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Section ARTICLES

Investigaciones Regionales

Modelling knowledge creation, investment decisions and economic growth in a spatial CGE setting

Francesco Di Comite*, Lesley Potters*

ABSTRACT: The expansion of knowledge is commonly understood as a key driver of economic growth. Yet, while knowledge production and economic growth have been extensively studied in isolation, few studies have tried to formalise the mechanism connecting the two elements from a spatial general equilibrium perspective. To fill this gap, in this paper we propose a model of knowledge creation building upon the multiregional spatial CGE model RHOMOLO to allow for endogenous knowledge production and investment decisions at the regional level. The innovation process is modelled through the interaction between researchers, investors and final good producers. Specifically, researchers in each region use their human capital together with local R&D-embedded capital and intermediates to produce ideas, enhanced by knowledge spillovers crossing regional borders. These ideas are then purchased by local investors and combined with their human capital and intermediate goods to be turned into new R&D-embedded capital, which adds up to the existing stock after having replaced the obsolete one. Lastly, after having paid a fixed entry cost, in each region firms produce goods for final and intermediate consumption by renting local R&D-embedded and human capital and combining it with an interregional bundle of intermediate goods, their productivity being enhanced by the availability of local public goods and services. The model is designed to be calibrated using a regionalised version of standard Social Accounting Matrices, such as the ones provided by the World Input Output Database.

JEL Classification: R13; R58; H54; C68; D58.

Keywords: multiregional spatial CGE; Endogenous R&D; Endogenous investment decisions.

* *European Commision, Joint Research Centre (JRC), Institute for Prospective Technological Studies (IPTS).*

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Modelización de creación de conocimiento, decisiones de inversión y crecimiento económico en un modelo espacial de equilibrio general computable

RESUMEN: La creación del conocimiento es habitualmente entendida como un vector clave de crecimiento económico. Mientras que la producción de conocimiento y el crecimiento económico han sido estudiados extensamente por separado, pocos estudios han intentado formalizar el mecanismo conectando los dos elementos desde la perspectiva de un modelo de equilibrio general espacial. Para rellenar este vacío, proponemos un modelo de creación de conocimiento aprovechando el modelo CGE multirregional RHOMOLO para la producción endógena de conocimientos y decisiones de inversión a nivel regional. El proceso de innovación se modeliza teniendo en cuenta la interacción entre investigadores, inversores y productores de bienes de consumo. Más en detalle, los investigadores en cada región usan su capital humano junto a activos que incorporan I+D y bienes intermedios para la producción de nuevas ideas, las cuales son mejoradas por la transferencia de conocimientos desde otras regiones. En la siguiente etapa, estas ideas son adquiridas por inversores locales y se combinan en el proceso de generar nuevos activos que incorporan I+D junto al capital humano y bienes intermedios, así aumentando el *stock* existente después de haber reemplazado la parte obsoleta. Por último, después del pago de los costes fijos de entrada, empresas regionales producen tanto bienes intermedios como bienes de consumo, alquilando capital humano y activos que incorporan I+D, combinándolos junto con un conjunto interregional de bienes intermedios en el proceso de producción, donde la disponibilidad de bienes y servicios públicos influye en su productividad. El modelo ha sido diseñado para ser calibrado con las versiones regionalizadas de matrices de contabilidad social, como son las que se pueden obtener de la base de datos World Input Output.

Clasificacion JEL: R13; R58; H54; C68; D58.

Palabras clave: CGE multiregional espacial; I&D endógeno; decisiones de inversión endógenas.

1. Introduction

What drives growth? Of the many institutional and economic factors interacting in bringing economic development about, including labour market participation, capital accumulation, good institutions and product market regulation, the focus in developed economies is increasingly turning to the expansion of knowledge. There is indeed a growing consensus, in both policy-oriented (Veugelers and Mrak, 2009) and academic (Bröcker and Soltwedel, 2010) literature, that the entire society is expected to benefit from the creation of marketable innovations, which foster investments, augment human capital and increase productivity and product variety. As stressed in the endogenous growth literature (as for example in Romer, 1994, or in Aghion and Howitt, 1998), the technological progress resulting from commercial innovation is the most straightforward way to endogenise the process of productivity growth, which has otherwise to be assumed exogenous. In practice, in these models one part

of the economy is assumed to be working on expanding the technological frontier, with the rest of the economy benefitting from the improved production capabilities (see Jones, 1995, or Romer, 1990). Economic growth then feeds back into knowledge creation by increasing its efficiency, in addition to the standard spatial spillovers capturing the positive externalities associated with neighbours' progress (Grossman and Helpman, 1991).

The objective of this paper is to bring this mechanism into a multiregional spatial CGE model setting. For this exercise, we build upon RHOMOLO, the European Commission's model used for the ex-ante impact assessment of EU Cohesion Policy at the regional level (Brandsma *et al.,* 2014), to present the possibility of including a mechanism of endogenisation of innovation and investments based on the accumulation of R&D-embedded capital.

A number of CGE models have applied a similar approach to the endogenisation of the R&D investment decision. In European Commission's QUEST III model realised by DG ECFIN (see Varga and In 't Veld, 2011, or Ratto *et al.,* 2009, for a detailed description), for example, a part of the skilled workers is employed in a specific R&D sector where new designs (blueprints) are invented as a function of previous technological stock, foreign technological stock and skilled workers in the R&D sector. In a more recent development of the model, non-liquidity constrained households buy the patents and rent it to the intermediate producing sector (see Varga and In 't Veld, 2011). Bye *et al.* (2009) describe a CGE model for measuring the implications of innovation policies in the small open economy of Norway. Here, the R&D sector produces patents to be acquired by capital firms for the production of a new capital variety. The production of new patents is a function of labour and is enhanced by the endogenous domestic spillovers from the accumulated stock of knowledge embodied in patents. However, most of the CGE models including explicitly an R&D sector lack a geographical dimension to determine spillovers and interactions between sectors of different economies, which are important dimensions to account for empirical validation and impact assessments (see Varga, 2015). Christensen (2013), for example, describes the development of a multi-sector dynamic general equilibrium model with R&D-driven growth with multiple nations. We also aim at merging an explicit accounting of the innovation process and the introduction of a spatial dimension of analysis, but we focus on a more disaggregated geographical unit of observation, which includes all the EU NUTS2 regions.

As for the structure of the paper, first a non-technical description is provided to describe the general framework of the model we build upon, RHOMOLO (Section 1.1), to present a preliminary explanation of the process of endogenisation of R&D (Section 1.2) and to outline the model (Section 1.3). Section 2 explains the knowledge-creation process. Section 3 focuses on how this knowledge is used in the production of R&D-embedded capital stock which is consequently used in the production of final and intermediate goods (Section 4). After that, the role of Households (Section 5) and Government (Section 6) are described. A discussion on the endogeneity of the R&D process ensues and, finally, we present conclusions and ideas for future development.

