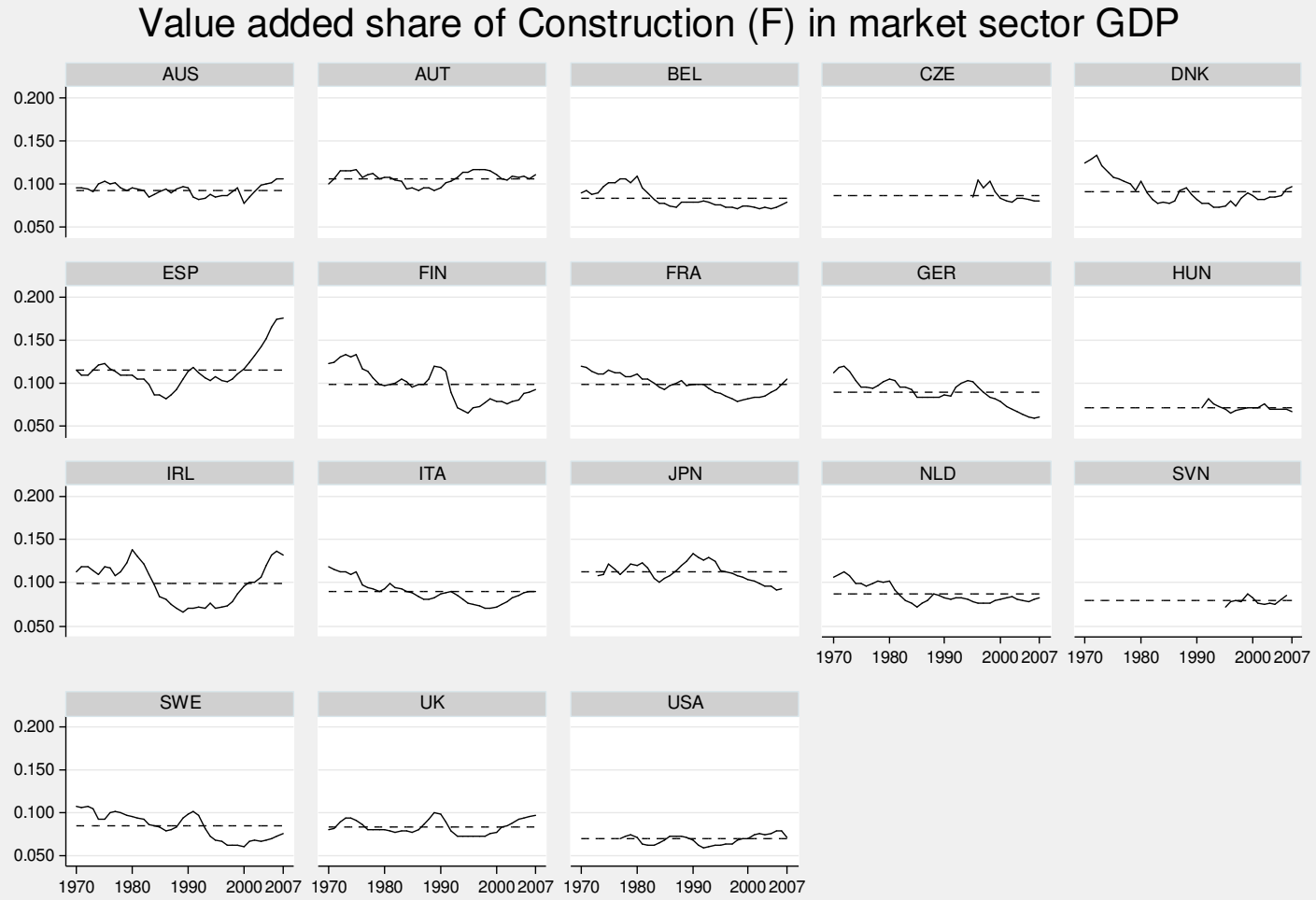
Source: EU KLEMS. Note: Dashed lines denote country means.

