CDMA07/23

Evaluating Economic Theories of Growth and Inequality: A Study of the Danish Economy[*]

Arnab Bhattacharjee[†]   Eduardo de Castro[‡]
(Late) Chris Jensen-Butler[§]

NOVEMBER 26, 2007

ABSTRACT

We present a model for studying regional and sectoral variation in total factor productivity (TFP) and develop an empirical test, based on the skewness of TFP distribution, to empirically distinguish between different growth theories. While negative skewness is consistent with the neo-Schumpeterian idea of catching up with leaders, zero skewness supports the neoclassical view that deviations from the frontier reflect only idiosyncratic productivity shocks. We argue that positive skewness corresponds to a model where the combination of exogenous technology with non-transferable knowledge accumulated in specific sectors and regions explains TFP. This argument provides the framework for an empirical model based on stochastic frontier analysis. The model is used to analyse regional and sectoral inequalities in productive efficiency across Danish sectors and regions.

JEL Classification: D24; O18; O3; O4.

Keywords: Regional growth models; Total Factor Productivity; Stochastic Frontier Analysis; Skewness.

* Corresponding author: Arnab Bhattacharjee. Address: School of Economics and Finance, University of St. Andrews, St. Andrews KY16 9AL, UK; Tel.: +44 (0)1334 462423, Fax: +44 (0)1334 462444; email: ab102@st-andrews.ac.uk

§School of Economics and Finance, University of St. Andrews, Scotland, UK;
‡Dept. of Political Science and Public Administration, University of Aveiro, Portugal.

1 Introduction

Understanding the mechanisms underlying economic growth and the explanation of persistent geographical inequalities in levels of productivity are issues of key research interest. While prior research on growth theory has considerably improved our understanding of these issues, it has also generated substantial debate. On the one end of the spectrum there is the neoclassical position adopted by exogenous and endogenous (or new) growth theories. At the other end there are theories based on the Schumpeterian ideas of creative destruction and catching up with the leaders and related ideas represented in the evolutionary and institutionalist approaches.

Like the literature on growth theories, the econometric literature on productivity has also developed several alternative approaches. The empirical models and inference methods can be categorised into two key methodologies: (a) the OLS regression based approach and the associated interpretation of the Solow residual as a measure of total factor productivity (TFP), and (b) frontier production function estimation where the distance from the highest achievable levels of productivity is interpreted as a measure of productive efficiency. The OLS approach assumes zero skewness in the distribution of productivity; it supports the neoclassical concept of exogenous and ubiquitous technology and the resulting view that deviations from the production frontier, either positive or negative, reflect only idiosyncratic productivity shocks. By contrast, negative skewness of the distribution of TFP is consistent with the combination of Schumpeterian and neoclassical approaches, where frontier technology is viewed as a pool of knowledge accumulated through the innovative action of leaders and available to any productive unit. However the capacity to use such technology depends on a costly and time consuming effort to catch up with the leader. Unfortunately, the observation in many empirical studies of a positively skewed distribution of TFP is therefore not consistent with either the above econometric methodologies or the corresponding theoretical views.

In this paper, we advance the literature by proposing a new model based on stochastic frontier analysis. Our approach draws on a combination of neoclassical, evolutionary and institutionalist ideas, and is consistent with a positively skewed cross-sectional distribution of productivity. The model is applied to a study of productivity differences across Danish regions and sectors.

Thus, the paper makes three main contributions. First, we argue that positive skewness is consistent with interpreting the production function as a floor. This base level of productivity sets the minimum standards of efficiency which every producer should meet, barring large negative shocks. This interpretation is consistent with the Schumpterian view of technological progress as a permanent attempt to overcome commonly available technical means.

Second, we develop a model which describes an economy, with various regional units and different sectors, evolving over time. The model enables decomposition of labour productivity into five components, related to different theoretical approaches: (a) capital accumulation, (b) technology embodied in capital goods, (c) public good technology available to all sectors and regions, (d) technical capabilities arising from region specific externalities, and (e) technological forge ahead through innovations in specific sectors. Components (b) to (e) are the determinants of TFP, while (a) to (d) are components of a production function describing the base level of labour productivity.

The capital labour ratio and vintage of capital stock represent the effect of capital accumulation and technology embodied in capital goods respectively. Region specific externalities, stressed by institutionalist approaches, define the level of the floor which is shared by all productive units located in the same region.

Component (e) corresponds to the Schumpeterian view of technological progress as a permanent attempt to overcome the productivity conditions provided by the floor. This component can be further divided into two elements: i) the time contingent capacity of each sector to be more or less productive than the overall pattern determined by the floor, which corresponds to the evolutionary concept of sector specific technological trajectories, and ii) the random element of success which moves each particular combination of region, sector and time, above or below the floor.

Third, we conduct an empirical analysis of productivity in the Danish economy, using panel data for 15 years (1979 to 1993), 9 sectors and the 12 regions of the country. Underlying the study are our own calculations of capital stock for a long period of time, as well as the estimation of the average age (or vintage) of capital stock. The degree of homogeneity within Denmark enhances the validity of assuming similar production functions across different sectors and regions of the country. The distribution of productivity implied by our estimated production function for Danish regions and sectors shows evidence of positive skewness, which is consistent with the assumption of the floor.

Our estimates of the production function reflect the importance of vintage of capital and region-specific capabilities, often omitted in empirical studies. The effect of both the capital labour ratio and vintage of capital stock show heterogeneity across the sectors. The productivity enhancing component representing the effect of disembodied technology shows substantial variation over sector and time, which has important institutional explanations.

The paper is organized as follows. In the next two sections we proceed with a short literature review, followed by a presentation of the proposed modeling approach, econometric methodology and data. The empirical results are presented in section four and the conclusions are summarized in section five.

2   Economic growth and inequality

Growth theory has two main objectives. The first is identification of the mechanisms underlying the process of economic growth and, in particular, the reasons why growth can be sustained in the long run, avoiding decreasing returns to productive factors. The second objective is the explanation of the observed persistent patterns of geographical inequality in economic performance. In this section, we present a selective review of the literature in the area, both theoretical and empirical, relevant to our model and methodology.

2.1   Neoclassical growth theory

Much of modern growth theory builds on the *neoclassical model of exogenous growth* (Solow, 1956, 1957; Swan, 1956) which views the accumulation of physical capital, associated with a permanent flow of technical progress, as the driver of economic growth. The neoclassical growth model assumes the Cobb-Douglas production function that, in its intensive form, is expressed as

$$y = Ak^{\alpha}, \tag{1}$$

where y and k are the output-labour ratio and the capital-labour ratio respectively, α is the capital elasticity of output, and A is the TFP representing technological capacity of the productive system. Under the model, A grows either as a purely exogenous process or through exogenous technical innovations which are embodied in capital goods (Solow, 1960). Diminishing returns to capital, combined with assumptions of constant savings rate and

constant growth of labour, generate a steady state growth rate depending only on the rate of exogenous technical progress.

Use of the above model for international or inter-regional comparisons are conditioned on some strong and often implausible assumptions such as ubiquity of technology and lack of mobility of capital and labour. Nevertheless, empirical analyses by a number of authors present evidence which, at least in qualitative terms, is in line with main predictions of the model (Barro, 1991; Mankiw *et al.*, 1992; Barro and Sala-i-Martin, 1995; Sala-i-Martin, 1997). The neoclassical model is much less successful in explaining observed patterns of inequality in quantitative terms (Prescott, 1998), unless additional assumptions, such as an arbitrary increase in the capital elasticity of output (Mankiw, 1995) or additional variables are included.

These additional assumptions or variables also fundamentally change the nature of the model. For example, inputs such as human capital or R&D investment imply that TFP depends on these factors, which is more in line with *endogenous growth theory*. This theory, based on the work of Romer (1986, 1990), assumes that technology is a private good which is produced by dedicated inputs, such as scientists, designers or research laboratories and accumulated by economic systems as a stock of ideas. If the accumulation of ideas is not restricted by the law of diminishing returns, a steady state growth process can be derived, under which TFP increases at a rate depending on the growth of labour force dedicated to innovation and on the extent to which labour is used efficiently.

Alternative models developed by Lucas (1988) assume the existence of a common pool of exogenous technology combined with different endogenous usage capacities, which in turn are contingent on the average level of human capital, accumulated either through formal learning or through learning-by-doing. However, the distinction between an exogenous technological frontier, defined at the global level, and the local efficiency, measured as a TFP gap in relation to the frontier is not clearly made by Lucas. This distinction is at the base of neo-Schumpeterian models, discussed below.

2.2   Neo-Schumpeterian theory of growth

The endogenous growth theory's prediction of distinct development paths is generally in line with the observed patterns of international or inter-regional divergence. However, the assumption of immobile technology in Romer (1986, 1990) and the lack of clear distinction between technological

frontier and efficiency in Lucas (1988) precludes the consideration of technological catching-up, which is a potentially important aspect of growth and convergence. Moreover, as discussed in Aghion and Howitt (2006), endogenous growth theory is not suitable to derive inferences and policy regarding technical progress, particularly in its relation to the rate of firm creation, the intensity of competition, or investment in different types of education.

Neo-Schumpeterian theory of growth builds on the well known concept of creative destruction as the basic process through which the upward movement of technological frontier proceeds (Aghion and Howitt, 1992). The technological frontier is defined as the envelope of all possible input-output combinations, representing the maximum output that can be produced using a given set of inputs. Interpreted slightly differently, the frontier is the outcome of the permanent attempts of firms and economic systems to forge ahead, overcoming the current best-practices. International flows of technology arise from the attempt to catch-up with the best practices (Grossman and Helpman, 1991), a process which in turn depends on the efforts of economic systems to increase their absorptive capacity (Arrow, 1969; Abramowitz, 1986; Fagerberg, 1988). The capacities to forge ahead and to catch up typically depend on specific types of human capital and R&D activities (Aghion and Howitt 2006).