1.1. A description of RHOMOLO

The point of departure for the model presented in this paper is RHOMOLO, a spatial Computable General Equilibrium (CGE) model designed to work at the regional level (see Brandsma *et al.,* 2013). We present the current version of RHOMOLO in this Section and then, in the rest of the paper, we propose one possible way to include a knowledge-creation process based on R&D-embedded capital accumulation. RHOMOLO currently consists of 267 NUTS2 regions of the EU27 and 6 NACE Rev. 1.1 industries (agriculture, manufacturing, construction, transport, financial services and public services). Each region is inhabited by households that receive income from labour (in the form of wages), capital (profits and rents) and transfers (from national and regional governments). The income is split between savings, consumption and taxes.

Each region contains 6 sectors that produce goods that are consumed by households, government or firms (in the same sector or in the others) as an input in their production process. Transport costs for trade between and within regions are assumed to be of the iceberg type and sector and region specific. This implies a 267 x 267 asymmetric trade cost matrix derived from the transport model TRANSTOOLS (Burgess *et al.* 2008; Petersen *et al.,* 2009).

The national government levies taxes on the income of households, firms and production factors and pays social contributions to the households. Due to its high dimensionality, the model is solved following a recursive static rather than in a full dynamic approach. It contains a sequence of short-run equilibria that are related to each other through the build-up of physical and human capital stocks.

In the current version of RHOMOLO productivity growth and R&D are currently modelled based on an empirical approach, which is explained in Lopez-Bazo and Manca (2012)[1]. They follow an approach à la Solow (1956) where R&D expenditures at the regional level are linked to Total Factor Productivity (TFP), which can be measured as the part of productivity increases that are not explained by the main inputs to the production process, which are labour and capital in RHOMOLO. The main elements assumed to explain the growth in regional TFP levels are R&D expenditures, technology transfers (as a measure of absorptive capacity), distance from the technological frontier and non-R&D expenditures. The role played by regional R&D investments in the RHOMOLO specification is therefore dual. First, by investing in R&D a region is able to catch-up faster with the technological frontier (the region with highest TFP). The catching-up term is based on models of economic growth that are widely used in the literature in a leader-follower context of economic development (see e.g. Barro and Sala-i-Martín, 1997; Howitt, 2000). Second, a higher level of regional R&D implies a higher level of regional innovation, which in turn has a positive effect on TFP. Although this way of semi-endogenising R&D brings some

[1] A similar approach has been taken for analysing the impact of non-R&D innovation expenditures. See Lopez-Rodriguez and Martinez (2014) for the empirical estimation of the impact of non-R&D innovation on TFP and Diukanova and López-Rodríguez (2014) for its implementation in RHOMOLO.

regional interaction dynamics in the form of productivity convergence, there are also reasons to explore alternative modelling approaches where decisions on how much to invest in capital and R&D are endogenous too[2].

1.2. Non-technical description of R&D endogenisation

This paper deviates from RHOMOLO by proposing an endogenous R&D sector and a corresponding endogenous capital investment sector. This Section gives a short overview of the main components of the model and how R&D is endogenously modelled. The sections hereafter describe the sectors, agents and market transactions in a more detailed and rigorous way.

The first step of the innovation process is undertaken by researchers involved in the creation of knowledge. Their output can be interpreted as ideas to develop new products or processes, which may be captured by patents when the model is taken to the data. Researchers combine their ingenuity (approximated by their human capital) with intermediates and rented R&D-embedded capital to produce ideas, this process being enhanced by the accumulated stock of available knowledge. This modelling approach amounts to assuming positive spillovers in research activities, as the creative process benefits from the observation of past and present ideas produced in their own region and in the others, following a spatial decay function. Section 2 describes the creation of knowledge more in detail.

Researchers can either work in the public domain, producing ideas that only augment the stock of knowledge, or sell their ideas to the private sector to investors willing to turn those ideas into productive capital. In terms of calibration, public research is determined by the level of public expenditure in R&D and the production of ideas in both the public and private domain is approximated by filings for patents. The existing stock of knowledge increases with the production of new ideas, after replacing older ideas, which are assumed to depreciate at a constant rate. The absorption of ideas from other regions is discounted by a measure of distance rooted in the economic geography's gravity literature.

Turning to investors, in order to turn ideas into productive capital they combine their own human capital with existing R&D-embedded physical capital in the region and a bundle of intermediate goods that are produced by the final goods sectors in all the regions. The new units of R&D-embedded capital generated as a result of this process are used to replace the obsolete capital and increase the regional stock, which is then rented for productive and innovative purposes. Section 3 gives a detailed explanation of the R&D-embedded capital price setting mechanisms, its production process and the accumulation of its stocks.

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[2] For example, R&D expenditures in RHOMOLO are currently exogenously given and do not feed back into the model to define future R&D intensities. Data on R&D and non-R&D expenditures come from EUROSTAT and the regional R&D intensities (R&D over GDP) are constant over time. For simulations on Cohesion Policy Funds committed to increasing R&D expenditures, the R&D intensities are shocked with the additional funds.

Firms in the final goods sector rent the R&D-embedded capital from investors within the region and use it as an input in their production function. This non-tradable aspect of the capital stock is one of the driving forces of heterogeneity across regions in the model. In the final goods sector, the regional stock of R&D-embedded capital is combined with human capital, intermediate goods and public goods and services to produce specific varieties of a tradable differentiated good for final and intermediate consumption. The production process of the final goods sector and its consumption is described in Section 4.

Households play a key role in the model. First, they provide high-skilled labour which can be turned into researchers, investors or labour in the intermediate/final goods sector, which also employs low-skilled workers. Second, they consume final goods shipped from all the regions and, third, they put aside savings that form a stock which is used as an investment for setting up firms in the final goods sector. The savings are aggregated at the EU level and flow freely to EU firms across all the regions in the form of equity that is needed to set up a final goods firm, as described in Section 5.

The inter-temporal stocks connecting one period to the other are physical R&D-embedded capital and human capital endowments in each region plus a national knowledge stock augmenting productivity in the R&D sector.

Different levels of government are assumed: regional, national and supranational (the European Union). Their role consists in taxing or subsidising certain activities; providing productivity enhancing public services; undertaking public research; and realising transfers across regions or nations. The combination of transfers across levels of government on one hand, and taxes and subsidies on the other, allows us to fine-tune redistributive policies in the model. For example public research can be funded at the national level by taxing ideas at the regional level, which amounts to subsidizing the production of ideas is specific regions. To maintain the model as simple as possible, we abstract from inter-temporal government optimisation and assume all the agents (public and private) to have balanced budgets.

