EUROPEAN CENTRAL BANK

EUROSYSTEM

WORKING PAPER SERIES

NO 1504 / JANUARY 2013

INTERNATIONAL R&D SPILLOVERS

TECHNOLOGY TRANSFER VS. R&D SYNERGIES

Alistair Dieppe and Jan Mutl

In 2013 all ECB publications feature a motif taken from the €5 banknote

Acknowledgements
We are grateful to Robert Inklaar, Wolfgang Keller, Rolf Strauch, Günter Coenen, and Seminar participants at the ECB for comments. The views expressed in this paper do not necessarily represent those of the ECB.

Alistair Dieppe (corresponding author)
European Central Bank; e-mail: alistair.dieppe@ecb.europa.eu

Jan Mutl
European Business School; e-mail: jan mutl@ebs.edu

Address	Kaiserstrasse 29, 60311 Frankfurt am Main, Germany
Postal address	Postfach 16 03 19, 60066 Frankfurt am Main, Germany
Telephone	+49 69 1344 0
Internet	http://www.ecb.europa.eu
Fax	+49 69 1344 6000

ISSN	1725-2806 (online)
EU Catalogue No	QB-AR-13-001-EN-N (online)

Abstract

We estimate a model of international technological spillovers that allows for both international and inter-sectoral technology transfer, as well as international and inter-sectoral synergies in research and development (R&D). Furthermore we allow for a dynamic interaction in explaining total factor productivity (TFP). Relative to the existing literature, our model enables us make a judgment on the relative importance of the channels of international technology transmission. We find that direct technology transfer is positive while there are negative R&D spillovers. However, since R&D is found to positively affect TFP in own sector, the model implies that after accounting for both R&D and TFP spillovers, there is a total positive impact of R&D on TFP in the same sector while the overall impact of R&D on TFP in other sectors and countries is negative. Our results indicate that, by not distinguishing among different channels of transmission, some models previously estimated in the literature may suffer from omitted variable bias.

Keywords: TFP, Total Factor Productivity, R&D, Research and Development, International Spillovers, Technology Transfer

JEL classification: C21, C23, D24, O30

Non-technical summary

A major source of technical change leading to productivity growth comes from research and development (R&D) expenditure, both domestic R&D and via spillovers from international R&D investment. This paper improves upon the current literature by using a more comprehensive approach that makes use of a richer model specification. In particular, we allow both inter-sectoral and international technology transfers. This approach is similar to studies done at firm or plant level which often include endogenous factor inputs. Such a model allows us to judge whether international and/or sectoral technological spillovers operate through technology being transferred among country-sectors, or whether there are direct synergies in R&D among country-sectors, or whether both of these channels operate at the same time. We are also able to quantify the size of the dynamic effects.

Since under our specification, TFP in one country-sector influences TFP in other country-sectors, we have to deal with such endogeneity both in estimating and interpreting the model. We have derived the formulae for computing the total impact of R&D and for estimating we employed a two-step GMM procedure, that is an extension of the method proposed by Arellano and Bond (1991).

Our results confirm that R&D positively affects TFP in own sector in a magnitude that is comparable with those found in the literature. Nonetheless, this appears to be only part of the story. By accounting for a larger set of interactions we find that there are positive technology transfers (TFP spillovers) but negative R&D spillovers. This is in contrast to the estimates from an incomplete model which imply positive R&D synergies. The findings hence point to a significant omission that could potentially bias the results obtained in the previous literature. We interpret the negative R&D spillovers as consistent with a model where there is competition for a scarce input in the R&D production sector.

We also find that the estimated impacts are highly heterogenous among different countries and/or sectors which poses a number of further interesting questions, such as whether these findings are robust to countries selected in the sample (due to for example heterogeneity in country's institutional characteristics).

1. Introduction

There is a substantial number of papers in the literature that show that the major source of technical change leading to productivity growth comes from research and development (R&D) expenditure, both domestic R&D and via spillovers from international R&D investment. Coe and Helpman (1995) were the first to test the prediction of the trade and growth models of Grossmann and Helpman (1991) by allowing foreign R&D spillovers via the trade channel by weighting foreign R&D with import weights. They found a positive and statistically significant effect from foreign R&D. This work was followed by Franzen (2002), Branstetter (2001) and others who extended Coe and Helpman's analysis to include sectoral impacts in a study for 14 OECD countries and 22 manufacturing industries. Whilst they found higher elasticities for both domestic and foreign R&D, the average influence of international R&D was found to be smaller than that of intra-country spillovers. To some extent these findings are contradicted by other studies, including Eaton and Kortum (1999) where the impact of domestic R&D is about 200 times the size of the average rate of international spillovers between the G-5 countries. Furthermore, a number of more recent studies, including Higon (2004) find that international spillovers were not significant or negative. McGahan and Silverman (2006) and Buckley and Kafouros (2008) suggest this could be due to scarce inputs in the R&D production sector.or because competition effects lead to a reduction in rival's profits (de Bondt 1996).

One issue in the literature is the mechanism through which improvements in technology are propagated. Trade is one of the possible channels that is considered (Eaton and Kortum, 2002), but other channels include FDI, mobility of human capital, or geographical distance. Typically these channels are factored in by using different weights in the aggregation of foreign R&D (see Mohnen, 1996 and Hall et al., 2010 for a review). Although Eaton and Kortum (2002) develop a general equilibrium model of trade and use it to estimate the trade channel. Keller (1998) showed that import shares in the construction of the foreign R&D variable are not, in fact, essential to obtain Coe and Helpman's results. Other more recent work has focussed both on the spatial dimension and geographical closeness (Keller, 2002).

Lumenga-Neso et al. (2001) extended the basic model by incorporating the concept of 'indirect' trade-related R&D spillovers. These indirect spillovers are associated with available (rather than produced) levels of R&D. In their analysis if Country A imports from Country B and Country B imports from Country C, C could transmit knowledge to Country A even if A does not trade directly with Country C. Their empirical results suggest that these 'indirect' trade-related spillovers are at least as important as the 'direct' ones.

In this paper we extend the model of Franzen (2002) by allowing both inter-sectoral and international technology transfers as well as allowing dynamics to play a role. We also include contemporaneous total factor productivity (TFP) spillovers and, as a result, our model also captures the 'indirect' spillovers as in Lumenga-Neso et al. (2001). By allowing for a richer set of interactions in the model, we capture other potential factors not accounted for by R&D, i.e. we take into account potential endogeneity of productivity across sectors and space. Indeed, studies at firm or plant level often include endogenous factor inputs. Our generalized model enables us to separate out direct R&D synergies versus other spillovers and to judge the relative importance of the channels of international technology transfer.

The rest of the paper is organized as follows. Section 2 starts by outlining the general model which allows for endogeneity of TFP. Section 3 then spells out some implications of our empirical model. This then creates a number of issues for estimation and for solving the model which we address in the fourth section. Finally, in section 5 we present our estimates of the general model, along with two more restricted variants, and to the extent possible compare our results to previous estimates. We close by offering conclusions in section 6.

2. Empirical Model

A firm makes decisions of how much to invest into accumulation of knowledge and physical capital. As Doraszelski and Jaumandreu (2007), we assume that productivity of firms in industry k, country i in period t, denoted by y_{ikt}, is affected by the investment choices that the firms in this industry made in period $t-1$. As a result, the actual productivity in period t can be decomposed into its expected part and a random shock. The expected component is a function of the information set of the firm at time $t-1$ and hence also depends on the actual productivity in time $t-1$. Our variable of interest (y_{ikt}) can therefore be expected to follow an autoregressive process. Unlike in Doraszelski and Jaumandreu (2007), we also assume that investment choices and productivity levels of other firms also affect y_{ikt}.