Chart 4b



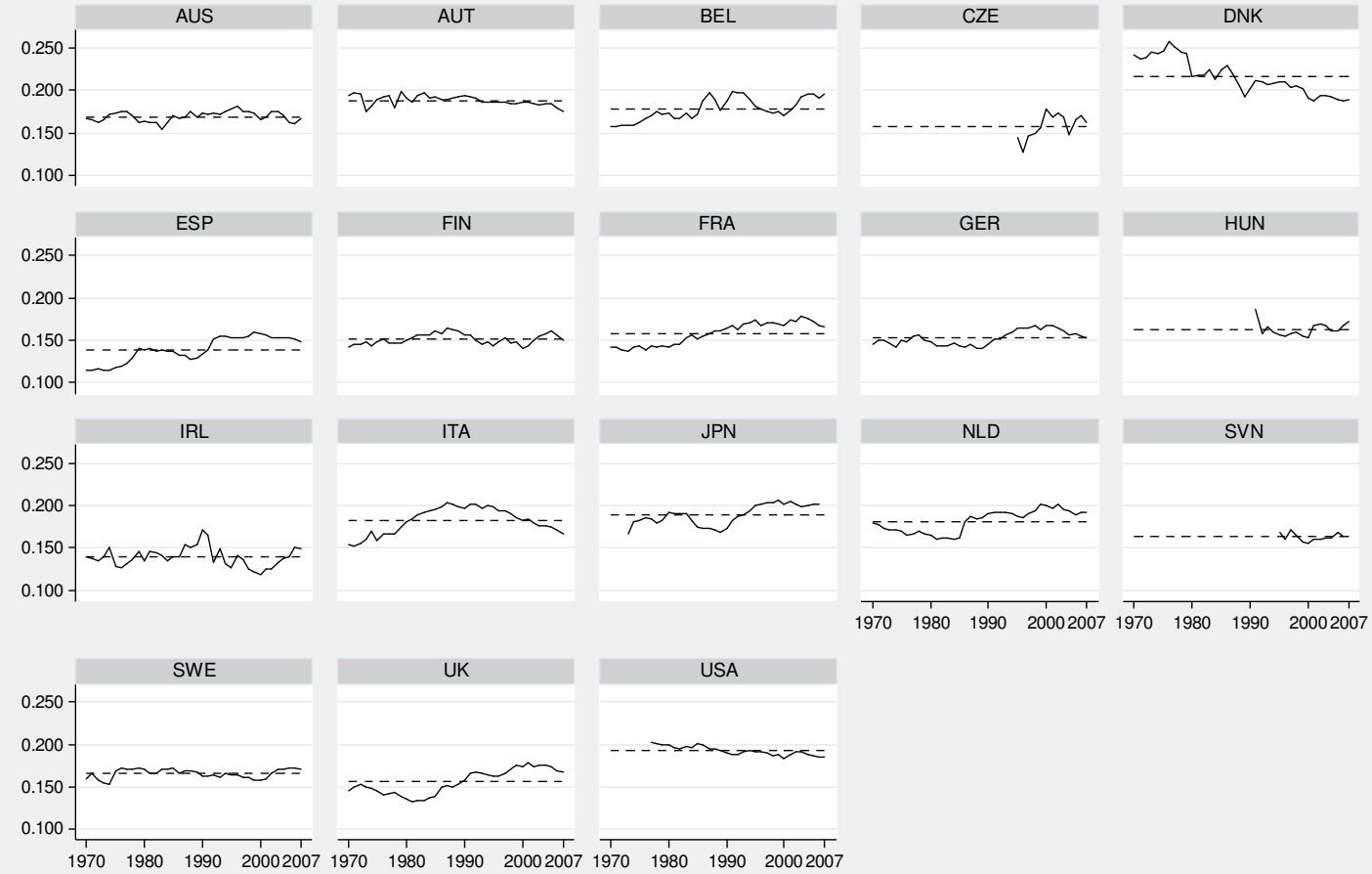
Source: EU KLEMS. Note: Dashed lines denote country means.