1.3. General outline of the model

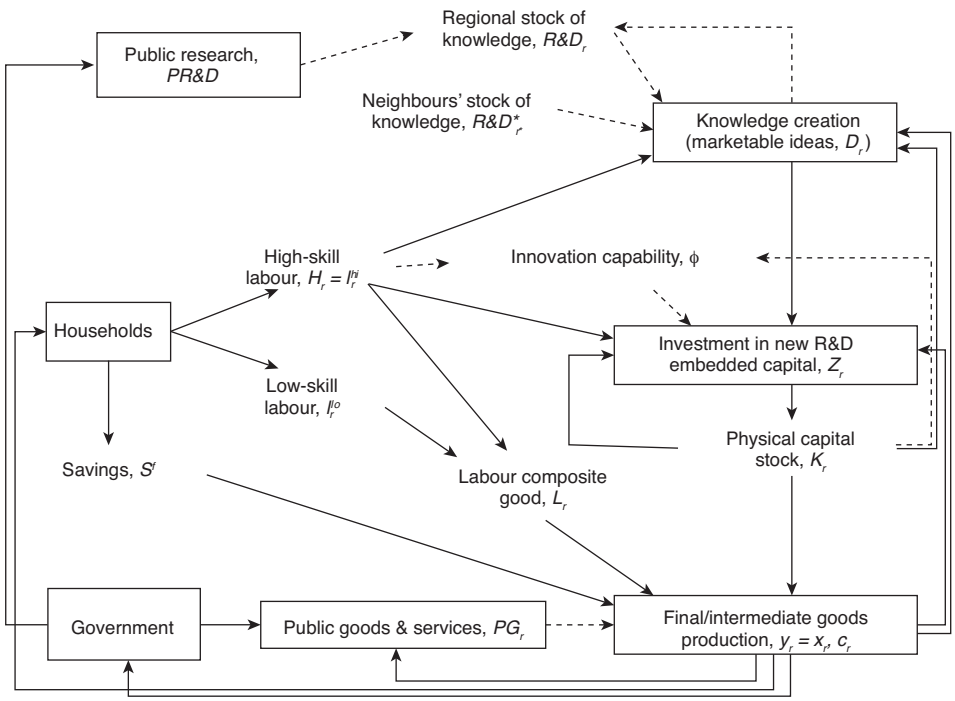
Turning to the general setting of our model, we take the general structure of a multi-region, multi-sector computable general equilibrium model whose inter-temporal dimension is granted by the presence of stocks, such as knowledge and physical capital stocks, built over time. Knowledge creation drives growth by increasing the availability of productive R&D-embedded capital in the regions, which are then rented to produce goods, knowledge and new R&D-embedded capital. The model is meant to cover all the EU regions, plus a region accounting for the rest of the world. Each region is inhabited by a representative household which consumes final goods, supplies high- and low-skilled labour and provides equity to final and intermediate goods producers through her savings. Each region is populated by final and interme-

diate goods producers, investors and researchers. The government in each country and region is allowed to collect taxes, pay out transfers and subsidies, fund public research and supply public goods and services (at the regional level).

Finally, turning to the geographical and sectorial dimension of the model, different industries are considered in the economy (six in the current version), each being characterised by an innovation and production process split into three parts: knowledge creation, R&D-embedded capital accumulation, and goods production. The ideas generated in the regional knowledge-creation process are assumed to be sold to investors only within the region, even if the accumulation of knowledge resulting from these ideas is assumed to spill over to the other regions. The R&D-embedded capital in which the local ideas are turned by regional investors are also not assumed to be traded, but they increase the knowledge stock available to firms located in the region. Final and intermediate goods are instead freely traded across regions. Finally Household savings are perfectly mobile across sectors and regions. Human and physical capital are assumed region-industry specific, but can move across sectors within a region. Figure 1 provides a schematic overview of the model.

Notice that for the sake of exposition the innovation and production processes are assumed to be carried out by independent actors (researchers, investors, goods producers) in a decentralised market equilibrium, but it may well be that the different

Figure 1. Schematic representation of the economy in RHOMOLO



activities are undertaken by agents within the boundaries of the same organisation (for example, a large innovative firm). Indeed, as shown in the following sections, the exchanges between researchers and investors and between investors and goods producers are assumed to happen under perfect competition, which means that prices emerging from the transactions equal costs and thus the process can be equally interpreted as describing transfer pricing within the same company. This approach has the advantage of allowing us to abstract from the differences between innovations and investments happening within firms and accounted at the cost value or purchased from specialised firms, which is a type of information often not available in input/output tables. The incentives for researchers, investors, goods producers to create ideas, capital and final goods are depend on the remuneration of their human capital provision, which equalises in the three processes in each region.

2. The knowledge-creation process

The economy consists of R regions referred to as r or q, that are part of M countries referred to as m. In each industry ind and region r, the knowledge creation activity is carried out by researchers (part of the high-skilled workforce), producing ideas (whose empirical proxy is patents), D_r and selling them to local investors[3]. The production of ideas requires the use of human capital ($H_{R\&D,r}$), intermediates ($X_{R\&D,r}$) and R&D-embedded capital ($K_{R\&D,r}$), augmented by regionally available stock of knowledge in the region, ρ_r, which includes locally accumulated knowledge, $R\&D_r$, and spillovers from other regions, $R\&D_{r*}$, approximated by cross-citations in patent applications, so that

$$\rho_r = \sum_{r*=1}^{R} (R\&D_{r*})^{\frac{1}{d_{r,r*}}} \tag{1}$$

where the stock of knowledge from other regions is weighted by a gravity parameter related to a measure of the extent of knowledge spillovers between each pair of regions, d_r (equal to 1 for local knowledge, i.e. $r* = r$)[4]. The process of creating new knowledge is modelled as a production function such as the following:

$$D_r = \zeta_{R\&D,r} (\rho_r)^{\omega_{R\&D}} (H_{R\&D,r})^{\in_{H_{R\&D}}} (X_{R\&D,r})^{\in_{H_{R\&D}}} \tag{2}$$

where $H_{R\&D,r}$ represent the part of regional high-skilled labour employed as researchers, and $K_{R\&D,r}$ and $X_{R\&D,r}$, respectively, the *R&D-embedded capital stock* rented and

[3] Notice that region-level elements by the subscript r and country-level elements are signalled by the subscript m throughout the text. Activities concerning knowledge production and investment have subscripts $R\&D$ and I, respectively. For a full list of parameters, identifiers and variables used in the paper, see Annex I to IV.