As remarked in the introduction, such assumptions extends the basic model of Coe, Helpman and Hoffmaister (2008) along the lines of Franzen (2002). In addition, we allow for the inter-sectoral and international spillovers to operate with a lag. Furthermore we extend the basic model to include gains from technology transfers (proxied by TFP spillovers both international and intersectoral). That is, we allow for TFP in one sector-country to influence TFP in another sector-country, in addition to the previously considered knowledge spillovers.

Figure 1 illustrates a simple two-sector model. Previously the literature would only allow for effects along the solid lines, as in the left-hand panel (A), where only own-sector R&D has a direct effect on own-sector TFP. Subsequently Coe and Helpman (1995) added the dashed lines, by allowing for spillovers from one sector to another[1]. Our model is illustrated in the

[1] There are various other extensions of Coe and Helpman (1995) such as Lichtenberg and van Pottelsberghe

right-hand panel (B), where there are direct technology transfers from TFP(1) to TFP(2) and vice versa. This approach is similar to studies done at firm or plant level which often include endogenous factor inputs, see Hall et al. (2010) for a survey.

Such a model allows us to judge whether international and/or sectoral technological spillovers operate through technology being transferred among country-sectors, or whether there are direct synergies in R&D among country-sectors, or whether both of these channels operate at the same time. We are also able to quantify the size of the dynamic effects.

As in the literature, we denote the weighted average of R&D and TFP in

- the same country but other sectors by superscript d;
- same sector but other countries by superscript o;
- other sectors in other countries by superscript f;

i.e.

$$\begin{array}{ll} y^d_{ikt} = \sum_{l=1}^{n_i} w^{iod}_{kl;i} y_{ilt}, & x^d_{ikt} = \sum_{l=1}^{n_i} w^{iod}_{kl;i} x_{ilt}, \\ y^o_{ikt} = \sum_{j=1}^{n_c} w^{int}_{ij;t} y_{jkt}, & x^o_{ikt} = \sum_{j=1}^{n_c} w^{int}_{ij;t} x_{jkt}, \\ y^f_{ikt} = \sum_{\substack{l=1 \\ l \neq k}}^{n_i} \sum_{j=1}^{n_c} w^{int}_{ij;t} w^{iom}_{kl;i} y_{jlt} & x^f_{ikt} = \sum_{\substack{l=1 \\ l \neq k}}^{n_i} \sum_{j=1}^{n_c} w^{int}_{ij;t} w^{iom}_{kl;i} x_{jlt} \end{array} \quad (1)$$

where

- y_{ikt} is the log of TFP of an industry k in country i at time t,
- x_{ikt} is the log of the R&D of an industry k in country i at time t,
- $w^{iod}_{kl;i}$ are domestic (input-output based) weights that relate to the 'closeness' of industries k and l in a country i,
- $w^{iom}_{kl;i}$ are import (input-output based) weights that relate the 'closeness' of industry k in country i to imports of industry l,
- $w^{int}_{ij;t}$ are weights that relate to the 'closeness' of two countries i and j at time t (international weights),
- n_i denotes the number of industries and n_c the number of countries in our sample.

de la Potterie (1998) and Geishecker and Bitzer (2006).

Using this notation, we write our general model as:

$$
\begin{aligned}
y_{ikt} = {} & \phi y_{ik,t-1} \\
& + \rho_0^d y_{ikt}^d + \rho_1^d y_{ik,t-1}^d + \rho_0^o y_{ikt}^o + \rho_1^o y_{ik,t-1}^o + \rho_0^f y_{ikt}^f + \rho_1^f y_{ik,t-1}^f \\
& + \beta_0^d x_{ikt}^d + \beta_1^d x_{ik,t-1}^d + \beta_0^o x_{ikt}^o + \beta_1^o x_{ik,t-1}^o + \beta_0^f x_{ikt}^f + \beta_1^f x_{ik,t-1}^f \\
& + \beta_0 x_{ikt} + \beta_1 x_{ik,t-1} + \mu_{ik} + \varepsilon_{ikt}.
\end{aligned} \tag{2}
$$

The parameters of the model are ϕ, ρ's and β's where we interpret the ρ coefficients are measuring technology transfers, and the β coefficients as measuring R&D spillovers. The disturbance is composed of individual effects μ_{ik} that vary across countries and sectors and independent innovation term ε_{ikt}. We assume that the weights w are known and observable and discuss their construction in Section 5.

As a robustness check, we also estimate two restricted versions of the full model. Variant 1 is where only R&D affects TFP, so there is no technology transfer (via TFP). Variant 2 extends Variant 1 by allowing for a lagged effect of own-sector TFP. In each case, we use the same estimation methodology as for the full model (even for the restricted versions) by allowing lagged impacts and estimating in first differences. These variants are a more general specification than typically estimated in the literature.

3. Model Implications and Interpretation

The model outlined above contains a rich set of interaction in time and space. Observe that the variables y_{ikt}^d, y_{ikt}^o and y_{ikt}^f are by definition endogenous. This is because we allow TFP in one country-sector to influence TFPs in other country-sectors (e.g. through y_{jlt}^f in equations for other countries j), which in turn affect the TFP in the original sector (through e.g. y_{ikt}^o and y_{ikt}^f). Consequently, we have to deal with such endogeneity both when estimating but as well when interpreting the model. Notice, for example, that in a simple model without direct TFP spillovers (i.e. when all ρ parameters are zero), the β coefficients can be interpreted as measuring the size of the impact of the different components of R&D. This is no longer true in the full model (equation 2) where β's no longer are the partial derivatives of TFP with respect to R&D.[2]

To derive the formulas for total impact of R&D and to motivate our estimation strategy, we first stack and then solve the model. Stacking over countries and sectors yields, after

[2]See also Fisher and LeSage (2007) for the same point in the context of growth convergence regressions with contemporaneous spatial spillovers.

collecting terms,

$$\begin{aligned}\mathbf{y}_t =& \left[\rho_0^d \mathbf{W}^{iod} + \rho_0^o \mathbf{W}_t^{int} + \rho_0^f \left(\mathbf{W}_t^{int} \odot \mathbf{W}^{iom}\right)\right] \mathbf{y}_t \\ &+ \left[\phi \mathbf{I}_{n_c n_i} + \rho_1^d \mathbf{W}^{iod} + \rho_1^o \mathbf{W}_{t-1}^{int} + \rho_1^f \left(\mathbf{W}_{t-1}^{int} \odot \mathbf{W}^{iom}\right)\right] \mathbf{y}_{t-1} \\ &+ \left[\beta_0 \mathbf{I}_{n_c n_i} + \beta_0^d \mathbf{W}^{iod} + \beta_0^o \mathbf{W}_t^{int} + \beta_0^f \left(\mathbf{W}_t^{int} \odot \mathbf{W}^{iom}\right)\right] \mathbf{x}_t \\ &+ \left[\beta_1 \mathbf{I}_{n_c n_i} + \beta_1^d \mathbf{W}^{iod} + \beta_1^o \mathbf{W}_t^{int} + \beta_1^f \left(\mathbf{W}_t^{int} \odot \mathbf{W}^{iom}\right)\right] \mathbf{x}_{t-1} \\ &+ \mu + \varepsilon_t, \end{aligned} \tag{3}$$

where $\mathbf{I}_{n_c n_i}$ is an $n_c n_i \times n_c n_i$ identity matrix and

$$\begin{aligned} \mathbf{y}_t &= \left(y_{11t}, .., y_{1n_it}, ..., y_{n_c1t}, .., y_{n_cn_it}\right)', \\ \mathbf{x}_t &= \left(x_{11t}, .., x_{1n_it}, ..., x_{n_c1t}, .., x_{n_cn_it}\right)', \\ \varepsilon_t &= \left(\varepsilon_{11t}, .., \varepsilon_{1n_it}, ..., \varepsilon_{n_c1t}, .., \varepsilon_{n_cn_it}\right)', \\ \mu &= \left(\mu_{11}, .., \mu_{1n_i}, ..., \mu_{n_c1}, .., \mu_{n_cn_i}\right)'. \end{aligned} \tag{4}$$