Chart 4c



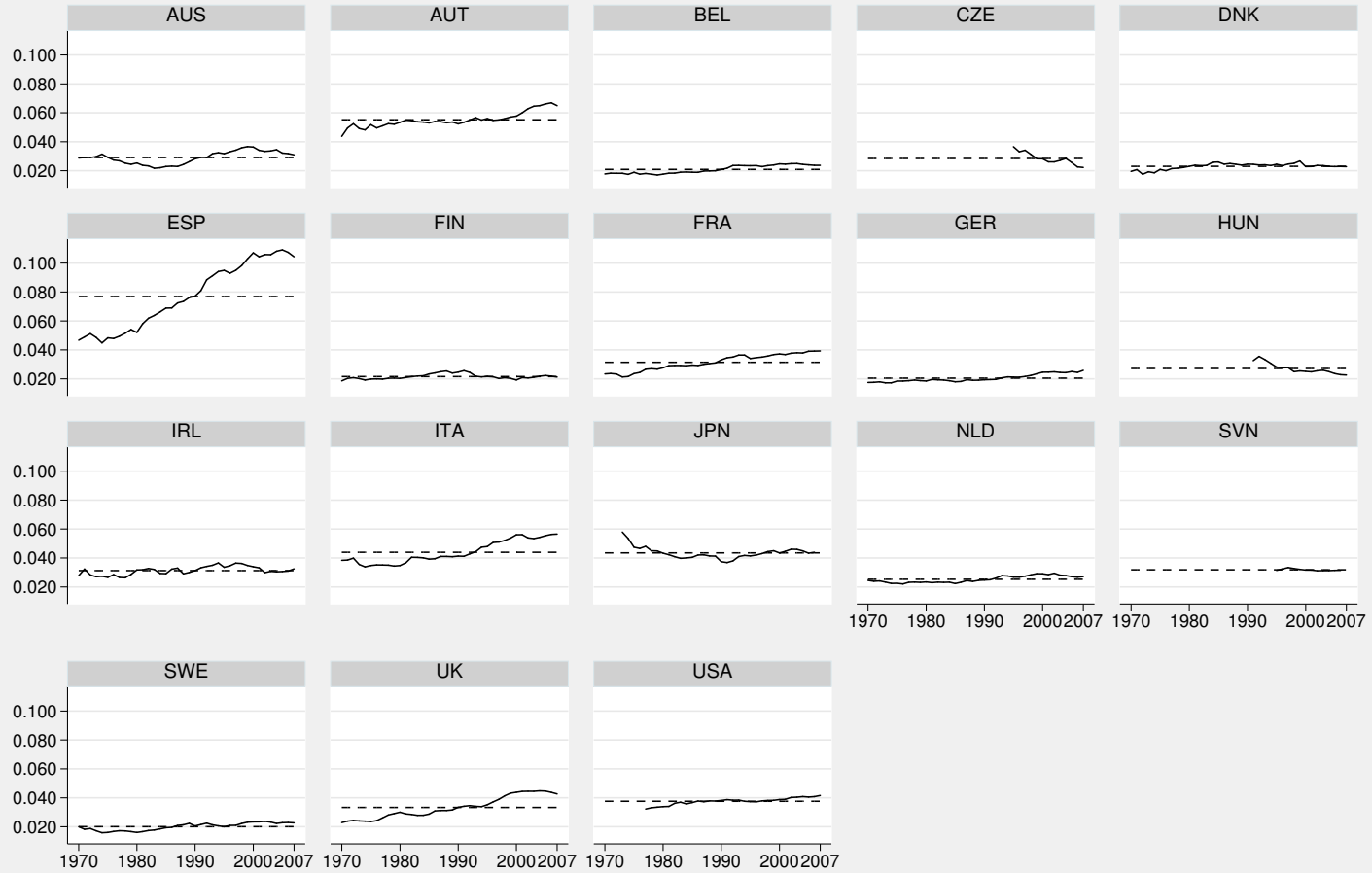
Source: EU KLEMS. Note: Dashed lines denote country means.