2.3 Evolutionary and institutional approaches

By contrast, the evolutionary approach (Nelson and Winter, 1982; Dosi *et al.*, 1988) views innovation as creating technological trajectories, rather than a universal benchmark which clearly defines a technological frontier. These trajectories are driven by technological paradigms, combining a set of established routines with a shared knowledge base, which determines the "notional opportunities of future technical advance" (Dosi, 1997, p. 1534). Such trajectories correspond to a stochastic process for TFP which all productive units share and, at the same time, try to surpass by developing specific learning processes (Nelson and Winter, 2002) targeted at the creation of non-shared innovations.

While the global technological trajectory is based on developments in the fields of natural sciences, engineering, management and other disciplines, specific learning processes occur at sectoral level, generating sectoral trajectories which are both driven by specific capacities to absorb, enhance and apply scientific and technical knowledge, as well as by changes in patterns of

demand. Inside each sector, specific firms compete with each other, trying to perform better than the common pattern provided by the respective sectoral trajectory, forging ahead through innovation.

The environment where they are embedded influences the success of individual firms in two distinct ways. On the one hand, performance depends on the availability of skilled workforce and on the synergies arising from interactions between firms and support organizations. On the other hand, entrepreneurial behavior is shaped by the combination of social and political factors stressed by the new institutional economics (Furobotn and Richter, 1992), such as the capacity of the legal system to ensure property rights, and the existence of a cultural and institutional framework which lowers transaction costs (Williamson,1996).

These environmental factors are spatially confined externalities with different scales of influence. Some factors, such as the legal and cultural framework or large research institutes, operate mainly at national level, generating national systems of innovation (Lundvall, 1992), other factors, such as skilled labour supply and networks linking firms and support institutions have a more limited territorial span, and are the basis of regional systems of innovation (Braczyk *et al.*, 1998).

2.4   Econometric implications

The various theoretical views have important implications for empirical modeling. Estimation of production functions using OLS methods correspond closely with the neoclassical approach. Here, all producers use the best purpose technology, and any deviation in their output, positive or negative, is attributed solely to idiosyncratic productivity shocks. This leads to the interpretation of the Solow residual as a measure of TFP (Solow, 1957).

This OLS based approach is, however, not particularly suitable for studying economies when they deviate from the equilibrium. For example, neo-Schumpeterian theory has generated a rich variety of empirical studies that attempt to identify both the evolution of the frontier and the catching up capacity of different countries and regions. In contrast with standard neoclassical theory, these studies treat investment in physical capital as an exogenous process and thus, rather than looking at the dynamics of capital accumulation, they are centred on comparative analyses of TFP levels. Neo-Schumpeterian empirical studies can be divided into two main approaches, according to the econometric techniques used.

7

The first approach is inspired by the work of Färe *et al.* (1994), who applied Data Envelopment Analysis (DEA) to a sample of OECD countries over a ten year period. Kumar and Russell (2002) develop a related methodology, where the evolution of labour productivity is decomposed into physical capital accumulation (movement along the frontier) and increase of TFP; rise in TFP results from a combination of technical progress (upward movement of the frontier) and catching up (movement towards the frontier). Being a purely nonparametric method, DEA has the important advantage that it does not require any functional specification for the production function. On the other hand, since DEA leaves no role for idiosyncratic productivity shocks, the methodology is not robust to measurement errors, outliers and other similar data aberrations. Because of these limitations, we do not focus on DEA in the current paper.

The second econometric approach uses Stochastic Frontier Analysis (SFA), a technique developed by Meeusen and Van den Broeck (1977) and Aigner *et al.* (1977) (see Kumbhakar and Lovell (2000) for an excellent exposition). SFA decomposes the residuals of an estimated production function into an efficiency component, corresponding to a negative valued random effect having a skewed distribution, and an idiosyncratic zero mean zero skewness random error. SFA is relatively robust to random noise arising from measurement errors and erratic variations in the level of TFP, and can accommodate idiosyncratic productivity shocks. Further, by explicitly modeling departures from the frontier as a combination of inefficiency and idiosyncratic shocks, SFA offers unique and useful interpretation combining the neo-Schumpeterian and neoclassical approaches. Because of these advantages; SFA has emerged as the most popular methodology to study TFP at the firm level, either for cross-section comparison of efficiencies (for example, Green and Mayes, 1991), or analysis of efficiency dynamics using panel data (Tsionas, 2006), or for analyzing geographical influences on the efficiency of firms in specific sectors (Coelli *et. al.*, 1999). SFA has also been applied to study TFP at the macroeconomic level, although less frequently. For example, Kneller and Stevens (2006), using panel data on manufacturing sectors of OECD countries, analyzed the skewed component of the error term, representing the distance to the technological frontier, as a function of the levels of investment in R&D and human capital, which in turn -are related to the absorptive capacity of the economic system.

Neo-Schumpeterian theory applied to SFA implies a negative skewness in the distribution of TFP (Carree, 2002), while standard OLS assumes a

symmetrical distribution. Therefore, the empirical observation in several studies that the cross-sectional distribution of TFP is positively skewed (see, for example, Green and Mayes, 1991, Fritsch and Stephan, 2004 or Krüger, 2006) casts serious doubts about the validity of the theoretical approaches adopted and the consistency of the estimation methods. These seemingly contradictory results have been explained as arising either from weakness of the frontier methodology, mainly concerning the lack of robustness with respect to violation of normality and measurement of skewness (Simar and Wilson, 2005; Krüger, 2006), or from a notion of super-efficiency (Green and Mayes, 1991).

3 A model of Danish sectoral and regional labour productivity

Based on the critical review presented in the previous Section, we think that the key structure of growth theory can be provided by the neoclassical production function, as defined in the capital vintage model (Solow, 1960), where labour productivity is decomposed in three fundamental elements: capital intensity, technology embodied in capital stock and a non-explained residual. However, our approach diverges from Solow's vintage model along two key dimensions.

First, we assume perfect physical capital mobility and therefore we look at capital accumulation as an exogenous process. As a consequence, rather than the dynamics of capital accumulation, the key element of our analysis is the capacity to use productive factors.

Second, we abandon the assumption of TFP as a technological blueprint which everybody can costlessly use, and follow the neo-Schumpeterian idea that TFP is the outcome of resource consuming attempts to overcome competitors. However, rather than sharing the neo-Schumpeterian view of TFP as the individual capacity to reach a universal technological frontier, we adopt the evolutionary perspective of competition as the effort of every economic unit to move beyond the basic productivity levels given by public domain generic technologies. Departing from these standards, each sector develops its own technological trajectory. In particular cases, successful innovations generate relatively high performance levels, while the remaining sectors are randomly spread around standard values. Within sectors, each firm tries to

develop particular ways to move beyond common trajectories, using its own resources and taking advantage of the externalities generated by their environment. In other words, rather than an inefficiency component reducing productivity from the frontier, we look at TFP as the result of a productivity enhancing innovative component raising productivity above a public domain technological background. This view is consistent with the positively skewed distribution found in several empirical studies based on SFA[1].

The above described assumptions are the basis for the economic productivity model presented in subsection 3.1. The econometric methodology developed to test alternative theoretical positions as well as estimation and robustness checks will be presented in subsection 3.2. Subsection 3.3 describes the Danish data used for empirical analysis.

3.1 Modeling economic productivity

The starting point of our model is the Cobb-Douglas production function in intensive form (Eqn. 1), applied to panel data across different regions and sectors and over time. Arguably, the incapacity of Cobb-Douglas function to take into account economies of scale or different elasticities of factor substitution are potential limitations (Klump and Preissler, 2000). However, in the analysis of economies of scale at the regional level, one of the most challenging issues is to understand whether an increase in output reflects a movement towards full capacity of the productive system, a larger scale of production or an increase in the number of productive units, which, in turn, can generate economies of agglomeration. Moreover, the concept of agglomeration economies can only be used under the strong assumption that regional boundaries correspond to the spatial clustering of units relevant to each particular sector. Thus, the adoption of a Cobb-Douglas function, implying that any internal or external scale economies appear as non-identifiable components of the TFP, is a lesser problem compared to the potential bias arising from spurious identification of scale effects, caused by heterogeneity in the size of different regions and sectors.

In order to relax the assumption of unitary elasticity of substitution,

---

[1]It is reasonable to think that positive skewness should be expected in sectors where innovation and creative destruction are more intense.Conversely, in mature sectors where a technological frontier is relatively well defined and the efficient use of public good technology is the main driver of competition, positive skewness will tend to decrease or even become negative.

more general specifications, such as the CES production function (Klump and Preissler, 2000; Masanjala and Papageorgiou, 2004) and translog model (Kneller and Stevens, 2006) have been used. Nevertheless, very high or low elasticities of substitution are acceptable, the resulting loss in rigor being compensated by the advantages of Cobb-Douglas functions: analytical simplicity, concavity, homogeneity and flexibility to incorporate additional elements.

We adapt the Cobb-Douglas function to the SFA framework drawing on the theoretical arguments presented above. SFA, originally proposed by Meeusen and Van den Broeck (1977) and Aigner *et al.* (1977), is based on the idea that the error term is a convolution of two independent components, one of which is truly idiosyncratic and the other one is strictly positive (or negative) valued. In contrast with previous studies, we explore the idea that the productivity enhancing positive component captures innovative activity raising certain sectors above common productivity standards at specific times. Further, the statistical distribution of the positive error component can be allowed to vary with other observed characteristics – the conditional mean model (Kumbhakar *et al.*, 1991; Reifschneider and Stevenson, 1991). In particular, when this effect varies with sectors and over time, but is invariant across the regions, the model corresponds closely with the view of innovation presented in subsection 2.4.