The matrices $\mathbf{W}^{iod}$, $\mathbf{W}^{iom}$ and $\mathbf{W}_t^{int}$ consist of entries $w_{kl;i}^{iod}$, $w_{kl;i}^{iom}$ and $w_{ij;t}^{int}$ respectively, and $\odot$ denotes the Hadamard product. To simplify notation, we define matrices

$$\begin{aligned} \mathbf{W}_0^y &= \rho_0^d \mathbf{W}^{iod} + \rho_0^o \mathbf{W}^{int} + \rho_0^f \left(\mathbf{W}_t^{int} \odot \mathbf{W}^{iom}\right), \\ \mathbf{W}_1^y &= \phi \mathbf{I}_{n_c n_i} + \rho_1^d \mathbf{W}^{iod} + \rho_1^o \mathbf{W}_{t-1}^{int} + \rho_1^f \left(\mathbf{W}_{t-1}^{int} \odot \mathbf{W}^{iom}\right), \\ \mathbf{W}_0^x &= \beta_0 \mathbf{I}_{n_c n_i} + \beta_0^d \mathbf{W}^{iod} + \beta_0^o \mathbf{W}_t^{int} + \beta_0^f \left(\mathbf{W}_t^{int} \odot \mathbf{W}^{iom}\right), \\ \mathbf{W}_1^x &= \beta_1 \mathbf{I}_{n_c n_i} + \beta_1^d \mathbf{W}^{iod} + \beta_1^o \mathbf{W}_t^{int} + \beta_1^f \left(\mathbf{W}_{t-1}^{int} \odot \mathbf{W}^{iom}\right). \end{aligned} \tag{5}$$

Observe that these are functions of the (unobserved) parameters. The model then simplifies to

$$\mathbf{y}_t = \mathbf{W}_0^y \mathbf{y}_t + \mathbf{W}_1^y \mathbf{y}_{t-1} + \mathbf{W}_0^x \mathbf{x}_t + \mathbf{W}_1^x \mathbf{x}_{t-1} + \mu + \varepsilon_t. \tag{6}$$

Under regularity assumptions,[3] we can then obtain the solution to our model as

$$\mathbf{y}_t = \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1} \left(\mathbf{W}_1^y \mathbf{y}_{t-1} + \mathbf{W}_0^x \mathbf{x}_t + \mathbf{W}_1^x \mathbf{x}_{t-1} + \mu + \varepsilon_t\right). \tag{7}$$

The solution implies that the total impact of R&D (in own country-sector, as well as in other

[3]The regularity conditions include assumptions on the weights matrices and the parameter space that guarantee the existence of the inverse in equation (7). Typical assumptions are that the weight matrices $\mathbf{W}^{iod}$, $\mathbf{W}^{iom}$ and $\mathbf{W}^{int}$ are absolutely row and column summable. These assumptions are likely to be satisfied in our setting and the inverse in equation (7) exists for the point estimates we obtain. See Section 3.1 for more discussion.

country-sectors) will be

$$\frac{\partial \mathbf{y}_t}{\partial \mathbf{x}_t} = \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1} \mathbf{W}_0^x, \tag{8}$$

which is a $n_c n_i \times n_c n_i$ matrix. Its diagonal elements are then total contemporaneous impact of R&D on the own sector-country TFP.[4] We label these '*own sector impact of R&D*' since they measure the overall impact of R&D in a particular sector on that sector productivity, after all the contemporaneous spillovers have been taken into account. Note that due to the difference in the weights across countries and sectors, the total impact of R&D on TFP will be different in different countries and sectors even in a model where all the coefficients are restricted to be homogeneous.

Off-diagonal elements of the matrix $\frac{\partial \mathbf{y}_t}{\partial \mathbf{x}_t}$ measure total contemporaneous impact of R&D in other sectors on the TFP.[5] We sort these to three groups according to whether they correspond to an effect of R&D in a sector in the same country, or whether it is the effect of R&D in the same industry in another country, or neither of these. In presenting our results we then label estimates of these impacts as '*other domestic sector impact of R&D,*' '*same sector other country impact of R&D,*' and '*other country other sector impact of R&D,*' respectively.

The total impact of R&D should not be confused with partial direct impacts that are contained in the different components of the matrix $\mathbf{W}_0^x$. These measure the direct effect of R&D on TFP without taking into account the contemporaneous spillovers of TFP among countries and sectors. The direct R&D effects can, however, be compared to the strength of the direct TFP spillovers which are contained in the different components of the matrix $\mathbf{W}_0^y$. Therefore, comparison of the signs of the corresponding coefficients ρ_0^x and β_0^x will allow us to compare the directions of R&D synergies and technology transfers.

3..1 Stability and Impulse Responses

Our model contains both spatial and time lags and we now, therefore, briefly define and discuss the stability conditions both in the time and space dimensions. We then explore the dynamic responses of the model.

Note that from the stacked model, e.g. in (6), it follows that dynamic properties of the model in the spatial dimension are governed by the eigenvalues of the matrix $\mathbf{W}_0^y$. In particular, for stability in space we require that the eigenvalues of the matrix $\mathbf{W}_0^y$ are uniformly less than one in absolute value. The closer the largest absolute eigenvalue of $\mathbf{W}_0^y$ is to the unit circle, the more intensive will be the international TFP spillovers implied by

[4] I.e. comparable to coefficient β_0 in a model without TFP spillovers.

[5] Comparable to coefficients β_0^d, β_0^o and β_0^f in a model without contemporaneous TFP spillovers.

our model. Observe that this stability condition also guarantees the existence of the inverse $(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1}$ and hence makes sure that the solution of the model is well defined, see for example Theorem 5.6.9 and Corollary 5.6.16 in Horn and Johnson (1985).

Analogically, we note that from the solution of the model, e.g. in equation (7), it follows that the dynamic properties of the model in the time dimension are governed by the eigenvalues of the matrix $(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \mathbf{W}_1^y$. To make sure that the model is dynamically stable in the time dimension we thus need the largest absolute eigenvalue of this matrix to be less than one. Note that this will depend not only on the strength of the lagged response of TFP, measured by entries in the matrix $\mathbf{W}_1^y$, but also on the strength of the contemporaneous TFP spillovers captured by entries in the matrix $\mathbf{W}_0^y$. That is, the time series properties of the model depend on the autoregressive parameter ϕ, the lagged TFP spillover parameters ρ_1^d, ρ_1^o, and ρ_1^f, the contemporaneous TFP spillover parameters ρ_0^d, ρ_0^o, and ρ_0^f, as well as on the spatial weights $\mathbf{W}^{iod}$ and $\mathbf{W}^{int}$.