Chart 4d



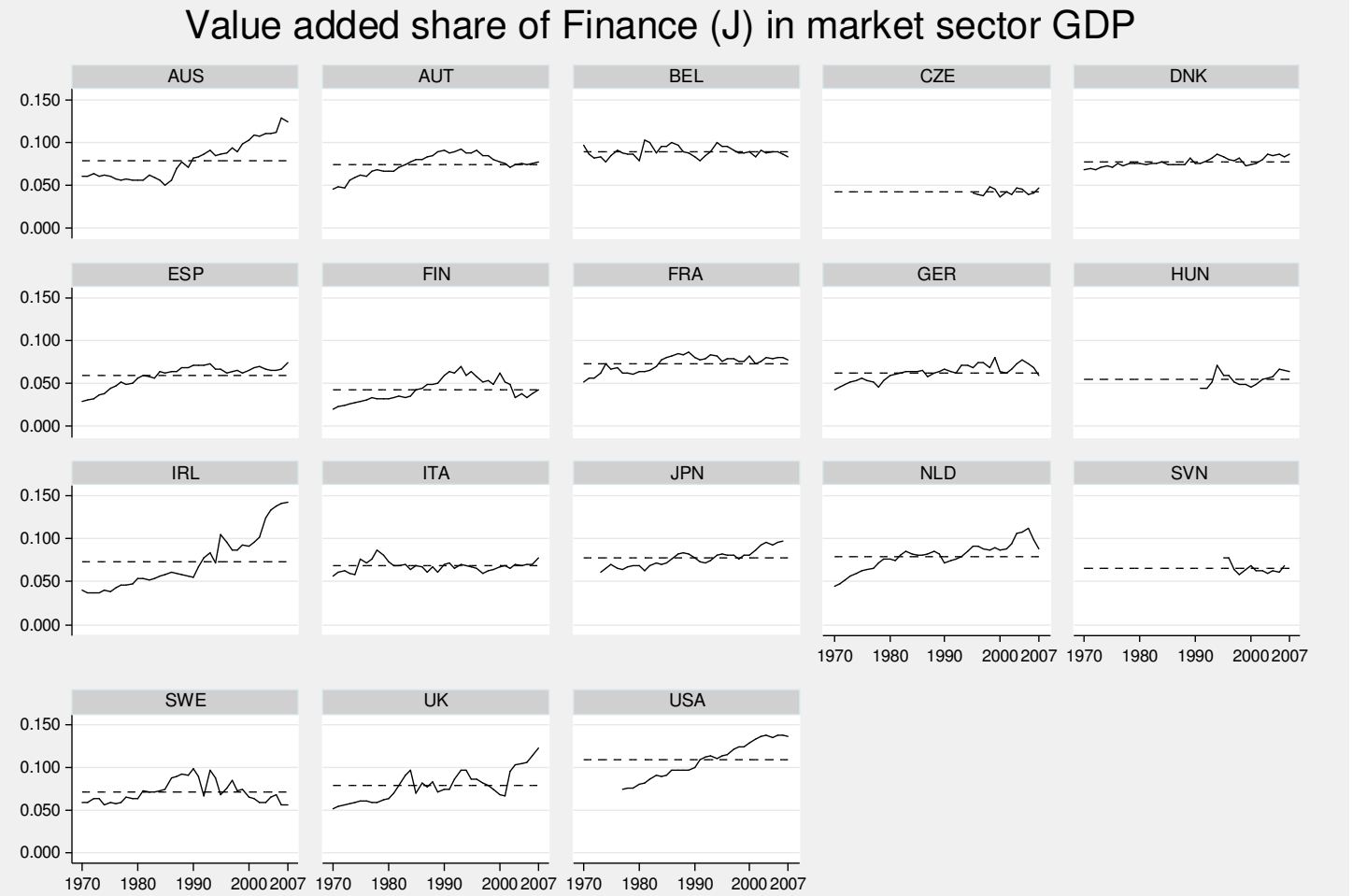
Source: EU KLEMS. Note: Dashed lines denote country means.

Chart 4e



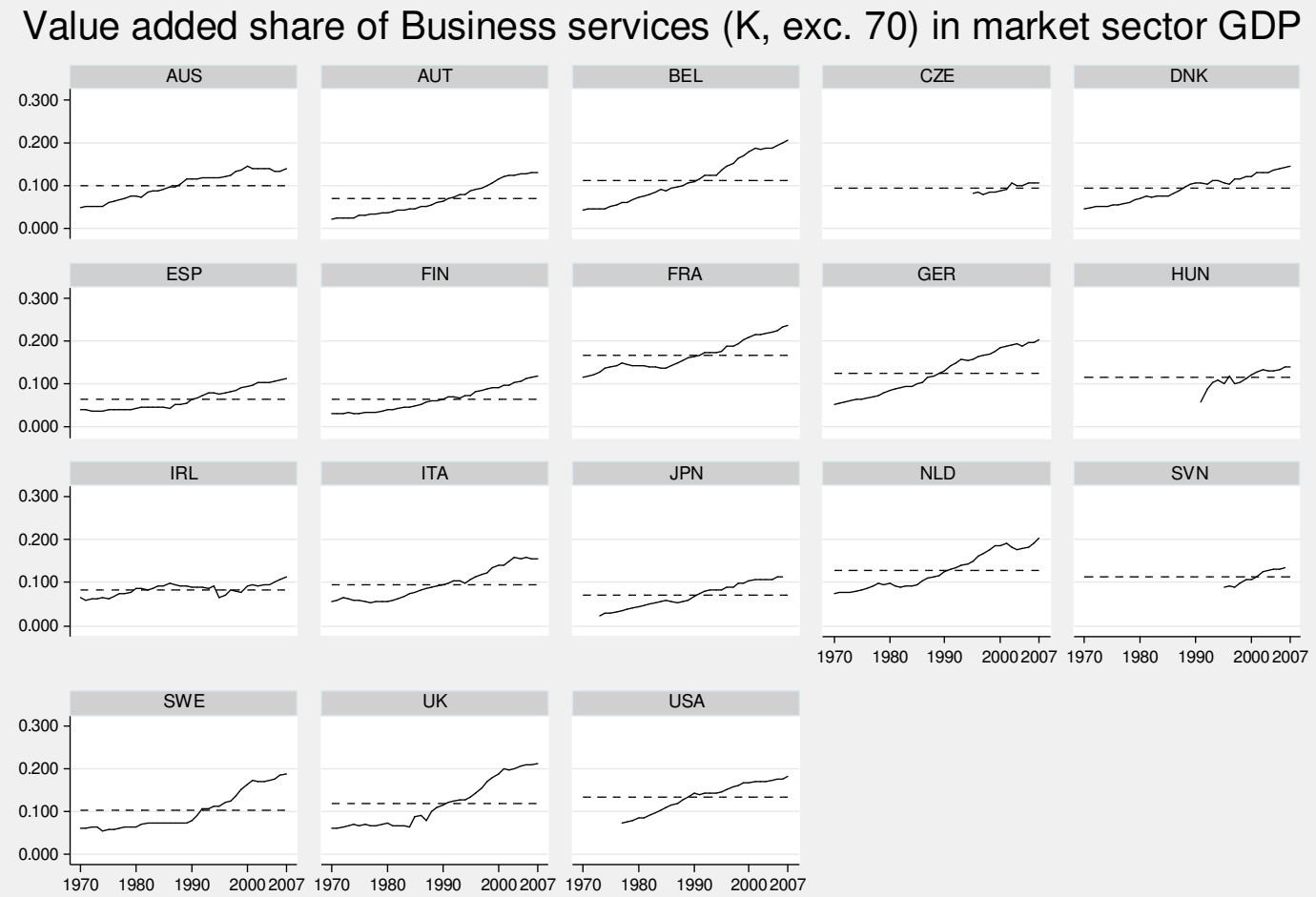
Source: EU KLEMS. Note: Dashed lines denote country means.