[4] There are different ways in which knowledge spillovers can be measured, ranging from direct knowledge exchange measures such as cross citations in patents to indirect measures such as volumes of bilateral trade or transport costs.

intermediates consumed for creating knowledge. The parameters $\in_{H_{R\&D}}$, and $\in_{X_{R\&D}}$ can be calibrated using the Community Innovation Survey (CIS)[5] data and Social Accounting Matrices (SAMs)[6], which can be used also to estimate the productivity level of the regional knowledge creation process as captured by the parameter $\zeta_{R\&D,r}$. The parameter $\omega_{R\&D}$ can be interpreted as the regional absorptive capacity of the immaterial knowledge stock, ρ_r, which can be approximated by the stock of ideas of each region, calculated by applying the Perpetual Inventory Method on the number of patent applications as provided at Eurostat. For the different skill levels of human capital by region, the ISCED levels[7] of the employees are applied, where ISCED levels 5+6 represent the high-skilled labour force. As for the bundle of intermediates, they can be measured as

$$X_{R\&D,r} = \left(\sum_{ind=1}^{IND} \sum_{q=1}^{R_m} \sum_{i=1}^{N_r} (\beta_{r,ind})^{\sigma} (x_{R\&D,r}^{i,q,ind})^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{3}$$

where $x_{R\&D,r}^{i,q,ind}$ is the quantity of (R&D) intermediates used by researchers in region and bought from firm in industry of region and the relative importance of each industry's output in the production process is $\beta_{r,ind}$.

The ideas generation function at the regional level D_r can then be seen as a Cobb-Douglas production function of high skilled labour $H_{R\&D,r}$, R&D-embedded capital $K_{R\&D,r}$, and intermediates $X_{R\&D,r}$. This means that returns to scale are decreasing in each factor, taken in isolation (such as the R&D stock), but constant with respect to the combination of all the factors, as ensured by the condition

$$\in_{H_{R\&D}} + \in_{K_{R\&D}} + \in_{X_{R\&D}} = 1. \tag{4}$$

The ideas produced in the private domain are then sold to investors located in the region where they are produced (i.e., there is no interregional trade of ideas comparable to intermediates and final goods)[8]. This assumption, combined with the lack of barriers to entry in creating knowledge, implies that each idea is sold at its marginal

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[5] The CIS offers country level data —obtained from questionnaires for individual firms— on the total innovation inputs per country: internal R&D (proxy for, since the main share for internal R&D consist of wages for researchers), external R&D (both outsourced R&D activities and acquisition of external knowledge and a proxy for) and acquisition of machinery and equipment (proxy for). For the missing countries we applied average shares. For DK we took the average of FI, SE and NO. For GR the average shares of ES, IT and PT. For the UK the average shares of DE, NL and FR were taken.

[6] See Potters *et al.* (2014) and Thissen *et al.* (2014) for a more detailed description of the construction and regionalisation of the Social Accounting Matrices for RHOMOLO.

[7] International Standard of Classification of Education (ISCED) levels are go from level 0 (pre-primary education) to level 6 (tertiary education —e.g. PhD). For the distinction between low, medium and high skilled labour we will refer respectively to the levels 0-2, 3+4 and 5+6.

[8] Since the aim of the model is to capture an innovation process that can happen either inside the boundaries of a firm or in a competitive market environment, ideas are implicitly assumed to be perfectly substitutable, which is of course a simplification but it allows us to keep the model general and tractable. In addition, there are no extensive, comparable datasets on the market value of patents.

costs of production and the quantity supplied depends on the availability of researchers, whose human capital has to be remunerated equally in the different activities in which it can be employed (i.e., as researchers, investors or employee in the final goods sector). This means that the supply of regional ideas ultimately depends on the skill level of the inhabitants of the region, on its R&D-embedded capital and access to intermediates, in addition to the available stock of knowledge.

The knowledge stocks in each region are assumed to increase with the development of marketable ideas produced in the private domain, D_r, and from ideas issued from public research, DP_r, with region-time-specific efficiency u_r. In addition, to capture the idea that old productive ideas may become obsolete and need to be replaced by new ones, the stock of ideas is assumed to depreciate at a constant rate, $\delta_{R\&D}$, assumed invariant across time and countries for simplicity. Formally, adding the time dimension, t:

$$R\,\&\,D_{r,t} = (1-\delta_{R\&D})\; R\,\&\,D_{r,t-1} + D_{r,t} + u_r DP_{r,t}. \tag{5}$$

Notice that the R&D stock so computed directly enters into the flow of new knowledge generated in region and in the neighbouring regions with decreasing returns. Also the flow of new ideas from public research, $DP_{r,t}$, is produced using the same technology as the flow of ideas in the private sector, scaled down by a region-specific parameter u_r capturing heterogeneities in the efficiency of public research as for example from the Quality of Government indicators (Charron *et al.,* 2012) or the Regional Innovation Scoreboard (2014). As for public research, the total amount invested in each region in hiring researchers, buying intermediates and renting R&D-embedded capital to produce ideas is financed by the national and regional government budgets, the former indicated as $PR\&D_r^m$ and the latter as $PR\&D_r$. Hence, for a given level $PR\&D$ the total output of public research is

$$DP_r = \frac{(PR\&D_r + PR\&D_r^m)\; u_r\; \zeta_{R\&D,r}(\rho_r)^{\omega_{R\&D}}}{\left(\dfrac{w_{R\&D,r}(1+t^w_{r,R\&D})}{\in_{H_{R\&D}}}\right)^{\in_{H_{R\&D}}}\left(\dfrac{p^k_{R\&D,r}(1+t^k_{r,R\&D})}{\in_{K_{R\&D}}}\right)^{\in_{K_{R\&D}}}\left(\dfrac{P^x_{R\&D,r}(1+t^x_{r,R\&D})}{\in_{X_{R\&D}}}\right)^{\in_{H_{R\&D}}}} \tag{6}$$

, where $w_{R\&D,m}$ and $p^k_{R\&D,r}$ are the rental price of labour and capital. In addition, $t^{\,w}_{r,R\&D}$, $t^{\,k}_{r,R\&D}$ and $t^{\,x}_{r,R\&D}$ are regional taxes or subsidies correspondingly on researchers' wages, rented capital and consumed intermediates. Regional governments are thus allowed to tax or subsidise inputs and outputs in the R&D sector. $P^{\,x}_{R\&D,r}$ is the price index of the bundle of intermediates:

$$P^x_{R\&D,r} = \left(\sum\nolimits_{ind=1}^{IND}\sum\nolimits_{r=1}^{R_m}\sum\nolimits_{i=1}^{N_{ind,q}}(\beta_{r,ind})^{\sigma}(p^{x,ind}_{R\&D,i,r})^{1-\sigma}\right)^{\frac{\sigma-1}{\sigma}} \tag{7}$$

where $\beta_{r,ind}$ is the relative importance of each industry's output in the production process and $p^{\,x,ind}_{R\&D,i,r}$ the price of intermediate used by researchers in region r and bought

from firm *i* in industry *ind* of region *q* and the relative importance of each industry's output in the production process is $\beta_{r,ind}$.