We can calculate impulse responses to a temporary increases in R&D stock in a particular sector. However, our model implies a nontrivial spatial and dynamic pattern even in absence of any changes to the R&D stock. Therefore, our impulse responses are calculated as differences among the trajectories of the TFP in this baseline and the TFP trajectories when R&D stock has been changed.

In particular the impulse responses are calculated as follows. First, recall that the model is

$$\mathbf{y}_t = (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} (\mathbf{W}_1^y \mathbf{y}_{t-1} + \mathbf{W}_0^x \mathbf{x}_t + \mathbf{W}_1^x \mathbf{x}_{t-1} + \mu + \varepsilon_t) .$$

Using backward substitution we get (assuming stability):

$$\begin{aligned}
\mathbf{y}_t &= (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} (\mathbf{W}_0^x \mathbf{x}_t + \mathbf{W}_1^x \mathbf{x}_{t-1} + \mu + \varepsilon_t) \\
&\quad + (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \mathbf{W}_1^y (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} (\mathbf{W}_1^y \mathbf{y}_{t-2} + \mathbf{W}_0^x \mathbf{x}_{t-1} + \mathbf{W}_1^x \mathbf{x}_{t-2} + \mu + \varepsilon_{t-1}) \\
&= \ldots \\
&= (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \left(\sum_{k=0}^{\infty} \left[\mathbf{W}_1^y (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \right]^k (\mathbf{W}_0^x \mathbf{x}_{t-k} + \mathbf{W}_1^x \mathbf{x}_{t-1-k} + \mu + \varepsilon_{t-k}) \right) \\
&= (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \mathbf{W}_0^x \mathbf{x}_t \\
&\quad + (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \left(\sum_{k=1}^{\infty} \left(\left[\mathbf{W}_1^y (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \right]^k \mathbf{W}_0^x + \left[\mathbf{W}_1^y (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \right]^{k-1} \mathbf{W}_1^x \right) \mathbf{x}_{t-k} \right) \\
&\quad + (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \left(\sum_{k=0}^{\infty} \left[\mathbf{W}_1^y (\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y)^{-1} \right]^k (\mu + \varepsilon_{t-k}) \right) .
\end{aligned}$$

Therefore, our impulse response are obtained for $k > 0$ as:

$$\frac{\partial \mathbf{y}_t}{\partial \mathbf{x}_{t-k}} = \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1} \left(\left[\mathbf{W}_1^y \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1}\right]^k \mathbf{W}_0^x + \left[\mathbf{W}_1^y \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1}\right]^{k-1} \mathbf{W}_1^x \right).$$

4. Estimation Methodology

Given the size of our panel, we treat the individual effects μ_{ik} as incidental parameters and use first differencing in time to obtain a model that can be consistently estimated. We employ a two-step GMM procedure which is an extension of the method proposed by Arellano and Bond (1991). Our procedure relies on moment conditions utilized by Arellano and Bond, appended by moment conditions for the contemporaneous spatial lags of the endogenous variables (y_{ikt}^d, y_{ikt}^o and y_{ikt}^f). The initial step of the GMM procedure is an instrumental variable estimation and hence we motivate our additional moment conditions in terms of instruments.

Recall that the solution to our model is

$$\mathbf{y}_t = \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1} \left(\mathbf{W}_1^y \mathbf{y}_{t-1} + \mathbf{W}_0^x \mathbf{x}_t + \mathbf{W}_1^x \mathbf{x}_{t-1} + \mu + \varepsilon_t\right). \tag{9}$$

Under regularity assumptions,[6] we can follow the approach of Kelejian and Prucha (1998) and expand the inverse in the above equation by a geometric series expansion:

$$\mathbf{y}_t = \sum_{s=1}^{\infty} \left(\mathbf{W}_0^y\right)^s \left(\mathbf{W}_1^y \mathbf{y}_{t-1} + \mathbf{W}_0^x \mathbf{x}_t + \mathbf{W}_1^x \mathbf{x}_{t-1} + \mu + \varepsilon_t\right). \tag{10}$$

Thus a valid set of instruments for $\Delta \mathbf{y}_t^d = \mathbf{W}^{iod} \Delta y_t$ includes:[7]

$$\mathbf{W}^{iod} \left(\mathbf{W}_0^y\right)^s \left(\mathbf{W}_1^y \mathbf{y}_{t-2-q} + \mathbf{W}_0^x \Delta \mathbf{x}_t + \mathbf{W}_1^x \Delta \mathbf{x}_{t-1}\right), \tag{11}$$

for $s, q \geq 0$. Note that the matrices $\mathbf{W}_r^y$ and $\mathbf{W}_r^x$ contain unknown parameters and hence

[6] This follows under the same regularity conditions that guarantee the existence of the inverse in the expression.

[7] Amemiya and Macurdy (1986)'s analysis for nonlinear IV suggests that the derivatives of the conditional mean yields the optimal instrument in forming the IV estimator. Thus an optimal instrument for $\Delta \mathbf{y}_t^d$ would be

$$\begin{aligned} &\mathbf{W}^{iod} \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1} \left(\mathbf{W}_1^y \mathbf{y}_{t-2} + \mathbf{W}_0^x \Delta \mathbf{x}_t + \mathbf{W}_1^x \Delta \mathbf{x}_{t-1}\right) \\ &+ \mathbf{W}^{iod} \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1} \mathbf{W}_1^y \left(\mathbf{W}_1^y \mathbf{y}_{t-2} + \mathbf{W}_0^x \mathbf{x}_{t-1} + \mathbf{W}_1^x \mathbf{x}_{t-2}\right) \\ &+ \mathbf{W}^{iod} \left(\mathbf{I}_{n_c n_i} - \mathbf{W}_0^y\right)^{-1} \mathbf{W}_1^y E\left[\mu | I_t\right], \end{aligned}$$

where I_t is the information set at time t. The term $E\left[\mu | I_t\right]$ then motivates using higher order lags of the variables as instruments.

these instruments are not feasible in the form they are expressed. However, after substituting and considering $s = 0$, we obtain that feasible and valid instruments include, among other terms, expressions of the form

$$\begin{aligned} \mathbf{W}^{iod}\mathbf{y}_{t-2-q} &= \mathbf{y}^{d}_{t-2-q}, \\ \mathbf{W}^{iod}\mathbf{x}_{t-p} &= \mathbf{x}^{d}_{t-p}, \end{aligned} \tag{12}$$

where $p = 0, 1, 2$ and $q \geq 0$. Analogically, valid instruments for $\Delta\mathbf{y}^{o}_{t}$ include $\mathbf{y}^{o}_{t-2-q}$ and $\mathbf{x}^{o}_{t-p}$, and valid instruments for $\Delta\mathbf{y}^{f}_{t}$ include $\mathbf{y}^{f}_{t-2-q}$ and $\mathbf{x}^{f}_{t-p}$. As a result, we consider a set of instruments consisting of twice and more lagged levels of the endogenous variables and all available current and lagged values of the exogenous variables. To overcome potential issues with endogeneity of R&D, and to obtain an estimator that is more robust, we only include the at least twice lagged levels of R&D among our set of instruments. Except for the extended set of moment conditions and the fact the all variables of the model are treated potentially as endogenous, the estimation procedure is the usual two-step GMM estimation.

5. Data and Results

5..1 Data Sources and Construction

Our panel data set covers 10 OECD countries and 12 sectors (see Table 3 in the appendix for a description of the sectors). The main source of the data is the KLEMS database (Timmer et al. 2007) where TFP is computed based on the value added basis. The estimates of TFP from this data are preferable to other estimates (e.g. from the OECD Stan database) as they take account of changes in the composition of the labour force as well as the effects of the rapid shift in investment towards Information and Communications Technology (ICT) goods in recent years.