The model is expressed, in intensive form as:

$$\ln y_{rit} = A_0 + \alpha_i . \ln k_{rit} + \eta_i . a_{rit} + \delta_r + u_{rit} + v_{rit} \qquad (2)$$

for region r, sector i and year t, where A_0 is the intercept, y_{rit} denotes output per worker, k_{rit} is the capital labour ratio, α_i is the sector-specific capital elasticity of output, a_{rit} denotes average age of the stock of capital, η_i is the sector-specific effect of the average age of capital and δ_r represents region-specific externalities. The error term has two components: u_{rit} is a positively skewed random effects error, which has a different distribution for each combination of sector and time, and v_{rit} is a zero mean idiosyncratic error.

According to Eqn. 2, labour productivity can be decomposed into the following elements:

1. *Public good technology*, represented by the intercept A_0, is the outcome of all all factors affecting productivity shared by every Danish region

11

and sector. In multicountry analysis, one may assume intercept heterogeneity, where the comparison of national values of A_0 would reflect the relative efficiency of national systems of innovation.

2. *Capital labour ratio* is the key element of neoclassical approaches. In our model, we assume that the impacts of capital labour ratio on productivity, denoted by α_i, potentially vary with the sectors

3. *Technology embodied in capital goods*, is either produced in the Danish capital goods sector or imported in the forms of machinery, components, licences, etc. Our model analyses the impact of embodied technology on labour productivity, which is given by the lag effect of using obsolete vintages of capital.

4. *Externalities affecting the performance of regional economies.* Each region has a particular mix of factors which affect the capacity of firms to compete under the conditions set by the Danish macroeconomic environment and specific sectoral technological trajectories. These factors primarily constitute the endowment of public infrastructure and technological support institutions, intensity of networking, entrepreneurial culture and the capacity to attract skilled labour; the effects are represented by region specific fixed effects, denoted by $\delta_r{}^2$. Since our analysis only covers a 15 year time span, we assume that δ_r can be assumed constant over time.

5. *Sector-specific technological trajectories* correspond to the time evolution of the error term u_{it} for a given sector i and represent the capacity of the sector to move above the common productivity standard. Given the homogeneity of Denmark, it may be reasonable to expect that, for each sector, all Danish regions share a common process of knowledge accumulation and adapt to changes in market conditions similarly. Thus, the error term is modeled to have a positively skewed error term, $u_{rit} = u_{it} \sim \mathbb{N}^+ \left(\mu, \sigma_u^2 \right)$.

6. *Time specific unexplained regional performance* is given by the idiosyncratic zero mean error term $v_{it} \sim \mathbb{N} \left(0, \sigma_v^2 \right)$. This component combines

---

[2]If differences in evolution of labour skills were a key element of regional differentiation, the inclusion of a corresponding variable would be necessary. Given the social homogeneity of Denmark, this is not necessary.

measurement errors with the effects of occasional events and omitted variables. The variance of this statistical white noise has an useful interpretation in the context of evolutionary theory. It reflects the capacity of Danish economy to generate variety, which creates short term inefficiency but a long term enlarged basis to select innovations.

3.2 Econometric methodology

Here, we adopt the empirical model discussed in the previous subsection and discuss the econometric methodology used for testing, estimation and robustness checks.

3.2.1 Testing alternative theories

Our econometric analysis uses a random effects methodology based on stochastic frontier analysis, applied to the model presented above (Eqn. 2). This stochastic frontier analysis framework can be compared with two alternative theoretical perspectives each having a corresponding way of interpreting the meaning of u_{rit}. The outcome of the empirical analysis can be used to determine which perspective better fits the data. The first alternative is the zero mean symmetric distribution of the composite error term corresponding to the traditional neoclassical view; in this case, the error term is dominated by v_{rit}, while u_{rit} is negligible in comparison. This is implemented by estimating a fixed effects model

$$\Delta \ln y^*_{rit} = \sum_{r=1}^{R} \left(\delta_r - \overline{\delta} \right) . I_r + \sum_{i=1}^{I} \alpha_i . I_i . \Delta \ln k^*_{rit} + \sum_{i=1}^{I} \eta_i . I_i . \Delta a^*_{rit} + \varepsilon^*_{rit}, \quad (3)$$

where

$$\Delta \ln y^*_{rit} \;\; = \;\; \Delta \ln y_{rit} - \frac{1}{R} \sum_{r=1}^{R} \Delta \ln y_{rit}, \quad \text{(similarly } \Delta \ln k^*_{rit}, \, \Delta a^*_{rit} \text{ and } \varepsilon^*_{rit}\text{)},$$

$$\text{and } \;\; \overline{\delta} \;\; = \;\; \frac{1}{R} \sum_{r=1}^{R} \delta_r,$$

using least squares dummy variables.

The second alternative corresponds to the neo-Schumpeterian view of catching up. In this case, u_{rit} measures the distance of each production

system from the frontier of production possibilities, a ceiling which reflects the optimum use of available technology in a given year. Therefore, u_{rit} has a non-positive value and can be interpreted as inefficiency or failure to reach the benchmark. The ceiling is only surpassed in exceptionally positive circumstances (positive values of the idiosyncratic component combined with very low levels of inefficiency). This view is consistent with the stochastic frontier production function model.

Which of the three approaches fits better the data is an empirical question which will be tested. If the concept of a ceiling stochastic frontier applies, the residuals from a fixed effects model must be asymmetrically distributed around the average with a negative value of the third moment, $\boldsymbol{E}\left(\varepsilon_{rit}^3\right)$ (Kumbhakar and Lovell, 2000, p. 73). This is because it is expected that the residuals are a combination of random noise with inefficiency, which skews their distribution negatively. Conversely, our view of innovation implies positive values for the third moment, while zero skewness is consistent with the neoclassical idea of idiosyncratic productivity shocks.

3.2.2 Estimation

Once the appropriate model is selected, maximum likelihood estimation can proceed using methods available in the literature. In the zero skewness case, OLS can be applied in a straightforward way. With negative skewness, a stochastic frontier production function can be estimated (Meeusen and Van den Broeck, 1977; Aigner *et al.*, 1977). Similarly, positive skewness can be addressed by estimating a stochastic frontier cost function (Schmidt and Lovell, 1979).

For estimation, we need to specify distributional and modeling assumptions on the two error components. With panel data, it is natural to explicitly model the dynamic pattern of the skewed error component (Cornwell *et al.*, 1990; Kumbhakar, 1990; Battesse and Coelli, 1992). The most general specification is given by the region invariant efficiency model[3], where

$$u_{rit} = u_{it} \sim \mathbb{N}^+\left(\mu, \sigma_u^2\right). \tag{4}$$

The zero mean idiosyncratic component v_{rit} is assumed to be normally distributed

$$v_{rit} \sim \mathbb{N}\left(0, \sigma_v^2\right).$$

---

[3] This is similar to what is known in the literature as the time invariant efficiency model, except that in our case invariance is across regions rather than time.

This model allows us to infer on the nature of innovative activity using estimates of time varying residuals from the model. For the stochastic frontier cost function, the commonly used residual is $\boldsymbol{E}\left(u_{rit}|\widehat{\varepsilon}_{rit}\right)$, for which we use the popular estimator proposed by Battesse and Coelli (1988). Recent literature has also focussed on incorporating exogenous influences on the distribution of the skewed error component.

In addition to estimates of the regression coefficients, stochastic frontier production or cost function analysis provides estimates of the mean μ and the error variances σ_u^2 and σ_v^2; the relative values of the error variances provide insights into the nature of the competitive process.

3.2.3   Robustness

We propose to check the robustness of our model estimates by comparing the results with some competing models. In this context, we consider two main alternatives to the specification of dynamics in the time invariant model (Eqn. 4). First, we may use the conditional mean model (Kumbhakar *et al.*, 1991), with

$$u_{rit} \sim \mathbb{N}^+\left(\mu_{it}, \sigma_u^2\right), \tag{5}$$

to identify sectors and years when innovative capacity were the most prominent[4]. In this model, we include the sector-time fixed effects in the skewed error component rather than in the production function itself[5]. Second, we can assume that the skewed error component pulls productivity back to the frontier over time – the time varying decay model (Battesse and Coelli, 1992)

$$u_{rit} = \exp\left[-\eta\left(t - T_{ri}\right)\right].u_{ri}, \quad u_{ri} \sim \mathbb{N}^+\left(\mu, \sigma_u^2\right), \tag{6}$$

where T_{ri} denotes the final time period for each sector-time combination (1993 in our case). The choice between these three specifications will be discussed in Section 4.

Finally, we also use results from the OLS based fixed effects estimation (Eqn. 3) for comparison.

---

[4]See Kumbhakar and Lovell (2000) for further references and detailed discussion of inference in stochastic frontier production and cost functions.

[5]In addition to sector-time effects on the conditional mean, we can also include additional fixed effects in the production function. The resulting model is (weakly) identified by functional form, but does not offer additional insights into the study of growth and inequality.

3.3 Annual data for Danish regions and sectors

The model described in the subsection 3.1 is applied to annual data from the Danish Local Authorities Research Institute (AKF) covering the period 1979-93; for further description of the data and discussion of related literature on Danish regions, see Hansen and Jensen-Butler (1996) and Jensen-Butler and Madsen (2005). For each year, we consider 12 Danish regions[6] and nine sectors[7]. The geographical location of the regions is shown in Figure 1.