Since in equilibrium private researchers are indifferent between working in the knowledge-creation process or in other activities of the economy and a competitive market for ideas drives profit to zero, profit maximization of the knowledge-creation process yields the following price:

$$P_{D,r} = \frac{\left(\frac{w_{R\&D,r}(1+t^{w}_{r,R\&D}}{\in_{H_{R\&D}}}\right)^{\in_{H_{R\&D}}} \left(\frac{p^{k}_{R\&D,r}(1+t^{k}_{r,R\&D}}{\in_{K_{R\&D}}}\right)^{\in_{K_{R\&D}}} \left(\frac{P^{x}_{R\&D,r}(1+t^{x}_{r,R\&D}}{\in_{X_{R\&D}}}\right)^{\in_{X_{R\&D}}}}{\zeta_{R\&D,r}(\rho_{r})^{\omega_{R\&D}}} \quad (8)$$

where $p_{D,r}$ is the price of ideas in region *r*. Regional governments are thus allowed to tax or subsidise inputs and outputs in the R&D sector.

3. The R&D-embedded capital production process

Turning to the regional investors, after having purchased the ideas, they use an interregional bundle of intermediates and rent local R&D-embedded capital and human capital to generate new R&D-embedded capital, increasing the regional stock. Since capital is not traded across regions but used for production and is rented only to the productive sectors of the regions where it is created, it represents one of the key sources of heterogeneity of economic outcomes across regions (together with human capital and the geographic location of the region).

In order to produce new R&D-embedded capital, investors buy all the ideas produced in the region, *Dr*, even if only a part of them are successfully transformed into successful ideas, $V_{I,r}$, depending on an endogenous regional innovation capacity ϕ_r:

$$V_{I,r} = D_r^{\phi_r}. \quad (9)$$

The rate of success in turning an idea into new R&D-embedded capital is determined by

$$\phi_r = \frac{KP_r}{KP_{EU}} \frac{HP_r}{HP_{EU}} \left(\frac{K_r}{K_{EU}}\right)^{\lambda} \left(\frac{H_r}{H_{EU}}\right)^{1-\lambda} \quad (10)$$

where is the amount of R&D-embedded capital in region $r(K_r)$ and in the whole EU (K_{EU}); is the number of high-skilled workers (approximated by the number of employees with education level ISCED 5+6) in region $r(H_r)$ and in the EU (H_{EU}). In addition, regional human capital and R&D-embedded capital endowments are also considered in per capita terms (HP_r and KP_r), where per capita variables are expressed as follows:

$$KP_r = \frac{K_r}{Pop_r} \;\; ; \;\; HP_r = \frac{H_r}{Pop_r}. \tag{11}$$

This specification is used to capture the key role played by the social interactions and a critical mass of investments in the innovation process by taking into account the relative endowment and absolute concentration of human and physical capital in a particular country vis-à-vis the rest of the EU[9]. The intuition is that absolute concentration may matter per se, as it increases the probability of productive interactions, imitation and productive complementarities, however also the relative endowment is important because richer regions (hosting a more than proportional share of capital and skilled labour vis-à-vis the rest of the EU) may still be very innovative because of factors related to the higher factor availability which are not captured in the model (as for example better education system because of a higher pool of skilled workers, or a more effective allocation of investments due to successful entrepreneurship history in the region).

Regional investors produce new R&D-embedded capital Zr, which increases the regional R&D-embedded capital stock, K_r, depreciating at rate δ_K[10]. The stock is thus assumed to be owned by the investors, who rent it to final goods and producers. At time t, the regional capital stock owned by investors can then be computed as:

$$K_{r,t} = K_{r,t-1}(1-\delta_K) + Z_{r,t}. \tag{12}$$

The investors in each region produce new capital by combining a bundle of inputs that can be traded across regions and locally available inputs. Considering all the investors in the region, the production of new R&D-embedded capital can be written as:

$$Z_r = V_{I,r}\zeta_{I,r}(K_{I,r})^{\in_{K_I}}(H_{I,r})^{\in_{H_I}}(X_{I,r})^{\in_{X_I}} \tag{13}$$

where $K_{I,r}$, and $H_{I,r}$ are the amounts of local R&D-embedded and human capital rented to the investors $X_{I,r}$ and captures the quantity of intermediate goods used by the investors in region r. The shares of each type of input are estimated based on the SAMs. The productivity level is captured by the parameter $\zeta_{i,r}$, which can be estimated based on micro-level studies such as Ortega-Argilés *et al.* (2011). The bundle of intermediates is computed as:

$$X_{I,r} = \left(\sum_{ind=1}^{IND} \sum_{q=1}^{R_m} \sum_{i=1}^{N_r} (\beta_{r,ind})^{\sigma} (x_{I,r}^{i,q,ind})^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{14}$$

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[9] For detailed analyses and literature of the impact of social agglomeration and clustering on the innovation capability, see Crescenzi *et al.* (2007), Storper and Venables (2004), Porter (2000) and Varga (2000).

10 The initial capital stock is calculated from the regional Social Accounting Matrices by assuming that the new capital generated is exactly what is needed to keep the system on a steady state growth path.

where $x_{I,r}^{i,q,ind}$ is the quantity of intermediates used by investors in region *r* and bought from firm *i* in industry *ind* of region *q* and the relative importance of each industry's output in the production process is $\beta_{r,ind}$. Constant returns to scale in the inputs are ensured by the condition:

$$\in_{K_I} + \in_{H_I} + \in_{X_I} = 1. \tag{15}$$

R&D-embedded capital is assumed not to be differentiated and therefore the competitive market price investors are able to charge $p_{I,r}^{z}$ equals their marginal costs of production plus the amortisation over the expected quantities produced in the $1/\delta_{NI}$ periods of the fixed cost of purchasing the idea[11]. For the sake of tractability, the rental price of new R&D-embedded capital is assumed to be equal to the rental price of the existing stock, i.e. $p_r^k = p_{I,r}^k$ [12]. The price of the newly produced units of capital consistent with zero profits at the industry level can then be written as:

$$p_{I,r}^{z} = \frac{\left(\frac{p_{I,r}^{k}(1+t_{I,r}^{k})}{\in_{K_I}}\right)^{\in_{K_I}} \left(\frac{w_{I,r}^{hi}(1+t_{I,r}^{w})}{\in_{K_I}}\right)^{\in_{H_I}} \left(\frac{p_{I,r}^{x}(1+t_{I,r}^{x})}{\in_{K_I}}\right)^{\in_{X_I}}}{\zeta_{I,r}(1+t_r^{z})} + \frac{p_m^D D_r (1+t_r^D)\phi_r \delta_{N_I}}{Z_r(1+t_r^{z})} \tag{16}$$

where the first terms accounts for the marginal costs of production and the second term for the fixed costs of buying D_r ideas, at p_r^D price, with a probability of turning them into R&D-embedded capital of ϕ_r. These fixed costs are then distributed over Z_r new units of R&D-embedded capital produced for $1/\delta_{NI}$ periods, net of taxes and subsidies. Concerning the first term, $p_{I,r}^{z}$ is the price of renting the R&D-embedded capital ($K_{I,r}$) used in the production process, $w_{I,r}^{hi}$ is the wage of investors in region *r* and $P_{I,r}^{x}$ is the price index of the bundle of intermediates ($X_{I,r}$) bought as inputs from the different industries. The price index of the intermediates reflects the factory prices of individual intermediate goods, $p_{i,I}^{x,q,ind}$, their trade costs incurred to ship goods from region *q* to *r*, $\tau_{q,r,ind}$, and the relative importance of each industry's output in the R&D-embedded capital production process, $\beta_{q,r,ind}$:

$$P_{I,r}^{x}\left(\sum_{ind=1}^{IND}\sum_{q=1}^{R}\sum_{i=1}^{N_{ind,q}}(\beta_{r,ind})^{\sigma}(p_{i,I}^{x,q,ind}\tau_{q,r,ind})^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{17}$$