R&D data comes from the OECD's ANBERD (Analytical Business Enterprise Research and Development) database. The R&D stock is derived using the perpetual inventory method assuming a depreciation rate. As in Coe and Hoffmaister (1999), R&D is measured in levels and is not indexed as in Coe and Helpman (1995) and Keller (1998). This allows us to capture size effects for R&D spillovers. The use of stocks is preferred to flows, as stocks allow us to capture medium to long term effects.

As we aggregate across sectors and countries the panel is balanced since the length of the available time series depends on the length of the minimum series. Therefore the dataset is limited to annual observations from 1988 to 2002 giving a total of 1800 observations, see figure 18 for nomalized plots of aggregate TFP and R&D stocks by country.

To construct the domestic (input-output based) weights $w_{kl;i}^{iod}$ that relate to the 'closeness' of industries k and l in a country i, we used the coefficients of the Leontief inverse of the domestic intermediate input-output tables provided by OECD (see Ahmad and Yamano, 2006). These I-O tables also allow us to distinguish between domestic and imported effects for the year 2000. Therefore, the weights $w_{kl;i}^{iom}$ on the import side are constructed in the same way as domestic but using the Leontief inverse of the import-based input-output tables. The weights, $w_{ij;t}^{int}$, that measure the 'closeness' of two countries i and j, were based on CIF imports in US$ from the IMF Direction of Trade Statistics and are computed as the share of bilateral imports in total imports.

The table below provides the summary statistics of the TFP (y) and R&D (x) variables as well as their weighted averages calculated using the different weights.

	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis
y	3.838106	4.012966	7.057009	0.024611	1.53836	-1.103209	4.285833
y^d	2.312866	1.660751	14.30593	0.008031	2.415239	2.158713	8.598918
y^o	0.548251	0.357619	3.355123	0	0.60655	1.974522	7.414163
y^f	0.5042	0.166621	5.797269	0.000805	0.841631	3.096261	15.17393
x	6.513747	7.114363	16.72643	0	4.020611	-0.23024	2.571914
x^d	4.729847	3.416278	34.75828	0.012759	5.484196	2.523707	11.01897
x^o	1.207124	0.748554	8.242168	0	1.468304	2.312601	9.270252
x^f	1.052929	0.330724	11.17556	0.001723	1.699557	2.836694	12.96215

5..2 Results

Table 1 presents the results of estimating the full model (1) along with two variants. Variant 1 is the simple model where all endogenous variables (TFP) are excluded, i.e. $\phi = \rho_0^d = \rho_1^d = \rho_0^o = \rho_0^o = \rho_0^f = \rho_0^f = 0$ and therefore only R&D operates. Variant 2 is an extension to Variant 1 where in addition to direct R&D impacts, there is also a lagged impact of own-sector TFP, i.e. $\phi \neq 0$.

In Variant 1, the model closest to the literature, as there is no endogeneity, the β coefficients can be interpreted as measuring the size of the impact of the different components of R&D. Compared to previous estimates, this variant both includes lags and separates out same sectors R&D both domestic and foreign. The same sector domestic impact has a coefficient of 0.11, which suggests a direct positive impact on TFP. The lagged term is slightly negative but not significant. The other sectors for same country coefficient, initially has a negative impact, but the lagged effect is significant and positive, suggesting that there is a delayed reaction for R&D to propagate through to TFP. Overall the combined effect is 0.12.

The same sector other country impact of spending of R&D is only significant on the lagged term with a positive coefficient of 0.15. Finally the impact of other sectors in other countries is negative and again only significant on the lagged term. However, this result of negative or no significant impact of foreign spillovers upon productivity is not at odds with findings from some other related studies (e.g. Aitken and Harrison 1999, McVicar 2002, Higon 2004) and could reflect a negative competition effect over any positive technological spillovers. Indeed, Branstetter (2001), and Keller (2002) show that knowledge spillovers are primarily intra-national. However, Keller (2004) argues that this bias towards intra-national spillovers has declined through time and they have become more international, and Mohnen (1996) shows that the impact is less robust to changes in the model specification. However, combining own-sector-foreign with other-sectors-foreign gives a positive result. This is in many ways consistent with the literature. Overall, though, the estimation does not provide a good fit to the data, implying that the simple model is missing other significant variables or channels.

We now turn to Variant 2, which extends Variant 1 with lagged same sector TFP. This implies that the lagged impacts cannot be directly interpreted. The lagged impact of same sector TFP is positive and highly significant with a coefficient of 0.14 suggesting that Variant 1 does not explain all factors for TFP. As in Variant 1 we find that the stock of same sector R&D capital is positively related to TFP with an elasticity of 0.06. The consequence of including lagged TFP is that the estimated direct impact of own sector R&D is smaller than in Variant 1. As with Variant 1 the foreign sectors impact seem to come through with a lag, but overall the results seem to be in line with other estimates in the literature. However, the p-value of the J-test reported in the last row of Table 1 (the Sagan test of over-identifying restrictions) suggest that the estimates might not be reliable.

The last column of Table 1 reports the estimated coefficients for the full model, which allows for both international and inter-sectoral technology transfer. Under this dynamic model, the impact of R&D cannot be directly ascertained from the model as contemporaneous cross-industry and spatial effects come through both via R&D and via TFP. However we observe that all the different channels are statistically significant which suggests that both technology transfer as well as international R&D spillovers are important. Furthermore the J-test confirms that our instrument set is valid. Our estimates imply that there are positive TFP transfers (the ρ coefficients are positive) and negative R&D spillovers (estimated β's are negative). This would be consistent with competition for scare resources in R&D production.

As discussed in Section 3, in order to compare the full model with Variants 1 and 2 we have to solve the model using equation (7) and derive the total impact of R&D once all the endogeneity has been taken into account, as in equation (8). This is measured by the partial derivative which is the response of TFP to a unit change in R&D. Table 2 reports average total impacts across 120 sectors-countries. These are directly comparable to the estimated coefficients of Variant 1. The estimates in Table 2 show that the contemporaneous overall own sector impact of R&D on TFP are positive but smaller in Variant 1. The results in Table 2 also show that the negative contemporaneous effects of the other sectors are partially offset in the second year. Overall, it seems that the positive own sector impact is quantitatively largest and more than offsets the negative cross sectoral spillovers. However, the results reported in Table 2 are means over all industries and countries and hide a significant amount of heterogeneity. This can be seen from the histograms in Figures 2-5. As the figures show there is cross-country heterogeneity, which is due to factors such as country size, sector size and differing impacts of sectors and countries, coming through the IO matrix and trade weights. The variations around the means reported in Table 2 reflects these differences. The histograms suggest that most industries have similar impacts but clearly there are some sectors which show relatively large effects compared to the others.

Figures 6 - 17 show the impulse responses to a temporary increase in R&D spending calculated as described in section 3.1. We group the impulse responses by originating sector - i.e. Figure 6 shows the responses to a shock in the wood sector in one country. Altogether this is 1200 (= 120 sectors times 10 countries) impulse responses in each figure. The impulse responses are converging towards zero over time, demonstrating that our estimates are dynamically stable. This can be seen directly by calculating the largest absolute eigenvalue of the matrix $\mathbf{W}_0^y$ (see Section 3.1) which for our estimated model is 0.8992.