The AKF database includes employment (in full time equivalent), as well as gross value added and gross fixed capital formation (in Danish kroner, at constant prices). Investment data are available for buildings (1950-1994), for machinery (1970-1994) and for transport (1974-1994).

The preparation of the data presented two challenges. First, quality data was available for investment at the regional and sectoral levels, but not for capital stock. In Appendix A, we describe two different ways in which we use the information on investment to construct data on capital stock; the two methods give very similar empirical results. Second, our formulation places special emphasis on the role of vintage of capital, an often neglected but important variable, which captures the effect of embodiment of technology in capital goods (Solow, 1960). We use similar methods as above to estimate the average age of capital by region, sector and year. The estimates (of capital stock and average age of capital) obtained were benchmarked against spatially aggregated data on depreciation rates and stock of capital at replacement cost, by sector and year (Source: Danmarks Statistik) for the period under consideration.

---

[6]Bornholm, Hovedstad or Greater Copenhagen metropolitan area, Vestsjælland (West Zealand), Storstrøm, Fyn (Funen), Søndre Jylland (Southern Jutland), Ribe, Vejle, Århus, Ringkøbing, Viborg and Nord Jylland (Northern Jutland). It may be noted that the above regional division of Denmark changed recently. This does not affect our empirical study, since the used data ends in 1994.

[7]Food, textiles, wood and furniture, paper and publishing, chemicals, glass and ceramics, metals and engineering, other manufacturing and public sector. The initial data set included 21 sectors, 12 of each are not used in this study. Agriculture was dropped because of substantial overlap with the oil and gas industries, the transport and communications sector was dropped because it was difficult to allocate the productive resources (labour and capital) to specific regions, while construction, electricity, gas and water were dropped because good investment data (required for computation of capital stock) were not available for all the regions, and finally, private services were dropped because investment data were not available at regional level.
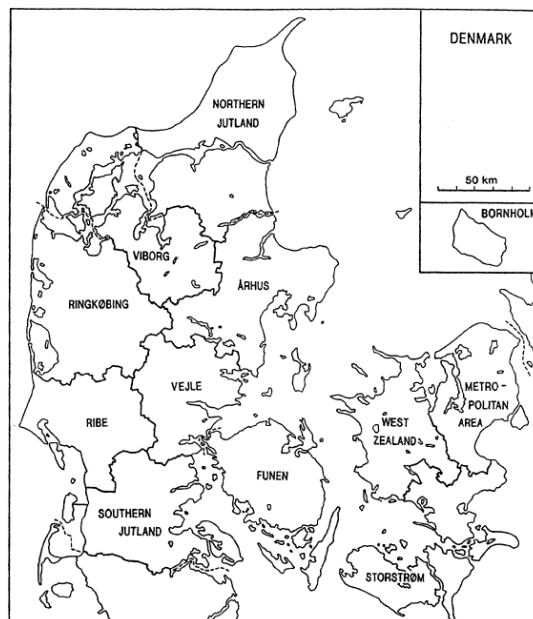
Figure 1: The Danish regions

4   Results

The estimation exercise was implemented using the econometric software
package STATA (version 9.2). The first step was the analysis of skewness
of residuals and the consequent choice of the appropriate econometric model
and the corresponding theoretical view. Initially, we used OLS based fixed
effects methodology to estimate the neoclassical production function (Eqn.
3). While the results were broadly in line with the SFA model, they do not
offer the possibility of studying technological forge ahead through innovations
in certain sectors and at certain times, which is central to neo-Schumpeterian
and evolutionary ideas.

Using these OLS estimates, we found a small number of large residuals,
positive and negative, which were likely to influence moment based inference
on the sign of skewness. However, we also observed a higher density of
residuals just below the median than just above, indicating positive skewness
in the residuals. In fact, the estimated skewness of residuals leaving out 0.6
per cent (9 out of 1590) extreme values is 0.2529 which, on the basis of

17

the D'Agostino *et al.* (1990) test, is different from zero at 5 percent level of significance[8]. This supports the view that the frontier is a floor, which describes a benchmark base level of production technology.

Based on the above evidence, we model the positively skewed regression error as a convolution of two error components. The first component, modeled as a truncated normal distribution, is productivity enhancing and closely matches our view of technological forge ahead. The other component is a zero-mean Gaussian random variable that reflects purely idiosyncratic productivity shocks.

The estimated production function, in relation to which the errors are defined, represents the floor described as the combined effect of technology endowed in capital goods and region-specific technical capabilities. In turn, technology endowed in capital goods has three components: (a) capital accumulation, or the effect of capital-labour ratio, (b) technology embodied in capital goods, representing technological progress in the form of productivity associated with different capital vintages, and (c) externalities affecting performance of regional economies. The first two of the above effects are allowed to vary across the sectors. Thus, the floor represents the base level of labour productivity that all producing units should attain, barring large negative shocks.

To this floor, we add the idiosyncratic zero-mean error representing productivity shocks, and a positive valued random component that measures a productivity augmenting departure from the floor. Since this skewed error component adds to the level of productivity that would otherwise have been observed (in other words, the frontier determines a floor) we estimate a stochastic frontier cost function. Therefore, the model, represents a useful innovation in relation to traditionally used methodologies.

We implemented the model (Eqn. 2) by estimating three different kinds of stochastic frontier cost functions, based on different assumptions about the dynamics of the productivity enhancing component:

(a) the model where productivity enhancing component is fixed for different sector × time combinations, but is a random draw from a common distribution (Eqn. 4),

---

[8]The medcouple, a recently proposed robust estimator of skewness (Brys *et al.*, 2004), based on all values of the residual including the extreme values was also positive.

(b) the model where the skewed component has a distribution invariant across the regions, but has a different mean for each sector × time combinations (Eqn. 5), and

(c) the time varying decay model (Eqn. 6).

Model (a) corresponds to the more general specification as it retains complete flexibility in the pattern of sector × time effects. One can use the average expected residuals corresponding to the skewed error component to better understand the nature of stochastic variation in innovation (technological forge ahead) in the different sectors. In the case of Model (b), the sector × time specific effects were incorporated by assuming that the conditional mean of the skewed error varies over different sector × time combinations. A potential problem with the implementation of this model is the large number of parameters to be estimated, and the consequent lack of parsimony[9]. Further, the obtained results (see Appendix B) were substantially different from those in Model (a), in particular regarding the capital-labour ratio coefficients. We consider this as evidence that the assumed structure in innovative capacity is not consistent with the underlying data generating process.

Under Model (c), every sector falls back to the frontier over time. This is because the frontier rises as a result of capital replacement ("creative destruction") and technical progress. However, we did not find empirical evidence in favour of productivity retracting to the frontier over time. In fact, our estimates point to heterogeneity, across sectors and regions, in the decay parameter η. Further, as argued above, we expect innovation to have different patterns of evolution over time in different sectors. We focus on Model (a) in our discussion below.

We conduct several additional checks for model validity. First, we experimented with alternative measures of capital stock and age (vintage) of capital. We found that the effect of vintage of different types of capital (machinery, buildings or transport) is somewhat different in different sectors. However, for the sake of parsimony, we only present results of a model where vintage is estimated from the average age combining all the three types of capital goods. We also used alternative estimates of capital stock and age

---

[9]We also estimated a simpler model where the conditional mean of the productivity enhancing public goods technology varied only over the sectors but not over time. The results did not change significantly.

of capital, based on nonlinear least squares of log of aggregate depreciation on lagged log-investment (see Appendix A for further details). The results using this alternative data construction were very similar.

Second, in line with prior empirical studies in the growth accounting tradition, we estimated models without a role for vintage of capital. The results were strikingly different. This finding has two important implications: (i) vintage of capital (representing technological progress) is an important determinant of variations in productivity across regions, sectors and time, and therefore supports our empirical model strongly, and (ii) omission of vintage of capital contributes to a serious omitted variables problem and thus to inconsistent estimates.

Third, we compared our parameter estimates with the fixed effects results, as well as a conventional stochastic frontier production function. The model estimates are qualitatively similar. However, as we have emphasized earlier, the interpretation of these models are quite different. Based on the finding of positive skewness and the above checks for model validity, we remain satisfied about the robustness of our selected specification.

Estimates of our production possibility frontier (Model a) are reported in Table 1, while Table 2 reports a decomposition of overall variance of labour productivity into the relative contributions from the different factors. Estimates of Model (a) omitting the effect of vintage of capital and estimates of Model (b) are presented in Table 3 in Appendix B.

Tables 1 and 2 report good support for our estimated stochastic frontier cost function model. Overall, the base level of productivity, described by capital accumulation, technology embodied in capital goods and region-specific externalities, explain half of the overall variation in labour productivity across sectors, regions and time in Denmark. The remaining 50 per cent is explained by the effect of innovation and idiosyncratic technology shocks. The skewed error variance representing innovation explains 11 per cent of the total variation while productivity shocks account for the remaining 39 per cent.