The regional government can tax or subsidise inputs and outputs used in process. The new R&D-embedded capital can be taxed or subsidised at rate $t_{Z,r}$, investors' labour at rate $t_{w,I,r}$, R&D-embedded capital rental at rate $t_{k,l,r}$, intermediates' purchase at rate $t_{x,I,r}$ and ideas at rate $t_{R\&D,r}$.

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[11] Implicitly, this amounts to assuming that the investors can use the operating profits on ideas bought in previous periods to buy the new ones.

[12] In order to keep the model tractable, it is assumed that agents are myopic and expect prices and output to be stable over time, even after temporary shocks.

4. Regional final and intermediate goods production

Firms in each region produce goods for final consumption (for consumers and governments) and intermediate consumption (for other firms, investors and researchers) by employing local labour, R&D-embedded capital and intermediates, the latter being also imported from other regions' producers. Firms producing goods are indicated as $i_r, j_r \in N_r$. Their output ($y_{i,r}$) is defined as $c_{i,r}$ when used for final consumption, when used to produce ideas, $x_{I,r}$, when used to produce R&D-embedded capital, $x_{i,r}$ when used to produce other goods and $x_{G,r}$ when used to produce regional public goods.

The production process is represented by a Cobb-Douglas combination of an aggregate CES bundle of low- and high-skilled regional labour[13], $L_{i,r}$; a bundle of imperfectly substitutable intermediates $X_{i,r}$ from producer $j \neq i$ from within the same region r and other regions q from each industry $ind \in IND$, weighted by an industry-region-specific preference parameter, $\beta_{r,ind}$; and a stock of undifferentiated regional R&D-embedded capital $K_{i,r}$. In addition, each region is associated with a specific manufacturing productivity level, $\zeta_{i,r}$, and has access to different public goods and services provided by the regional government (PG_r) and by the national government (PG_r^m) by combining available intermediates with a region-specific efficiency level. Finally, a fixed amount of financial capital, FCi,r is needed to set up firms. This is financed by the households' savings stock in the EU, which is rented from regional entrepreneurs. The production function for the regional final and intermediate good firms can then be written as follows:

$$y_{i,r} = \zeta_{i,r} GS_{m,r}^{\in_{G_m}} GS_r^{\in_{G_r}} X_{i,r}^{\in_{X_i}} K_{i,r}^{\in_{K_i}} L_{i,r}^{\in_{L_i}} - FC_{i,r} \tag{18}$$

where:

$$L_{i,r} = \left(\sum_{e=lo,hi} \gamma_e (l_{i,r}^e)^\sigma \right)^{\frac{1}{\sigma}} \tag{19}$$

where $l_{i,r}^e$ is the amount of labour of skill level $e = lo, hi$ (respectively, low and high) used in the final goods sector of region r. The term γ_e represents the relative contribution of each skill level in the overall bundle of labour used in the final goods sector;

$$X_{i,r} = \left(\sum_{ind=1}^{IND} \sum_{q=1}^{R_m} \sum_{j=1}^{N_{ind,q}} \left(\beta_{r,ind} \right)^\sigma \left(x_{i,r}^{j,q,ind} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{20}$$

where $x_{i,r}^{i,q,ind}$ is the quantity of intermediates bought in the final goods sector of region r from firm j in industry of region q and $\beta_{r,ind}$ the relative importance of each industry's intermediate in the production process of regional public goods and services:

[13] Data on low skilled (ISCED level 0-2) and medium skilled (ISCED levels 3-4) come —just as high skilled labour— from the EUROSTAT database.

$$GS_r = \zeta_{G,r}\left(\sum_{ind=1}^{IND}\sum_{q=1}^{R_m}\sum_{i=1}^{N_r}\left(\beta_{r,ind}\right)^{\sigma}\left(x_{G,r}^{i,q,ind}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \tag{21}$$

where $x_{G,r}^{i,q,ind}$ is the quantity of intermediates bought from firm *i* in industry *ind* of region *q* to produce public goods and services, *GS,* in region *r*. The term $\zeta_{G,r}$ captures the efficiency of public expenditures at the regional level and is approximated by the Quality of Government indicator as developed by Charron *et al.* (2012)[14]. Public goods and services are non-rival and are freely provided to private companies. Their supply depends on an exogenously given amount of resources, $E_{G,r}$, financed by the regional government budget, which is calibrated using government spending as reported in the regional Social Accounting Matrices. The amount of regional public goods and services provided can be computed as

$$GS_r = \frac{E_{G,r}\zeta_{G,r}}{P_{G,r}^{x}\left(1+t_{i,r}^{x}\right)}\ ; \tag{22}$$

where

$$P_{G,r}^{x} = \left(\sum_{q=1}^{R}\sum_{ind=1}^{IND}\sum_{i=1}^{Ng,r}\left(\beta_{r,ind}\right)^{\sigma}\left(p_{G,r}^{i,q,ind}\tau_{q,r,ind}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{23}$$

As for the provision of goods and services at the national level, a similar logic applies, with

$$GS_m = \zeta_{G,m}\left(\sum_{ind=1}^{IND}\sum_{q=1}^{R_m}\sum_{i=1}^{N_r}\left(\beta_{r,ind}\right)^{\sigma}\left(x_{G,m}^{i,q,ind}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \tag{24}$$

And, an exogenously given amount of national resources devoted to the provision of public goods and services, $E_{G,r}$, the total amount produced in country *m* is

$$GS_m = \frac{E_{G,r}\ \zeta_{G,m}}{P_{G,m}^{x}}\ , \tag{25}$$

where

$$P_{G,m}^{x} = \left(\sum_{q=1}^{R}\sum_{ind=1}^{IND}\sum_{i=1}^{Ng,r}\left(\beta_{r,ind}\right)^{\sigma}\left(p_{G,m}^{i,q,ind}\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{26}$$

[14] This QoG indicator has been constructed by combining national indicators on corruption, rule of law, government effectiveness and accountability from the World Bank's World Governance Indicators data with regional indicators obtained from a EU wide survey of 34 000 inhabitants in 172 NUTS1 and NUTS2 regions.