6. Conclusions

This paper improves upon the current literature by using a more comprehensive approach that makes use of a richer model specification. In particular, we allow for both international and inter-sectoral technology transfer as well as international and inter-sectoral synergies in R&D. Furthermore we allow for a dynamic interaction in explaining TFP. Since under our specification, TFP in one country-sector to influences TFP in other country-sector, we have had to deal with such endogeneity both in estimating and interpreting the model. We have derived the formulae for computing the total impact of R&D and we employed a two-step GMM procedure, that is an extension of the method proposed by Arellano and Bond (1991), to estimate the model.

Our results confirm that R&D positively affects TFP in own sector in a magnitude that is comparable with those found in the literature. Nonetheless, this appears to be only part of the story. By accounting for a larger set of interactions we find that there are positive technology transfers (TFP spillovers) but negative R&D spillovers. This is in contrast to the estimates from an incomplete model which imply positive R&D synergies. The findings hence point to a significant omission that could potentially bias the results obtained in the previous literature. We interpret the negative R&D spillovers as consistent with a model where there is competition for a scarce input in the R&D production sector or leads to reduced profits in rival firms.

We also find that the estimated impacts are highly heterogenous among different countries and/or sectors which poses a number of further interesting questions, such as whether these findings are robust to countries selected in the sample (due to for example heterogeneity in country's institutional characteristics. c.f. Coe, Helpman and Hoffmaister, 2008).

References

[1] Ahmad, N. and N. Yamano, 2006, "The OECD Input-Output Database: 2006 Edition", *OECD STI* Working paper 2006/8

[2] Aitken, B. and Harrison, A., 1999,"Do domestic firms benefit from foreign direct investment? Evidence from Venezuela." *American Economic Review*, 89, pp 605-618

[3] Amemiya, T., and T. E. Macurdy, 1986. "Instrumental Variable Estimation of an Error-Components Model." *Econometrica* 54: No4, 869-881.

[4] Arrelano, M., and S.R. Bond, 1991, "Some Tests of Specification for Panel Data: Monte Evidence and an Application to Employment Equations", *Review of Economic Studies*, 58, 277-297.

[5] Branstetter, Lee, 2001, "Are Knowledge Spillovers International or Intranational in Scope? Microeconometric Evidence from the U.S. and Japan." *Journal of International Economics*, 53, pp 53-79.

[6] Buckley, P. J., and M. I. Kafouros, 2008, "Under what conditions do firms benefit from the research efforts of other organizations?", Research Policy Volume 37, Issue 2, pp 225–239.

[7] Coe, David and Helpman, Elhanan, 1995, "International R&D spillovers" *European Economic Review*, 39, pp. 859-87.

[8] Coe, D. and A. Hoffmeister, 1999, "Are There International R&D Spillovers Among Randomly Matched Trade Partners? A Response to Keller", *International Monetary Fund Working Paper* 99/18.

[9] Coe, D., E Helpman, and A. Hoffmaister, 2008, "International R&D Spillovers and Institutions.", *International Monetary Fund Working Paper* No. 08/104.

[10] De Bondt, R., 1996, "Spillovers and innovative activities.", *International Journal of Industrial Organisation* 15, pp. 1–28.

[11] Doraszelski, U., J. Jaumandreu, 2007, "R&D and productivity: Estimating production functions when productivity is endogenous", Universidad Carlos III de Madrid, Working Paper 07-86/52.

[12] Eaton, J., and Kortum, S., 1999, "International technology diffusion: theory and measurement" *International Economic Review*, 40, pp 537-70

[13] Eaton, J., and Kortum, S., 2002,“Technology, geography and trade” *Econometrica*, 70 pp1741-79

[14] Fisher, M.M. and J. LeSage, 2007, "Spatial Growth Regressions: Model Specification, Estimation and Interpretation", *mimeo*, Texas State University.

[15] Franzen, 2002, “Intersectoral and International R&D Knowledge Spillovers and Total Factor Productivity.” *Scottish Journal of Political Economy* Vol.49, No.3.

[16] Geishecker and Bitzer (2006): What Drives Trade-Related R&D Spillovers? Decomposing Knowledge-Diffusing Trade Flows", Economics Letters, 93, 2006, pp. 52-57.

[17] Grossmann, G. and Helpman, E., 1991, “Innovation and Growth in the Global Economy.” *Cambridge*, MA: MIT Press

[18] Hall, Bronwyn H., Jacques Mairesse, Pierre Mohnen, 2010, "Measuring the Returns to R&D", In: Bronwyn H. Hall and Nathan Rosenberg, Editor(s), Handbook of the Economics of Innovation, North-Holland, 2010, Volume 2, Pages 1033-1082, ISSN 2210-8807,

[19] Higon, Ma Dolores Anon, 2004, “The Impact of R&D Spillovers on UK Manufacturing TFP: A Dynamic Panel Approach” Working paper, Aston University

[20] Horn, R.A. and C.R Johnson, 1985, "Matrix Analysis", *Cambridge University Press*, NY, USA.

[21] Kelejian, H.H. and I.R. Prucha, 1998, "A generalized spatial two-stage least squares procedure for estimating a spatial autoregressive model with autoregressive disturbances", *Journal of Real Estate Finance and Economics* 17, 99-121.

[22] Keller, Wolfgang, 1998 “Are International R&D Spillovers Trade-related? Analyzing spillovers among randomly matched trade partners.” *European Economic Review*, 42, pp.1469-82

[23] Keller, W., 2002, “Geographic localization of international technology diffusion.” *American Economic Review*, 92, pp 120-142.

[24] Keller, W., 2004, “International Technology Diffusion” *Journal of Economic Literature*, 42, pp. 752 – 782.

[25] Lichtenberg, F. R., and B. van Pottelsberghe de la Potterie, 1998, "International R&D spillovers: A comment", *European Economic Review* 42, pp. 1483-1491.

[26] Lumenga-Neso, O., M.W. Schiff and M. Olarreaga, 2001, "On 'indirect' trade-related R&D spillovers". *Policy research working papers* 2580. Washington, D.C. : World Bank, Development Research Group.

[27] McGahan, A. M., B.S. Silverman, 2006, "Profiting from technological innovation by others: the effect of competitor patenting on firm value ", *Research Policy*, 35 (2006), pp. 1222–1242.

[28] McVicar, D., 2002, "Spillovers and foreign direct investment in UK manufacturing". *Applied Economics Letters* **9**: 297-300.

[29] Mohnen, P., 1996, "R&D Externalities and Productivity Growth" ,*STI Review*, OECD 18, pp 39-66

[30] Timmer, M.P., M. O'Mahony and B. van Ark, 2007, "EU KLEMS Growth and Productivity Accounts: An Overview.", *International Productivity Monitor* 14: 71-85. Centre for the Study of Living Standards.