Table 1: Model (a) Estimates[10]

Variable	Coefficient	Variable	Coefficient
Region Dummies		Capl.-Lab. Ratio	
– Bornholm (base)	0	– Food	0.251^{**} (6.76)
– Hovedstad	0.249^{**} (8.53)	– Textiles	0.279^{**} (12.73)
– Vestsjælland	0.240^{**} (8.26)	– Wood/Furniture	0.332^{**} (11.31)
– Storstrøm	0.074^{**} (2.58)	– Paper/Publishing	0.392^{**} (10.87)
– Fyn	0.147^{**} (4.91)	– Chemicals	0.209^{**} (6.43)
– Søndre Jylland	0.257^{**} (8.88)	– Glass/ Ceramics	0.318^{**} (10.12)
– Ribe	0.273^{**} (9.13)	– Metals/ Engg.	0.388^{**} (10.60)
– Vejle	0.222^{**} (7.21)	– Other mfg.	0.345^{**} (11.49)
– Århus	0.196^{**} (6.44)	– Public sector	0.269^{**} (6.95)
– Ringkøbing	0.265^{**} (8.34)		
– Viborg	0.174^{**} (5.70)	Constant	8.891 (1.08)
– Nord Jylland	0.137^{**} (4.61)		
Avge. Vintage of Capl.		Sample size	1,590
– Food	0.042^{**} (5.60)	Wald χ^2 goodness-of-fit	954.05
– Textiles	0.019^{**} (4.47)	d.f. / p-value	29 / 0.00
– Wood/Furniture	0.005 (1.11)		
– Paper/Publishing	-0.005 (-0.70)	$\ln \widehat{\sigma}^2$, $\sigma^2 = \sigma_u^2 + \sigma_v^2$	-2.926^{**} (-38.90)
– Chemicals	0.048^{**} (5.42)	$\widehat{\sigma}^2$	0.0536
– Glass/ Ceramics	0.011^{+} (1.66)	Skewed err. var., $\widehat{\sigma}_u^2$	0.0119
– Metals/ Engg.	-0.001 (-0.21)	Idiosyn. err. var., $\widehat{\sigma}_v^2$	0.0418
– Other mfg.	0.012^{**} (2.81)		
– Public sector	0.015^{+} (1.69)	$\widehat{\mu}$	0.766 (0.09)

[10] z-values in parentheses.
$^{+}$, *, ** : significant at 10 percent, 5 percent and 1 percent levels respectively.

Table 2: RELATIVE CONTRIBUTIONS TO VARIATION
IN LABOUR PRODUCTIVITY

Factors	Variance (percent of total)
Region-specific externalities (δ_r)	0.011481 (10.7)
Capital accumulation (effect of K/L ratio, $\alpha_i . \Delta \ln k_{rit}$) $+\delta_r$	0.051462 (47.9)
Benchmark production function – Total effect (incl. vintage and covariance between factors)	0.053744 (50.1)
Excess Productivity (increment over the floor)	0.053631 (49.9)
of which, – Technological Forge Ahead/ Innovation	0.011864 (11.0)
– Idiosyncratic Productivity Shocks	0.041767 (38.9)
TOTAL VARIATION IN LABOUR PRODUCTIVITY	0.107375 (100.0)

Understanding the relative contribution of externalities affecting performance of regional economies, and sector-specific effects of capital accumulation (K/L ratio) and vintage of capital, is a bit more complicated. This is because these explanatory factors are correlated with each other. However, relative importance of these factors can be approximately judged by first estimating a production function where only region-specific fixed effects are included, and then expanding the model to include the capital-labour ratio and vintage of capital. These estimates indicate that region-specific externalities explain about 11 per cent of the variation in labour productivity, while including sector-specific effects of capital accumulation into the model increases explained variation to about 48 per cent. Adding the effect of vintage of capital, we get the 50 per cent contribution mentioned above.[11]

The estimates of the effects of different factors of production closely match our *a priori* expectations. The systematic effect of localized disembodied technology in the most backward region of Bornholm (the base region, set to

---

[11]These figures must be treated with caution because of potential omitted variable bias. However, the effect of omitted variables here is reduced because we are not inferring on the coefficient estimates as such, but only on the overall contributions of the variables to the total variance.

zero) is significantly smaller than all the other regions. Ribe and Ringkøbing have the highest estimated effect, followed by Søndre Jylland, Hovedstad or Greater Copenhagen, Vestsjælland and Vejle. While Århus has a middle position in terms of regional externalities, Storstrøm, Nord Jylland and Fyn are regions having lower capabilities. The relative ordering of the regions closely follows the findings of prior research on regional inequality within Denmark (see, for example, Hansen and Jensen-Butler, 1996).

The estimated effects of capital accumulation show substantial variation across the sectors, ranging from 0.21 and 0.25 for chemicals and food industry respectively to about 0.39 for the metals and engineering and paper and publishing sectors. The effects of technology embodied in capital goods (vintage of capital) also varies widely across the sectors, and is significant at 1 per cent level of significance in the chemicals (0.048), food (0.042) and textile (0.019) industries.

A comparison of the estimates in Table 1 and the first set of estimates in Table 3 is very informative. First, Table 1 shows that the effect of capital vintage is significant in most sectors. Further, omitting the effect of age of capital substantially changes the estimates of return on capital (Table 3). This points to an important omitted variable bias if vintage of capital is ignored, which can be explained by the investment dynamics within Danish sectors.[12] Unfortunately, in most empirical studies, such an effect of age of capital is not included generally because of lack of data.

In Model (a) (Eqns. 2 and 4), the pattern of time-variation of innovative capacity is left quite unrestricted, except for the assumption that the skewed random effects vary over sector-time combinations but not across regions. This assumption is, however, logical in this context, since we include region-specific fixed effects in the description of the floor. Therefore, the estimated expected values of the error components conditional on the values of combined residuals, $\boldsymbol{E}\left(u_{it}|\widehat{\varepsilon}_{rit}\right)$, reflects the variation in innovative capacity. In other words, using the estimates of the model, we predict the sector-time specific effects of technology forge ahead as the expected value of the offset above the floor, conditional on the residual (representing a sample realiza-

---

[12]In the case of chemicals and food industries, the synergies between capital deepening and modernisation are evidenced by the reduction of K/L coefficients in Table 1. For the remaining sectors, the effect is opposite suggesting that capital-labour ratio and modernisation in capital developed in opposite directions.

tion of the composite error ε_{rit}).[13] These estimates highlight an important advantage of the methodology adopted in this paper, in that it facilitates understanding the effect of sectoral technological trajectories through the Schumpeterian notion of technology forge ahead.

In addition to the evolution over time discussed above, the expected productivity enhancing error components in the various sectors also inform substantially about different sectoral technological trajectories. Not withstanding decline over the period of analysis, efficiency is highest in the chemicals sector, while other industries lag far behind; these remaining sectors are in turn led by textiles and the food/beverage industries. At the other end of the spectrum, the public sector and metals/ engineering, with low innovative capacity, lie relatively closer to the floor representing the minimum standard of production possibilities. These observations are in line with previous research on innovative activity within Denmark (Jensen-Butler, 1992; Edquist and Lundvall, 1993).

In Figure 2, we plot the estimated sector-time specific effects of innovation for several selected sectors. Different technological trajectories emerge from these plots. For the chemicals and food industries, innovative capacity shows a secular decline over the period 1979–1993. This may be due the fact that productivity changes in these industries have been increasingly driven by processes of automation and the absorption of general purpose technologies, rather than R&D in new product development. Similar inferences have been drawn, for the Danish food industry, by Edquist and Lundvall (1993) and Essletzbichler and Winther (1999). The textiles and public sectors also show a decline in innovative capacity from around the middle of the 1980s. The pattern in metals/engineering and wood/furniture sectors shows a sharp rising trend from 1979 to about 1982-83, then a decline till about 1991, and evidence of a small increase thereafter. This follows the pattern of major R&D initiatives in the engineering sector until the mid 1980s. Paper and publishing and glass/ceramics demonstrate a rise in R&D since the late 1980s; this evidence is in line with the emergence of ceramics as an important intermediate product in many goods.

The above results also demonstrate quite strongly why the time varying decay model (Battesse and Coelli, 1992) may not be appropriate for study-

---

[13] An alternative methodology would be estimating the conditional mean model (Eqns. 2 and 5) and using the estimated coefficients on the sector-time dummies. However, this approach imposes stronger assumptions which do not appear to be consistent with the data.

ing sectoral and regional variation in productivity. The dynamic behavior of innovation is heterogeneous and systematic differences in innovation capacity consistently raise productivity above the benchmark level for the most efficient sectors.
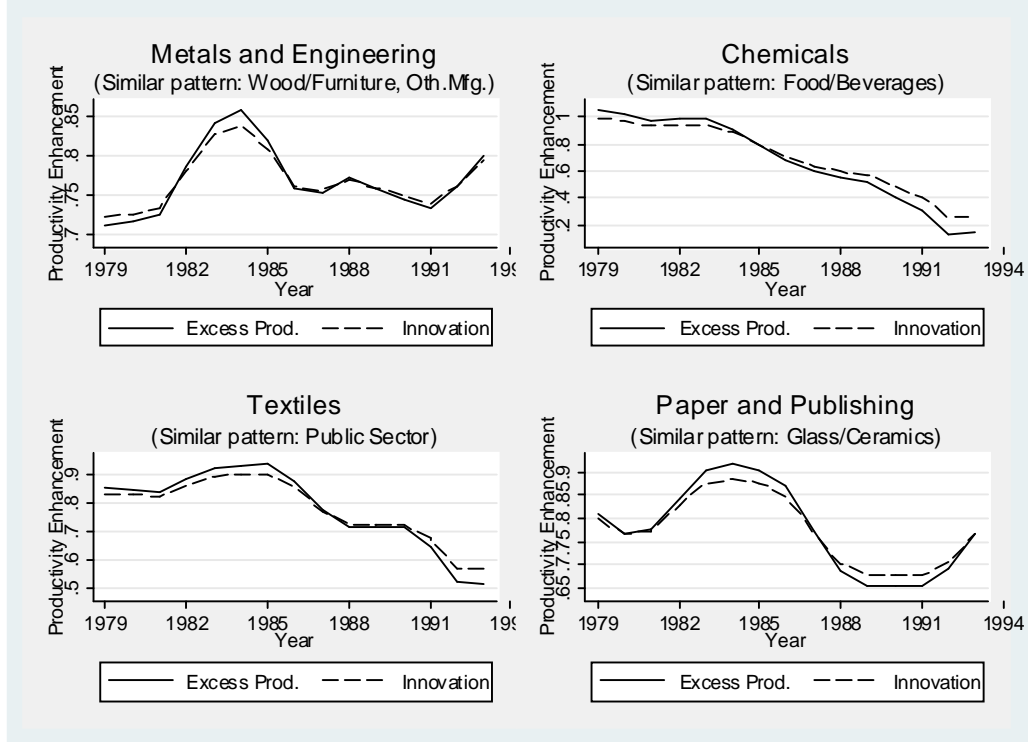
Evolution of Productivity Enhancing Innovation and Composite Residuals: Selected Sectors

5 Conclusion

In this paper, we make three main contributions. First, we develop a methodology for evaluating alternative theoretical views on economic growth and inequality, based on the skewness of productivity residuals. The method is related to Krüger (2006), but extended to include positive skewness patterns which are often observed in empirical studies.