Chart 4f



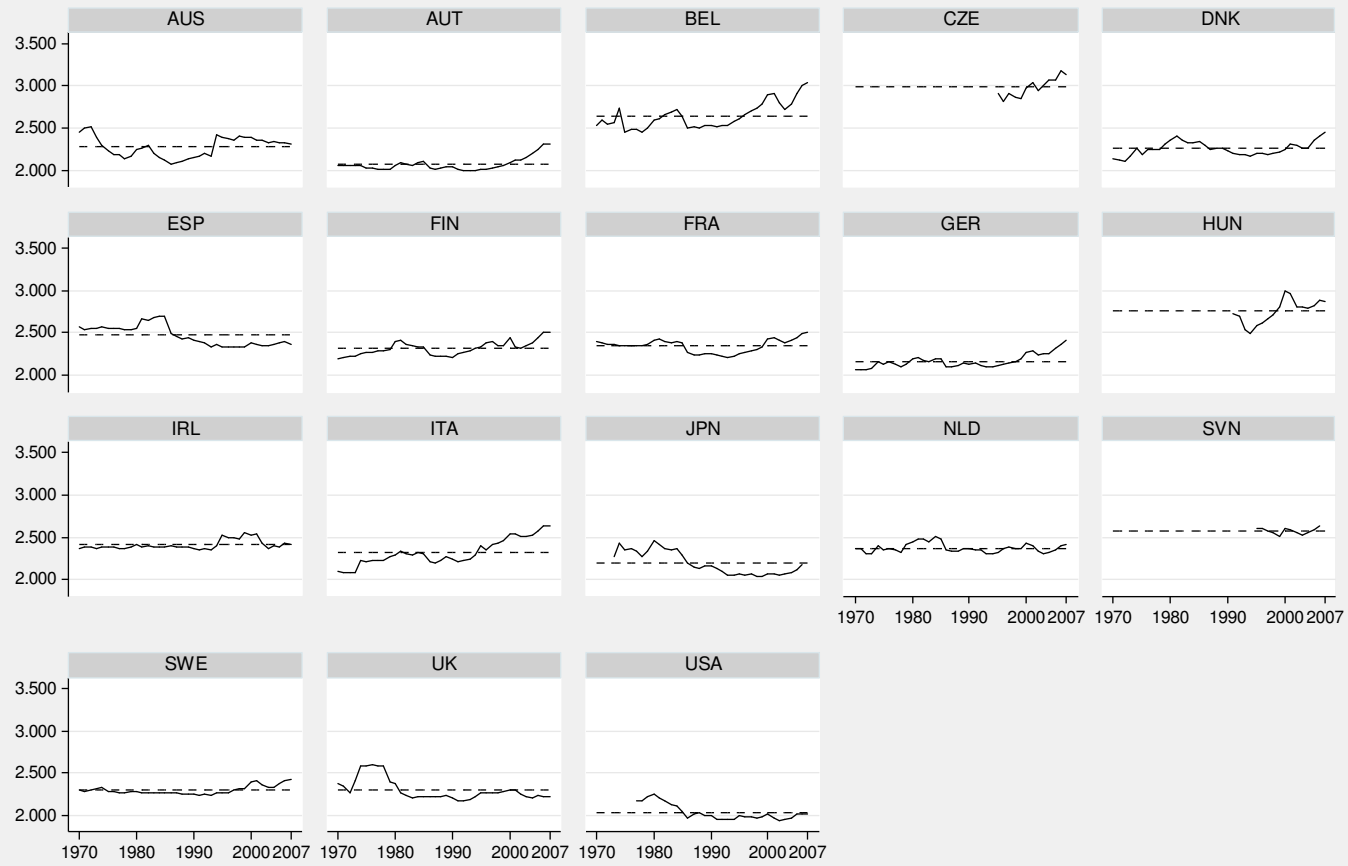
Source: EU KLEMS. Note: Dashed lines denote country means.