The amount of national public goods allocated to region can thus be measured as

$$GS_{m,r} = GS_m \frac{Pop_r}{Pop_m}, \tag{27}$$

Again, to ensure constant returns to scale in the inputs, the following condition should hold:

$$\in_{G_m} + \in_{G_r} + \in_{X_i} + \in_{K_i} + \in_{L_i} = 1. \tag{28}$$

The preferences of final goods consumers $U(Cr)$ are expressed by a standard CES utility function. For the sake of tractability, the substitutability between varieties is equal to the substitutability between intermediate inputs in the different sectors of the economy:

$$U(C_r) = \left(\sum_{ind=1}^{IND} \sum_{q=1}^{R} \sum_{i=1}^{N_{s,q}} \beta_{r,ind} \left(c_r^{i,q,ind} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{29}$$

where the representative consumer in region $r \in R$ buys $i \in N_r$ varieties from all the EU regions and the rest of the world, $q \in R$, of each $ind \in IND$ industry, each weighted by an industry-region-specific preference parameter, $\beta_{r,ind}$[15]. The budget constraint for household in region r is

$$\sum_{ind=1}^{IND} \sum_{q=1}^{R} \sum_{i=1}^{N_r} \left[p_{c,r}^{q,i,ind} (1 + t_{c,r}) \tau_{q,r,ind} \right] c_r^{i,q,ind} = l_{h,r}^c \tag{30}$$

where $I_{h,r}^c$ is the part of income used for consumption, measured as a constant share of total income $(1 - s_r)$ the rest going to savings:

$$l_{h,r}^c = (1 - s_r) I_{h,r} \tag{31}$$

The resulting price index in region r for final consumption goods (indexed by c), given iceberg bilateral trade costs $\tau_{q,r,ind} > 1$ is:

$$P_r^c = \left(\sum_{ind=1}^{IND} \sum_{q=1}^{R} \sum_{i=1}^{N_{s,q}} \left(\beta_{r,ind} \right)^{\sigma} \left(p_{c,r}^{i,q,ind} \tau_{q,r,ind} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{32}$$

where $t_{r,ind}$ are consumption taxes or subsidies for industry *ind* in region r. The resulting consumption of variety i produced in region q and sold in region r for industry *ind* is equal to:

[15] Notice that the same parameter is used to capture the relative importance of each industry's output in the production process and the industry-region-specific preference parameter. While a simplification, it makes the model more tractable, easier to calibrate and is a standard assumption in the literature with vertical linkages.

$$c_r^{i,q,ind} = \left(\frac{1}{\beta_{r,ind}} \frac{p_{c,r}^{q,i,ind}(1+t_{c,r})\tau_{q,r,ind}}{P_r^c} \right)^{-\sigma} \frac{I_r^c}{P_r^C} \,. \tag{33}$$

The profit function associated with final and intermediate goods firms in each industry can be written in compact form as:

$$\Pi_r^i \left[p_{c,r}^i (1+t_{c,r}) - MC_r^i \right] y_r^i - f_r^i (1+t_m^f)(1+t_r^f) \tag{34}$$

where —given the functional forms of intermediate and final demand— prices are determined applying a constant mark-up on costs that depends on the level of substitutability $(1 - \sigma)$,

$$p_{c,r}^i = \frac{MC_{i,r}}{1-\sigma} \tag{35}$$

Marginal costs can be computed as:

$$MC_{i,r} = \frac{\left(\frac{W_{i,r}\left(1+t_{i,r}^w\right)}{\in_{w_i}} \right)^{\in_{w_i}} \left(\frac{p_{i,r}^k\left(1+t_{i,r}^k\right)}{\in_{K_i}} \right)^{\in_{K_i}} \left(\frac{P_{i,r}^x\left(1+t_{i,r}^x\right)}{\in_{X_i}} \right)^{\in_{X_i}}}{\zeta_{i,r}(PG_r)^{\in_{KG}}} \tag{36}$$

where

$$P_{i,r}^x = \left(\sum_{q=1}^{R} \sum_{ind=1}^{IND} \sum_{i=1}^{N_{g,r}} \left(\beta_{r,ind}\right)^{\sigma} \left(p_{i,v,ind}^{x,q} \tau_{q,r,ind} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}}; \tag{37}$$

$$W_{i,r} = \left(\sum_{e=lo,hi} \gamma_e [w_{i,r}^e]^{\frac{\sigma}{\sigma-1}} \right)^{\frac{\sigma-1}{\sigma}} . \tag{38}$$

Therefore, the price equation can be rewritten as:

$$p_{i,r}^c = \frac{\left(\frac{W_{i,r}\left(1+t_{i,r}^w\right)}{\in_{w_i}} \right)^{\in_{w_i}} \left(\frac{p_{i,r}^k\left(1+t_{i,r}^k\right)}{\in_{K_i}} \right)^{\in_{K_i}} \left(\frac{P_{i,r}^x\left(1+t_{i,r}^x\right)}{\in_{X_i}} \right)^{\in_{X_i}}}{(1+t_r^c)\,(1-\sigma)\,\zeta_{i,r}(PG_r)^{\in_{KG}}}. \tag{39}$$

Finally, the remuneration of equity $f_{i,r}$ (which can be seen as an annual fixed costs paid for setting up a firm) is equal to the endogenously determined returns on finan-

cial capital r_f times the units of financial capital needed to set up a firms $FC_{i,r}$, which is exogenously given:

$$f_{i,r} = r_{i,f}\ FC_{i,r}. \tag{40}$$

The total remuneration of financial capital per firm per region can be obtained using the zero-profit condition:

$$\Pi_{i,r} = 0 \qquad f_{i,r} = \left[\frac{MC_{i,r}(t_{i,r}+0)}{(1-\sigma)\ (1+t_m^f)\ (1+t_r^f)}\right] y_{i,r} \tag{41}$$

where $t_{f,m}$ and $t_{f,r}$ are, respectively, national and regional taxes or subsidies on the rental of financial capital.

Returns on financial capital can be computed based on the assumptions that total savings are a fixed share of total income and free mobility of financial capital is assumed across regions in such a way that $f_i = f_{i,r}$. Therefore, a process of bidding up of the scarce resource leads to an equalisation in financial capital remuneration within the EU, net of taxes and subsidies. This leads to:

$$r_{i,f} = \frac{f_i}{FC_i} = \frac{MC_{i,r}(1-\theta)}{\left(1-\sigma\right)\left(1+t_m^f\right)\left(1+t_r^f\right)\ FC_i} y_{i,r}. \tag{42}$$

The equalisation of capital remuneration in turn determines the share of EU firms hosted by each EU region, as seen in the next section.

5. Households' savings and income

The financial capital sector is composed of savings first pooled from households across all EU regions and then allocated frictionless to final and intermediate goods firms across all the EU regions in the form of equity, equalising returns in all regions. An exogenously defined fixed quantity of capital, FC_i, is needed to set up a final goods firm. Firms then bid up for the units of capital to be employed in the productive process until total savings' returns could not be higher by marginally changing their allocation across regions.