Second, based on a synthesis of neoclassical, neo-Schumpeterian and institutionalist ideas, we develop a model that is consistent with positive skewness. The model is broadly based on the neoclassical tradition of using a Cobb-Douglas production function in intensive form. In addition to capital accumulation, special emphasis is placed on the role of technology embodied in capital goods (or capital vintage effects) and region-specific externalities. In a sharp departure from the literature, and based on evolutionary ideas, we assume an economic system where the production function describes a common productivity benchmark which all producers must achieve in order to survive. At the same time, some producers forge ahead through quality enhancing innovations, which is also consistent with the evolutionary and institutionalist approaches. Finally, following the neoclassical tradition, all agents are also faced with idiosyncratic productivity shocks. This model is consistent with positive skewness, and can be estimated using the stochastic frontier cost function methodology. Other authors (Green and Mayes, 1991; Fritsch and Stephan, 2004; Krüger, 2006) have discussed positive skewness in similar contexts, but have not offered adequate explanation for this evidence.

Third, we apply our empirical model to study regional and sectoral variation in productivity in the Danish economy. Our empirical results identify several new findings. We detect an important role for vintage of capital, while the estimated region-specific externalities are consistent with previous literature. Further, we find evidence on positive skewness. Probably, our most important new findings are in the patterns in technological trajectories ahead across different sectors. These findings inform substantially about the magnitude and evolution of innovative capacity in the Danish industry.

While the above results broadly conform to prior studies, further analyses of the institutional causes of such changes and inferences for public policy is an object of future research. More explicit modeling of innovation, particularly investment in R&D and human capital, are future directions of research. Further, a key feature of our methodology that offers useful extensions is nonparametric modeling of technological trajectories in different sectors. While we observe several interesting patterns in the dynamics of innovative capacity, representing these features in terms of appropriate order restrictions will be a challenging problem for future research. Similarly, understanding the nature of spatial diffusion and its effect on the process of regional convergence is also an interesting research question. Finally, developing Bayesian inference, with *a priori* beliefs on different theoretical positions reflected in suitable prior distributions of skewness, will be an exciting direction of further work.

References

[1] Abramovitz, M. (1986). Catching up, forging ahead, and falling behind. *Journal of Economic History* **46**, pp. 385–406.

[2] Aghion, P. and Howitt, P. (1992). A model of growth through creative destruction. *Econometrica* **60**, pp. 323–351.

[3] Aghion, P. and Howitt, P. (2006). Appropriate growth policy: a unifying framework. The 2005 Joseph Schumpeter Lecture. *Journal of the European Economic Association* **4**, pp. 269–314.

[4] Aigner, D.J., Lovell, C.A.K. and Schmidt, P. (1977). Formulation and estimation of stochastic frontier of production function models. *Journal of Econometrics* **6**, pp. 21–37.

[5] Arrow, K. (1969). Classificatory notes on the production and transmission of technical knowledge. *American Economic Review* Papers and Proceedings **59**, pp. 29–35.

[6] Barro, R.J. (1991). Economic growth in a cross section of countries. *Quarterly Journal of Economics* **106**, pp. 407–443.

[7] Barro, R.J. and Sala-i-Martin, X. (1995). *Economic Growth*. McGraw-Hill: New York.

[8] Battesse, G.E. and Coelli, T.J. (1988). Prediction of firm-level technical efficiencies with a generalized frontier production function and panel data. *Journal of Econometrics* **38**, pp. 387–399.

[9] Battesse, G.E. and Coelli, T.J. (1992). Frontier production functions, technical efficiency, and panel data with application to paddy farmers in India. *Journal of Productivity Analysis* **3**, pp. 153–169.

[10] Braczyk, H.J., Cooke, P. and Heidenreich, M. (1998). *Regional Innovation Systems*. UCL Press: London.

[11] Brys, G., Hubert, M. and Struyf, A. (2004). A robust measure of skewness. *Journal of Computational and Graphical Statistics* **13**, pp. 996–1017.

[12] Carree, M.A. (2002). Technological inefficiency and the skewness of the error component in stochastic frontier analysis. *Economics Letters* **77**, pp. 101–107.

[13] Coelli, T., Perelman, S. and Romano, E. (1999). Accounting for environmental influences in stochastic frontier models: with application to international airlines. *Journal of Productivity Analysis* **11**, pp. 251–273.

[14] Cornwell, C., Schmidt, P. and Sickles, R. (1990). Production frontiers with cross-sectional and time-series variation in efficiency levels. *Journal of Econometrics* **46**, pp. 185–200.

[15] D'Agostino, R. B., Balanger, A. and D'Agostino, R. B., Jr. (1990). A suggestion for using powerful and informative tests of normality. *American Statistican* **44**, pp. 316–321.

[16] Dosi, G. (1997). Opportunities, incentives and the collective patterns of technological change. *Economic Journal* **107**, pp. 1530–1547.

[17] Dosi, G., Freeman, C., Nelson, R.R., Silverberg, G. and Soete, L. (1988). (Eds.) *Technical Change and Economic Theory*. Pinter Publishers: London.

[18] Edquist, C. and Lundvall, B.-Å. (1993). Comparing the Danish and Swedish systems of innovation. In: Nelson, R.R. (Ed.) *National Innovation Systems. A Comparative Analysis*. Oxford University Press: Oxford, pp. 265–295.

[19] Essletzbichler, J. and Winther, L. (1999). Regional technological change and path-dependency in the Danish food processing industry. *Geografiska Annaler* **81 A**, pp. 179–196.

[20] Fagerberg, J. (1988). Why growth rates differ. In: Dosi, G., Freeman, C., Nelson, R.R., Silverberg, G. and Soete, L. (1988). (Eds.) *Technical Change and Economic Theory*. Pinter Publishers: London, pp. 432–457.

[21] Färe, R., Grosskopf, S., Norris, M. and Zhang, Z. (1994). Productivity growth, technical progress and efficiency change in industrialized countries. *American Economic Review* **84**, pp. 66–83.

[22] Fritsch, M. and Stephan, A. (2004). The distribution and heterogeneity of technical efficiency within industries – An empirical assessment. Discussion Paper **453**, DIW Berlin.

[23] Furobotn, E.G. and Richter, R. (1992). (Eds.) *The New Institutional Economics: A Collection of Articles from The Journal of Institutional Economics.* Texas A&M University Press: College Station, TX.

[24] Green, A. and Mayes, D. (1991). Technical inefficiency in manufacturing industries. *Economic Journal* **101**, pp. 523–538.

[25] Grossman, G.M. and Helpman, E. (1991). *Innovation and Growth in the Global Economy.* MIT Press: Cambridge, MA.

[26] Hansen, F. and Jensen-Butler, C. (1996). Economic crisis and the regional and local economic effects of the welfare state: the case of Denmark. *Regional Studies* **30**, pp. 167–187.

[27] Jensen-Butler, C. (1992). Rural industrialization in Denmark and the role of public policy. *Urban Studies* **29**, pp. 881–904.

[28] Jensen-Butler, C. and Madsen, B. (2005). Decomposition analysis: an extended theoretical foundation and its application to the study of regional income growth in Denmark. *Environment and Planning* A **37**, pp. 2189–2208.

[29] Klump, R. and Preissler, H. (2000). CES production functions and economic growth. *Scandinavian Journal of Economics* **102**, pp. 41–56.

[30] Kneller, R. and Stevens, P.A. (2006). Frontier technology and absorptive capacity: evidence from OECD manufacturing industries. *Oxford Bulletin of Economics and Statistics* **68**, pp. 1–21.

[31] Krüger, J.J. (2006). Using the manufacturing productivity distribution to evaluate growth theories. *Structural Change and Economic Dynamics* **17**, pp. 248–258.

[32] Kumar S. and Russell, R. (2002). Technological change, technological catch-up, and capital deepening: relative contributions to growth and convergence. *American Economic Review* **92**, pp. 527–548.

[33] Kumbhakar, S.C. (1990). Production frontiers, panel data and time-varying technical inefficiency. *Journal of Econometrics* **46**, pp. 201–211.

[34] Kumbhakar, S.C., Ghosh, S. and McGuckin, J.T. (1991). A generalized production frontier approach for estimating determinants of inefficiency in US dairy farms. *Journal of Business and Economic Statistics* **9**, pp. 279–286.