Chart 4g



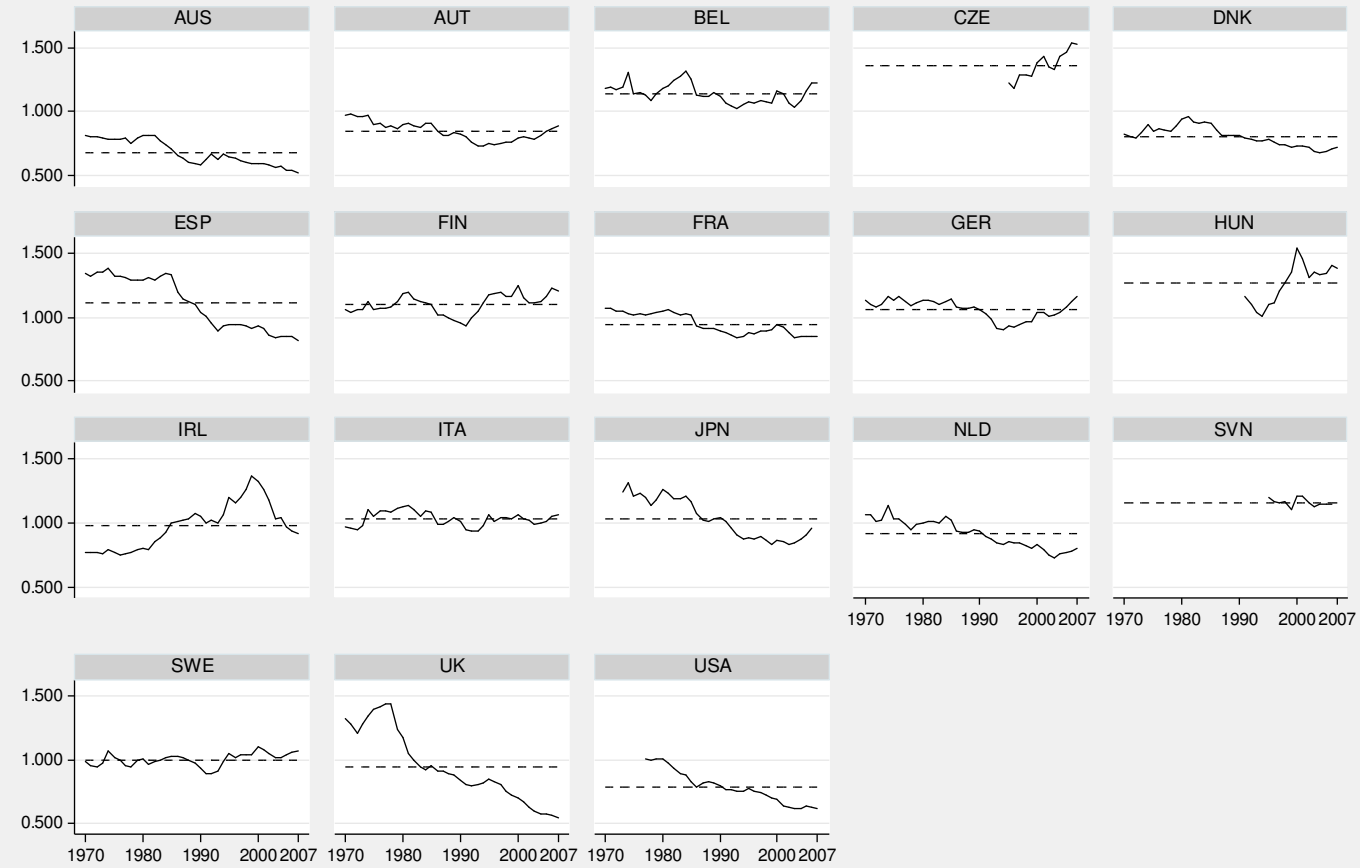
Source: EU KLEMS. Note: Dashed lines denote country means.