Appendix

Table 1: GMM Estimates

(Sample 1988-2002, 10 countries, 12 sectors)

	Variant 1	*Variant 2*	*Full model*
$y_{ik,t-1}$		0.1434**	0.7848**
$y^d_{il,t}$			0.5308**
$y^d_{il,t-1}$			-0.3928**
$y^o_{jk,t}$			0.8556**
$y^o_{jk,t-1}$			-0.5413**
$y^f_{jl,t}$			0.5295**
$y^f_{jl,t-1}$			-0.7244**
$x_{ik,t}$	0.1120*	0.0574*	0.0763**
$x_{ik,t-1}$	-0.0097	0.0161	-0.0641**
$x^d_{il,t}$	-0.1620	-0.024	-0.1627**
$x^d_{il,t-1}$	0.2858**	0.1682	0.1510**
$x^o_{jk,t}$	0.0428	0.0890	-0.3716**
$x^o_{jk,t-1}$	0.1477**	0.2236**	0.3868**
$x^f_{jl,t}$	0.0163	0.0421	-0.1262**
$x^f_{jl,t-1}$	-0.1218**	-0.1755**	0.1979**
No. Observations	1800	1800	1800
S.E. of regression	0.115117	0.115285	0.142732
J-statistic	0	75.865	108.7457
(p-value)		(0.0000)	(0.41)

Notes: All variables in logs. Left-hand-side variable is log of TFP ($y_{ik,t}$)

*** denotes significance at the 5% level*

Table 2: Average total Impact of R&D on TFP
(Full model, sample 1988-2002, 10 countries, 12 sectors)

	t	$t-1$
Total own sector own country R&D impact: $\mathbf{x}_{ik}$	0.067	0.042
Total other domestic sectors impact of R&D: $\mathbf{x}^{d}_{il}$	−0.017	0.013
Total same sector other country impact of R&D: $\mathbf{x}^{o}_{jk}$	−0.006	0.006
Total other sector other country impact of R&D: $\mathbf{x}^{f}_{jl}$	−0.001	0.001

Notes: Unweighted average

Table 3: Description of sectors

Sector	**Description**	**ISIC coding**
FOD	Food	15-16
TEX	Textile	17-19
WOD	Wood and Paper	20-22
COK	Fuel	23
CHE	Chemicals	24
RUB	Rubber	25
NME	Minerals	26
MET	Metals	27-28
MEQ	Mech. Eng.	29
ELT	El. Eng.	30-33
TRA	Transport eq.	34-35
MAR	Other Man.	36-37