[35] Kumbhakar, S.C. and Lovell, C.A.K. (2000). *Stochastic Frontier Analysis*. Cambridge University Press: Cambridge, UK.

[36] Lucas, R.E. Jr. (1988). On the mechanics of economic development. *Journal of Monetary Economics* **22**, pp. 3–42.

[37] Lundvall, B.-Å. (1992). (Ed.) *National Systems of Innovation*. Francis Pinter: London.

[38] Mankiw, N.G. (1995). The growth of nations. *Brookings Papers on Economic Activity* **1**, pp. 275–326.

[39] Mankiw, N.G., Romer, D. and Weil, D. (1992). A contribution to the empirics of economic growth. *Quarterly Journal of Economics* **107**, pp. 407–437.

[40] Masanjala, W.H. and Papageorgiou, C. (2004). The Solow model with CES technology: nonlinearities and parameter heterogeneity. *Journal of Applied Econometrics* **19**, pp. 171–201.

[41] Meeusen, W. and Van den Broeck, J. (1977). Efficiency estimation from Cobb-Douglas production functions with composed error. *International Economic Review* **18**, pp. 435–444.

[42] Nelson, R.R. and Winter, S.G. (1982). *An Evolutionary Theory of Economic Change*. Harvard University Press: Cambridge, Mass.

[43] Nelson, R.R. and Winter, S.G. (2002). Evolutionary theorising in economics. *Journal of Economic Perspectives* **16**, pp. 23–46.

[44] Prescott, E.C. (1998). Needed: a theory of total factor productivity. Lawrence R. Klein Lecture 1997. *International Economic Review* **39**, pp. 525–551.

[45] Reifschneider, D. and Stevenson, R. (1991). Systematic departures from the frontier: a framework for the analysis of firm inefficiency. *International Economic Review* **32**, pp. 715–723.

[46] Romer, P.M. (1986). Increasing returns and long-run growth. *Journal of Political Economy* **94**, pp. 1002–1037.

[47] Romer, P.M. (1990). Endogenous technological change. *Journal of Political Economy* **98**, pp. S71–S102.

[48] Sala-i-Martin, X. (1997). I just run two million equations. *American Economic Review* Papers and Proceedings **87**, pp. 178–183.

[49] Schmidt, P. and Lovell, C.A.K. (1979). Estimating technical and allocative inefficiency relative to stochastic production and cost frontiers. *Journal of Econometrics* **9**, pp. 343–366.

[50] Simar, L. and Wilson, P.W. (2005). Estimation and inference in cross-sectional, stochastic frontier models. Technical Report **0541**, Institut de Statistique, Université Catholique de Louvain.

[51] Solow, R.M. (1956). A contribution to the theory of economic growth. *Quarterly Journal of Economics* **70**, pp. 65–94.

[52] Solow, R.M. (1957). Technical change and aggregate production function. *Review of Economics and Statistics* **39**, pp. 312–320.

[53] Solow, R.M. (1960). Investment and technical progress. In: Arrow, K.J., Karlin. S. and Suppes, P. (Eds.) *Mathematical Methods in the Social Sciences*, Proceedings of the First Stanford Symposium 1959. Stanford University Press: Stanford, pp. 89–104.

[54] Swan, T.W. (1956). Economic growth and capital accumulation. *Economic Record* **32**, pp. 334–361.

[55] Tsionas, E.G. (2006). Inference in dynamic stochastic frontier models. *Journal of Applied Econometrics* **21**, pp. 669–676.

[56] Williamson, O.E. (1996). *The Mechanisms of Governance*. Oxford University Press: Oxford, UK.

Appendix A: MEASUREMENT OF CAPITAL STOCK AND VINTAGE

As discussed in the text, a major challenge was in using annual data on investment in buildings, machines and transport at the region and sector level to estimate capital stock and the age of capital. Essentially, our data construction strategy was to obtain annual capital stock estimates by aggregating depreciated values of lagged investment for several preceding years. The depreciation rates used varied by the type of investment as well as with the lag. Vintage of capital for each year at the region × sector level was similarly estimated as a weighted average of the age of capital, taking the depreciated value of capital stock as the respective weight for each vintage.

Crucially, the estimation of both capital stock and age of capital relied on obtaining appropriate depreciation rates for different types of capital. For this purpose, we used two alternative methods.

Method 1: In this rather simplistic formulation, we considered fixed depreciation rates of 1/30, 1/10 and 1/6 of initial book value per year for buildings, machines and transport respectively. These fixed depreciation rates approximately matched average annual depreciation rates for aggregate capital stock in Denmark over the period of analysis.

Following this depreciation scheme, we computed total value of capital stock for each sector, region and year (1979-1993). Thus, capital stock, by type of capital, in the year t for region r and sector i was estimated as:

$$K_{rit}^{(tr)} = \sum_{u=0}^{5} \frac{(6-u)}{6} . I_{ri,t-u}^{(tr)}; K_{rit}^{(ma)} = \sum_{u=0}^{9} \frac{(10-u)}{10} . I_{ri,t-u}^{(ma)}; K_{rit}^{(ba)} = \sum_{u=0}^{29} \frac{(30-u)}{30} . I_{ri,t-u}^{(ba)}$$

where $K_{rit}^{(tr)}, K_{rit}^{(ma)}$ and $K_{rit}^{(ba)}$ denote capital stock in transport, machinery and buildings respectively and similarly $I_{rit}^{(tr)}, I_{rit}^{(ma)}$ and $I_{rit}^{(ba)}$ denote investment by type of capital goods.

We used a similar procedure to estimate the average age of capital. For this purpose, a weighted average was used, where the age of investment in each year was simply weighted by its depreciated value in the current year. For example, average age of transport capital in the year t for region r and sector i was estimated as:

$$a_{rit}^{(tr)} = \frac{1}{K_{rit}^{(tr)}} . \sum_{u=0}^{5} \frac{(6-u)}{6} . (u + 0.5) . I_{ri,t-u}^{(tr)}$$

32

where $a_{rit}^{(tr)}$ is the average age of transport capital (in years). It is assumed that investments during a given year have an average age of 6 months when the accounting year closes. The average age of capital for the other types of capital were computed similarly.

Method 2: The above method is simplistic and may not be satisfactory, in that it assumes a fixed rate of depreciation of capital irrespective of the vintage. It also assumes that capital depreciates at a constant rate rather than a compounded depreciation rule[14].

As an alternative, we collected data (from Danmarks Statistik) on total depreciation and stock of capital at replacement cost, by sector and year for the entire period under study. Using these data, we estimated a non-linear regression model regressing log of aggregate depreciation on lagged log-investments for several previous years[15].

The estimated compounded depreciation rates were the following:
Buildings: past 1-12 years – 0.018; 13-20 years – 0.040; 21-28 years – 0.084.
Machinery: past 1-3 years – 0.000; 4-6 years – 0.079; 7-9 years – 0.372.
Transport: past 1-3 years – 0.078; 4–5 years – 0.360.
For each capital type, we assumed zero depreciation for the current year.

There were several nice features of these estimation results. First, the R^2 is 0.988, which is very good given that we have 144 observations and only 8 estimated depreciation parameters. The residuals showed some evidence of heteroscedasticity, but autocorrelation was not significant. Second, for each type of capital, the residual undepreciated capital is relatively low. After 28 years, 29 percent of initial investment in buildings remain; 19 percent of machinery remain after 9 years; and 22 percent of transport investment remain undepreciated after 5 years. Third, the *a priori* expected relationship of increasing depreciation rates with vintage of capital is maintained in the estimates.

Assuringly, the empirical results obtained by adopting the two alternative depreciation rules to compute capital stock and age of capital are very similar. Hence, in the interests of clarity in exposition, we report empirical results only using Method 2. Results using Method 1 are available with the authors.

---

[14]Under this method, transport investment incurred in a year depreciates to zero in 6 years' time, for example.

[15]Previous 28 years for buildings, 9 years for machinery and 5 years for transport.

Table 3: Estimates for Alternative Models[16]

Variable	Model (a) without vintage	Model (b)
REGION DUMMIES		
– Bornholm (base)	**0**	**0**
– Hovedstad	0.290** (9.89)	0.239** (8.29)
– Vestsjælland	0.288** (9.85)	0.225** (8.20)
– Storstrøm	0.115** (3.89)	0.054* (1.96)
– Fyn	0.213** (7.34)	0.129** (4.54)
– Søndre Jylland	0.297** (10.18)	0.252** (8.90)
– Ribe	0.357** (12.33)	0.243** (8.72)
– Vejle	0.298** (10.01)	0.186** (6.40)
– Århus	0.267** (9.10)	0.160** (5.59)
– Ringkøbing	0.349** (11.74)	0.229** (7.74)
– Viborg	0.253** (8.75)	0.135** (4.68)
– Nord Jylland	0.197** (6.67)	0.113** (3.99)
AVGE. VINTAGE OF CAPL.		
– Food	–	0.060** (6.43)
– Textiles	–	0.032** (8.28)
– Wood/Furniture	–	0.023** (3.45)
– Paper/Publishing	–	0.046 (4.11)
– Chemicals	–	0.069 (12.48)
– Glass/ Ceramics	–	0.037** (4.65)
– Metals/Engg.	–	0.002 (0.56)

---

[16] z-values in parentheses. The final column reports estimates of a conditional mean model, where $\widehat{\mu}$ varies across sector-time combinations.

+, *, ** : significant at 10 percent, 5 percent and 1 percent levels respectively.

Table 3: ESTIMATES FOR ALTERNATIVE MODELS (Contd.)