Chart 5



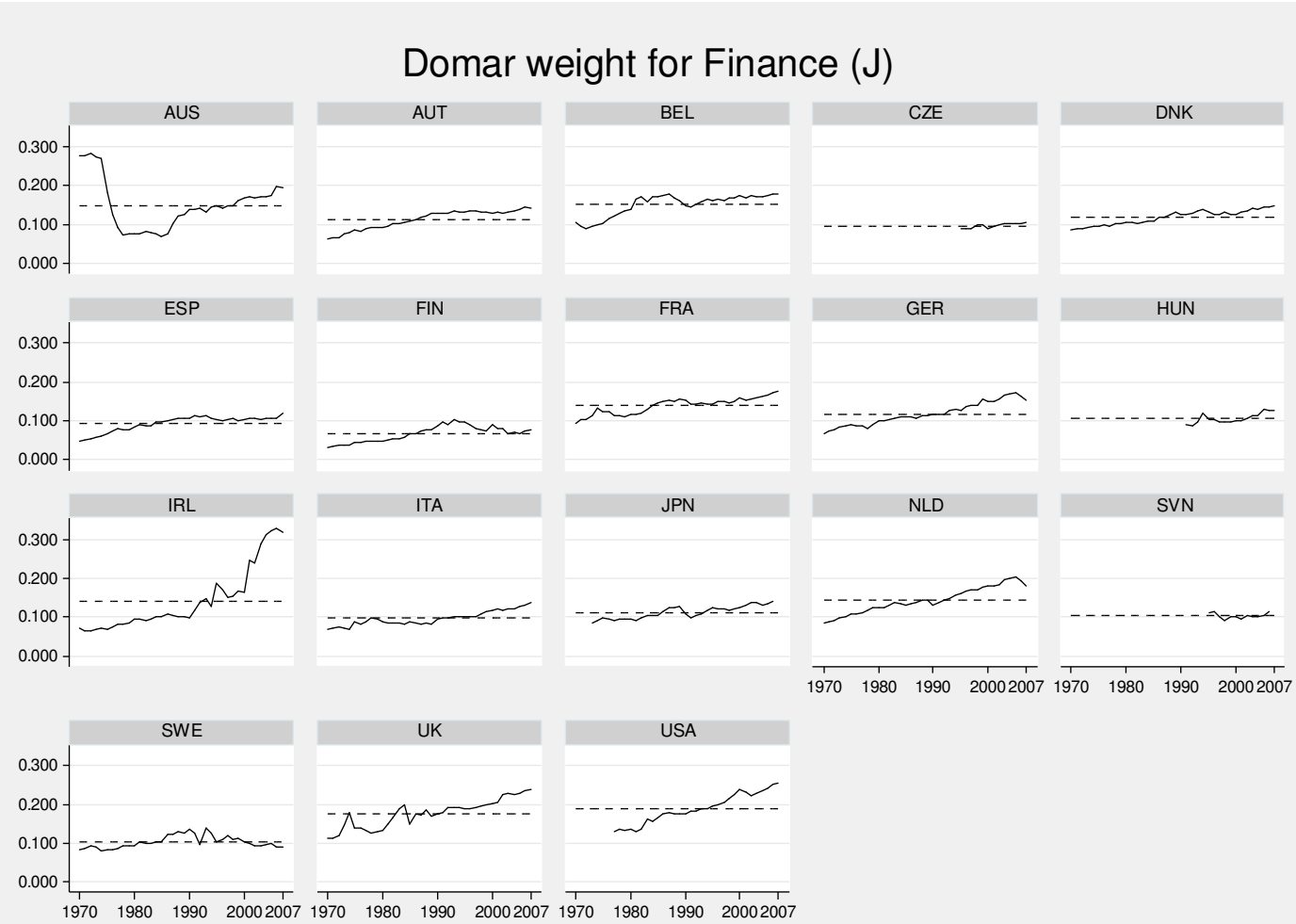
Source: EU KLEMS. Note: Domar weights are for market sector GDP. Dashed lines denote country means.