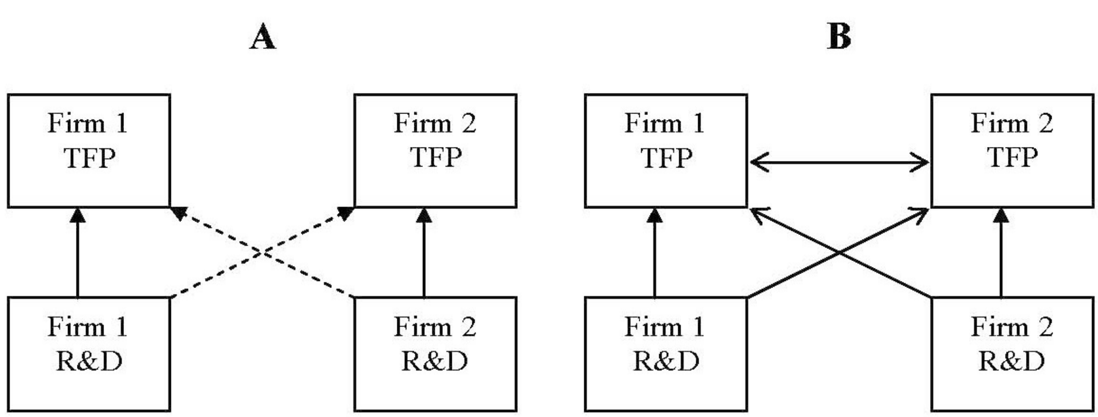

Figure 1: Channels of Interaction

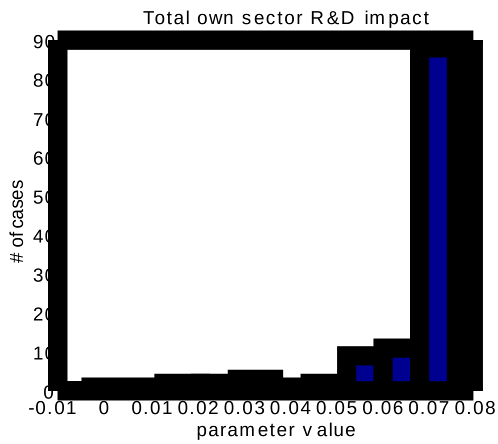

Figure 2

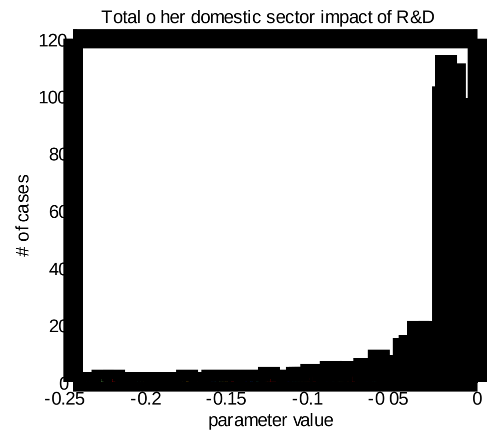

Figure 3

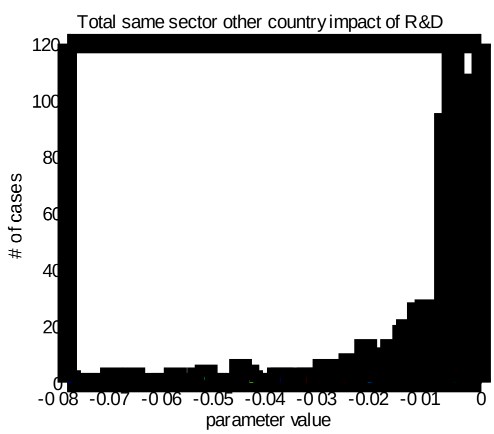

Figure 4

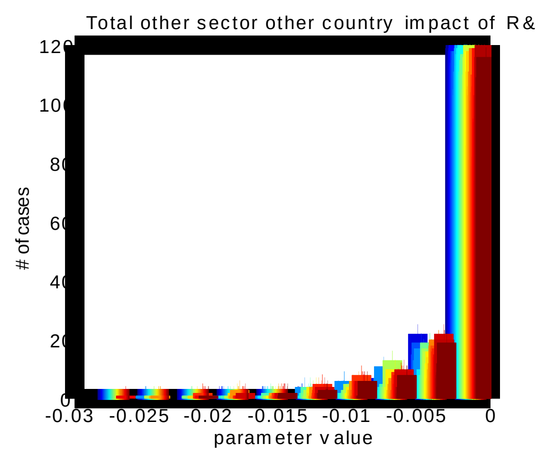

Figure 5

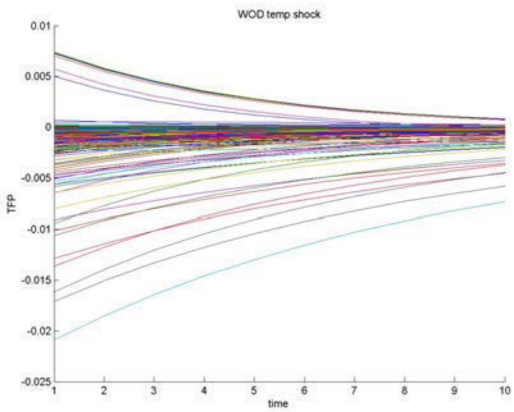

Figure 6

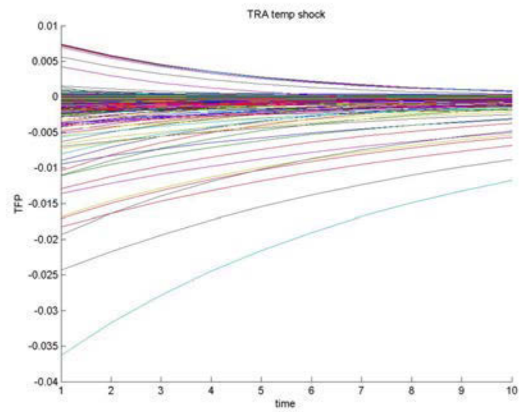

Figure 7

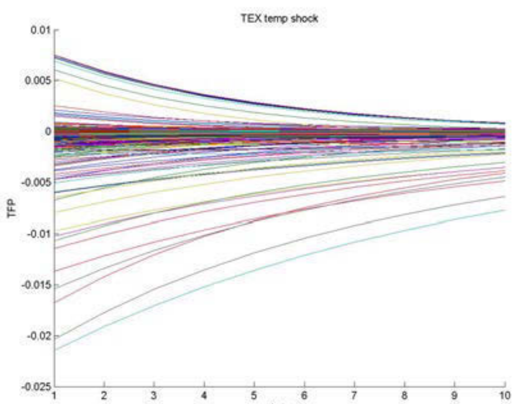

Figure 8

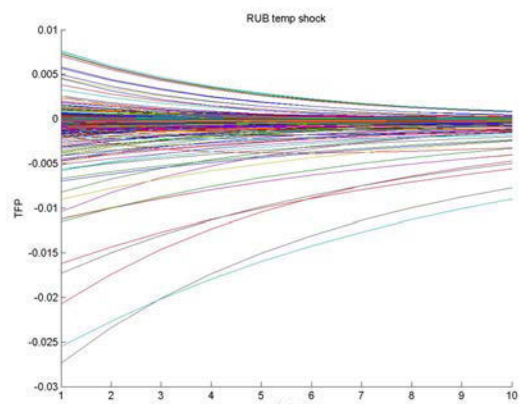

Figure 9

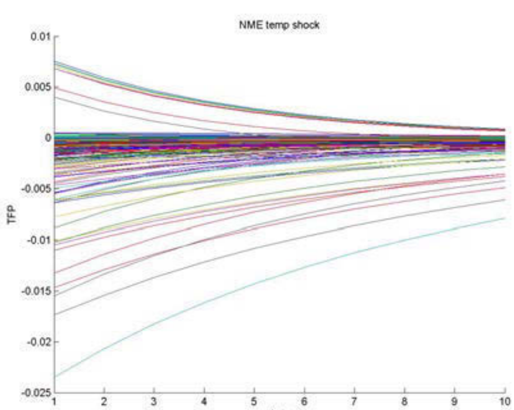

Figure 10

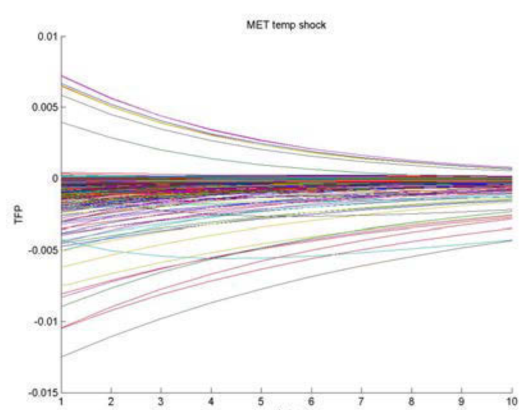

Figure 11

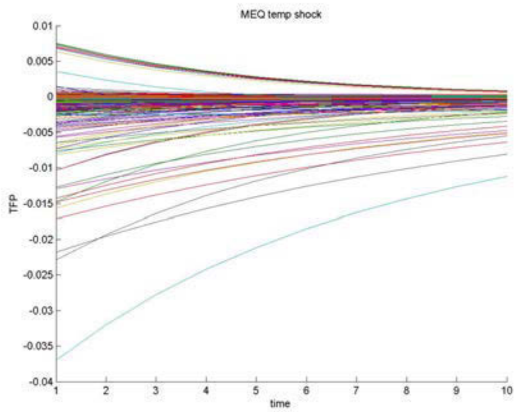

Figure 12

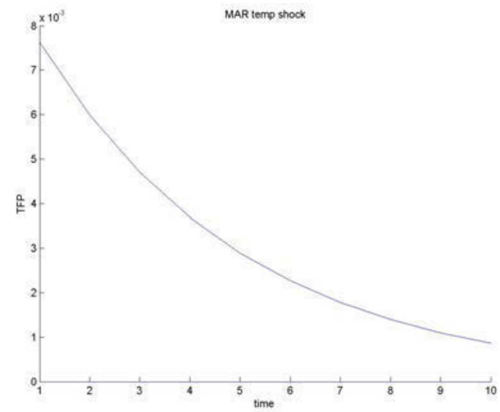

Figure 13

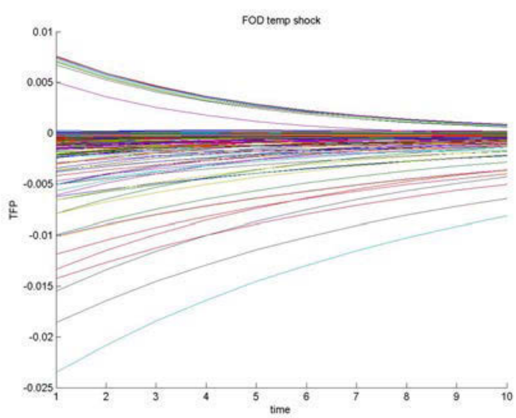

Figure 14

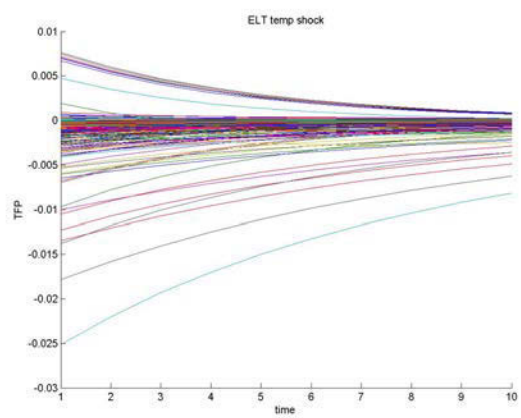

Figure 15

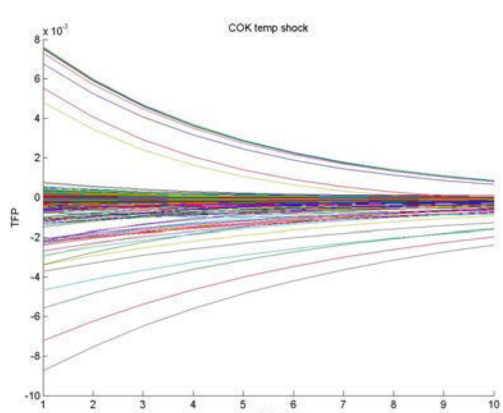

Figure 16

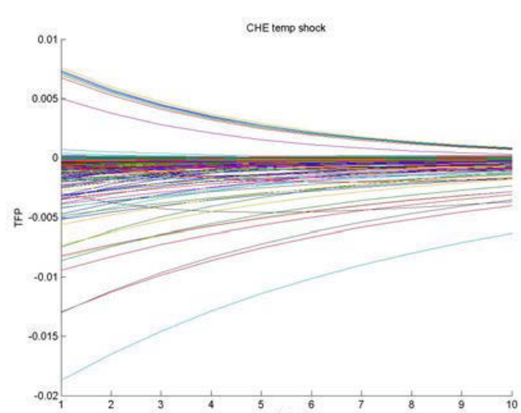

Figure 17

Figure 18: TFP and R&D normalised