Variable	Model (a) without vintage	Model (b)
– Other mfg.	–	0.014** (2.79)
– Public sector	–	0.057** (3.03)
CAPL.-LAB. RATIO		
– Food	0.364** (17.71)	0.270** (5.25)
– Textiles	0.273** (12.74)	0.296** (12.00)
– Wood/Furniture	0.284** (13.03)	0.339** (8.61)
– Paper/Publishing	0.296** (13.73)	0.213** (3.24)
– Chemicals	0.332** (16.87)	0.129** (4.05)
– Glass/ Ceramics	0.296** (15.06)	0.273** (6.68)
– Metals/ Engg.	0.305** (13.96)	0.500** (17.66)
– Other mfg.	0.312** (14.05)	0.422** (11.18)
– Public sector	0.258** (13.01)	0.181$^+$ (1.95)
CONSTANT	9.665 (0.85)	9.002** (79.66)
Sample size	1,590	1,590
Wald χ^2 goodness-of-fit	1129.62	1582.34
d.f. / p-value	20 / 0.00	29 / 0.00
$\ln \widehat{\sigma}^2$, $\sigma^2 = \sigma_u^2 + \sigma_v^2$	−2.884** (−79.54)	−3.181** (−29.23)
$\widehat{\sigma}^2$	0.0559	0.0415
$\widehat{\mu}$	0.320 (0.03)	–
Idiosyn. err. var., $\widehat{\sigma}_v^2$	0.0524	0.0413
Skewed err. var., $\widehat{\sigma}_u^2$	0.0035	0.0002

ABOUT THE CDMA

The **Centre for Dynamic Macroeconomic Analysis** was established by a direct grant from the University of St Andrews in 2003. The Centre funds PhD students and facilitates a programme of research centred on macroeconomic theory and policy. The Centre has research interests in areas such as: characterising the key stylised facts of the business cycle; constructing theoretical models that can match these business cycles; using theoretical models to understand the normative and positive aspects of the macroeconomic policymakers' stabilisation problem, in both open and closed economies; understanding the conduct of monetary/macroeconomic policy in the UK and other countries; analyzing the impact of globalization and policy reform on the macroeconomy; and analyzing the impact of financial factors on the long-run growth of the UK economy, from both an historical and a theoretical perspective. The Centre also has interests in developing numerical techniques for analyzing dynamic stochastic general equilibrium models. Its affiliated members are Faculty members at St Andrews and elsewhere with interests in the broad area of dynamic macroeconomics. Its international Advisory Board comprises a group of leading macroeconomists and, ex officio, the University's Principal.

Affiliated Members of the School

Dr Fabio Aricò.
Dr Arnab Bhattacharjee.
Dr Tatiana Damjanovic.
Dr Vladislav Damjanovic.
Prof George Evans.
Dr Gonzalo Forgue-Puccio.
Dr Laurence Lasselle.
Dr Peter Macmillan.
Prof Rod McCrorie.
Prof Kaushik Mitra.
Prof Charles Nolan (Director).
Dr Geetha Selvaretnam.
Dr Ozge Senay.
Dr Gary Shea.
Prof Alan Sutherland.
Dr Kannika Thampanishvong.
Dr Christoph Thoenissen.
Dr Alex Trew.

Senior Research Fellow

Prof Andrew Hughes Hallett, Professor of
    Economics, Vanderbilt University.

Research Affiliates

Prof Keith Blackburn, Manchester University.
Prof David Cobham, Heriot-Watt University.
Dr Luisa Corrado, Università degli Studi di Roma.
Prof Huw Dixon, Cardiff University.
Dr Anthony Garratt, Birkbeck College London.
Dr Sugata Ghosh, Brunel University.
Dr Aditya Goenka, Essex University.
Prof Campbell Leith, Glasgow University.
Dr Richard Mash, New College, Oxford.
Prof Patrick Minford, Cardiff Business School.
Dr Gulcin Ozkan, York University.

Prof Joe Pearlman, London Metropolitan
    University.
Prof Neil Rankin, Warwick University.
Prof Lucio Sarno, Warwick University.
Prof Eric Schaling, Rand Afrikaans University.
Prof Peter N. Smith, York University.
Dr Frank Smets, European Central Bank.
Prof Robert Sollis, Newcastle University.
Prof Peter Tinsley, Birkbeck College, London.
Dr Mark Weder, University of Adelaide.

Research Associates

Mr Nikola Bokan.
Mr Farid Boumediene.
Mr Johannes Geissler.
Mr Michal Horvath.
Ms Elisa Newby.
Mr Ansgar Rannenberg.
Mr Qi Sun.

Advisory Board

Prof Sumru Altug, Koç University.
Prof V V Chari, Minnesota University.
Prof John Driffill, Birkbeck College London.
Dr Sean Holly, Director of the Department of
    Applied Economics, Cambridge University.
Prof Seppo Honkapohja, Cambridge University.
Dr Brian Lang, Principal of St Andrews University.
Prof Anton Muscatelli, Heriot-Watt University.
Prof Charles Nolan, St Andrews University.
Prof Peter Sinclair, Birmingham University and
    Bank of England.
Prof Stephen J Turnovsky, Washington University.
Dr Martin Weale, CBE, Director of the National
    Institute of Economic and Social Research.
Prof Michael Wickens, York University.
Prof Simon Wren-Lewis, Oxford University.

RECENT WORKING PAPERS FROM THE
CENTRE FOR DYNAMIC MACROECONOMIC ANALYSIS

Number	Title	Author(s)
CDMA06/12	Taking Personalities out of Monetary Policy Decision Making? Interactions, Heterogeneity and Committee Decisions in the Bank of England's MPC	Arnab Bhattacharjee (St Andrews) and Sean Holly (Cambridge)
CDMA07/01	Is There More than One Way to be E-Stable?	Joseph Pearlman (London Metropolitan)
CDMA07/02	Endogenous Financial Development and Industrial Takeoff	Alex Trew (St Andrews)
CDMA07/03	Optimal Monetary and Fiscal Policy in an Economy with Non-Ricardian Agents	Michal Horvath (St Andrews)
CDMA07/04	Investment Frictions and the Relative Price of Investment Goods in an Open Economy Model	Parantap Basu (Durham) and Christoph Thoenissen (St Andrews)
CDMA07/05	Growth and Welfare Effects of Stablizing Innovation Cycles	Marta Aloi (Nottingham) and Laurence Lasselle (St Andrews)
CDMA07/06	Stability and Cycles in a Cobweb Model with Heterogeneous Expectations	Laurence Lasselle (St Andrews), Serge Svizzero (La Réunion) and Clem Tisdell (Queensland)
CDMA07/07	The Suspension of Monetary Payments as a Monetary Regime	Elisa Newby (St Andrews)
CDMA07/08	Macroeconomic Implications of Gold Reserve Policy of the Bank of England during the Eighteenth Century	Elisa Newby (St Andrews)
CDMA07/09	S,s Pricing in General Equilibrium Models with Heterogeneous Sectors	Vladislav Damjanovic (St Andrews) and Charles Nolan (St Andrews)
CDMA07/10	Optimal Sovereign Debt Write-downs	Sayantan Ghosal (Warwick) and Kannika Thampanishvong (St Andrews)
CDMA07/11	Bargaining, Moral Hazard and Sovereign Debt Crisis	Syantan Ghosal (Warwick) and Kannika Thampanishvong (St Andrews)
CDMA07/12	Efficiency, Depth and Growth: Quantitative Implications of Finance and Growth Theory	Alex Trew (St Andrews)

CDMA07/13	Macroeconomic Conditions and Business Exit: Determinants of Failures and Acquisitions of UK Firms	Arnab Bhattacharjee (St Andrews), Chris Higson (London Business School), Sean Holly (Cambridge), Paul Kattuman (Cambridge).
CDMA07/14	Regulation of Reserves and Interest Rates in a Model of Bank Runs	Geethanjali Selvaretnam (St Andrews).
CDMA07/15	Interest Rate Rules and Welfare in Open Economies	Ozge Senay (St Andrews).
CDMA07/16	Arbitrage and Simple Financial Market Efficiency during the South Sea Bubble: A Comparative Study of the Royal African and South Sea Companies Subscription Share Issues	Gary S. Shea (St Andrews).
CDMA07/17	Anticipated Fiscal Policy and Adaptive Learning	George Evans (Oregon and St Andrews), Seppo Honkapohja (Cambridge) and Kaushik Mitra (St Andrews)
CDMA07/18	The Millennium Development Goals and Sovereign Debt Write-downs	Sayantan Ghosal (Warwick), Kannika Thampanishvong (St Andrews)
CDMA07/19	Robust Learning Stability with Operational Monetary Policy Rules	George Evans (Oregon and St Andrews), Seppo Honkapohja (Cambridge)
CDMA07/20	Can macroeconomic variables explain long term stock market movements? A comparison of the US and Japan	Andreas Humpe (St Andrews) and Peter Macmillan (St Andrews)
CDMA07/21	Unconditionally Optimal Monetary Policy	Tatiana Damjanovic (St Andrews), Vladislav Damjanovic (St Andrews) and Charles Nolan (St Andrews)
CDMA07/22	Estimating DSGE Models under Partial Information	Paul Levine (Surrey), Joseph Pearlman (London Metropolitan) and George Perendia (London Metropolitan)

For information or copies of working papers in this series, or to subscribe to email notification, contact:

Johannes Geissler
Castlecliffe, School of Economics and Finance
University of St Andrews
Fife, UK, KY16 9AL

Email: jg374@at-andrews.ac.uk; Phone: +44 (0)1334 462445; Fax: +44 (0)1334 462444.