Chart 6a



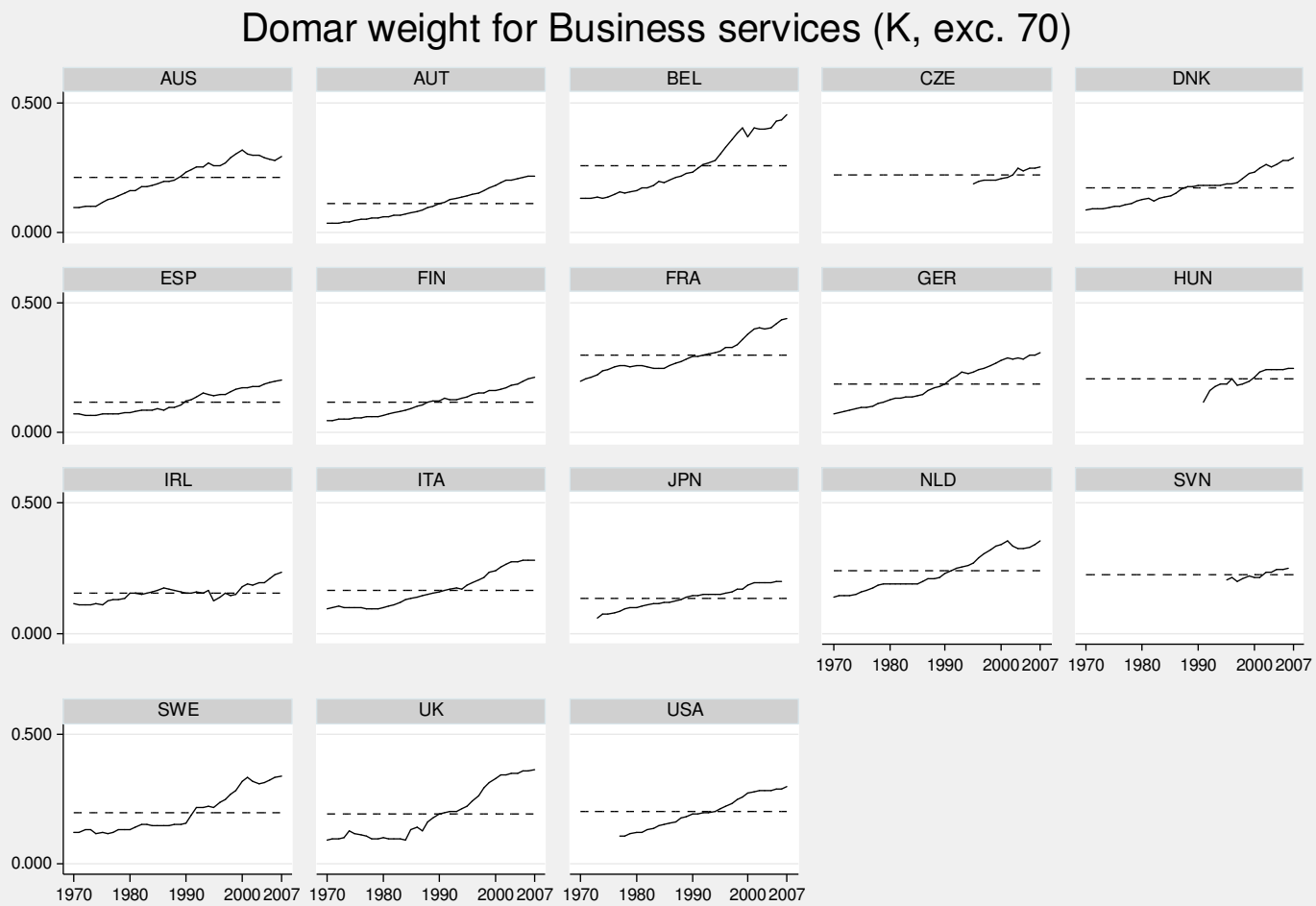
Source: EU KLEMS. Note: Domar weights are for market sector GDP. Dashed lines denote country means.

Chart 6b



Source: EU KLEMS. Note: Domar weights are for market sector GDP. Dashed lines denote country means.

Chart 6c



Source: EU KLEMS. Note: Domar weights are for market sector GDP. Dashed lines denote country means.

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