In every period t, households add savings $s_r\ I_{h,r}$ to their total stock, which gets depreciated at rate δ_s (which can be thought of as inflation or deflation, if negative), so that

$$S_{r,t}^f = (1-\delta_s)S_{r,t-1}^f + s_{r,t}\ l_{h,r,t}. \tag{43}$$

The total savings stock, S^f, equals the sum of all regions' savings stocks S_r^f, which follow the accumulation equation as shown in equation (43) and:

$$S^f = \sum_r^R S_r^f . \tag{44}$$

It can be assumed that not all the savings are turned efficiently into equity, but that a transformation parameter ϕ_{FC} accounts for compliance costs, search costs or any other source of inefficiency, so that:

$$F = \phi_{FC} \; S^f . \tag{45}$$

Whereas the total number of firms in the whole EU can then be easily set as

$$N = \frac{F}{FC_i}, \tag{46}$$

the number of firms in each region will depend on the equalisation of financial capital remuneration seen in the previous section. So it will be local characteristics such as the availability of R&D-embedded capital, local public goods and services, firms' productivity and so on to determine the patterns of economic agglomeration and dispersion across regions.

Household income is the sum of wages of researchers, investors and employees in the goods sectors, plus the remuneration received from the rental of financial capital across regions. In addition, regional and national governments can deliver social transfers. Total household income at the regional level can then be computed as:

$$\begin{aligned} L_{h,r} = & \sum_{ind=1}^{IND} w_{R\&D,r} H_{R\&D,r,ind} + \sum_{ind=1}^{IND} w_{I,r}^{hi} H_{I,r,ind} + \\ & + \sum_{ind=1}^{IND} W_{i,r} L_{i,r,ind} + \phi_{FC} S_r^f + TR_{h,r}^r + TR_{h,r}^m \end{aligned} \tag{47}$$

where TR_h^m are transfers from the national government to households and TR_h^r are transfers from the regional government to households.

6. Government

Finally, we sum up all the leverages of policy intervention observed in the different sectors of the economy analysed so far and thus define the national and regional governments' budget, which is assumed to be balanced.

6.1. National government budget

The national government can tax or subsidise financial capital rental. It is also allowed to transfer resources directly to regions or households. Its budget can then be written as follows:

$$t_m^f \sum_{r=1}^{R_m} \sum_{i=1}^{N_m} f_{i,r} + \left(\sum_{r=1}^{R_m} TR_m^r + TR_m^{EU} \right) - \left(TR_r^m + TR_h^m + TR_{EU}^m \right) - \\ - PR\&D_m - E_{G,m} = 0, \tag{48}$$

where $t_m^f \Sigma_{r=1}^{Rm} \Sigma_{i=1}^{Nr}$ *fi,r* are subsidies or taxes on rental of financial capital of firms *i* in regions $r \in R_m$; TR_r^m are transfers from the national government to regional governments; TR_h^m are transfers from the national government to households; TR_m^r are transfers from the regions to the national governments; TR_m^{EU} are the ECP funds transferred to each country; $PR\&D_m$ is the national funding of public research, $PR\&D_m$ $\Sigma_{r=Rm}$ $PR\&D_r^m$; $E_{G,m}$ is the budget allocated to the provision of the national public good.

6.2. Regional government budget

The regional government can provide productivity-enhancing public goods and services and tax or subsidise wages, intermediates and financial and physical capital rental. It is also allowed to transfer resources directly to households or to the national government. The regional government budget can then be written as:

$$\left(w_{R\&D,r}^{hi} \tau_{R\&D,r}^w H_{R\&D,r} + p_{R\&D,r}^k t_{R\&D,r}^k K_{R\&D,r} + p_{R\&D,r}^x t_{R\&D,r}^x X_{R\&D,r} + p_m^D D_r t_r^D \right) + \\ + \left(w_{I,r}^{hi} H_{I,r} t_{I,r}^w + p_{I,r}^k K_{I,r} t_{I,r}^k + P_{I,r}^x X_{I,r} t_{I,r}^x \right) + \left(TR_r^m + TR_r^{EU} \right) - \left(TR_h^r + TR_m^r \right) + \\ + \left(Wi_{I,r} L_{i,r} t_{i,r}^w + p_{i,r}^k K_{i,r} t_{I,r}^k + P_{i,r}^x X_{i,r} t_{i,r}^x + t_r^f \sum_{r=1}^{R_m} \sum_{i=1}^{N_r} f_{i,r} \right) - E_{G,r} - PR\&D_r = 0 \tag{49}$$

Here:

- $w_{R\&D,r}^{hi} \tau_{R\&D,r}^w H_{R\&D,r}$ are subsidies or taxes on wages of researchers;
- $p_{R\&D,r}^k t_{R\&D,r}^k K_{R\&D,r}$ are subsidies or taxes on R&D-embedded capital rental by researchers;
- $p_{R\&D,r}^x t_{R\&D,r}^x X_{R\&D,r}$ are subsidies or taxes on intermediates purchased by researchers;
- $w_{I,r}^{hi} H_{I,r}^k t_{I,r}^{hi}$ are subsidies or taxes on wages of investors;
- $p_{I,r}^k K_{I,r} t_{I,r}^k$ are subsidies or taxes on R&D-embedded capital rental by investors;
- $P_{I,r}^x X_{I,r} t_{I,r}^x$ are subsidies or taxes on intermediate goods purchased by investors;
- $p_m^D D_r t_r^D$ are subsidies or taxes on the purchase of ideas (bought by investors);
- $W_{i,r} L_{i,r} t_{i,r}^w$ are subsidies or taxes on wages of employees in the goods sector;
- $p_{i,r}^k K_{i,r} t_{i,r}^k$ are subsidies or taxes on R&D-embedded capital rental by goods firms;
- $P_{i,r}^x X_{I,r} t_{i,r}^x$ are subsidies or taxes on intermediate goods purchased by goods firms;

— $t_r^f \sum_{r=1}^{Rm} \sum_{i=1}^{Nr} f_{i,r}$ are subsidies or taxes on rental of financial capital of firms in;
— TR_h^r are social transfers from the regional government to households;
— TR_h^m are social transfers from the national government to households;
— TR_m^r are transfers from the regional government to the national government;
— TR_r^m are transfers from the national government to the regional government;
— TR_{EU}^m are contributions to the EU budget of each country;
— TR_r^{EU} are the ECP funds transferred to each region;
— $E_{G,r}$ is the money spent on acquiring inputs for the provision of public goods and services;
— $PR\&D_r$ is the regional funding of public research.

6.3. EU budget

The EU receives the contributions to its budget from the countries and redistributes this —in the form of ECP funds— to both national and regional governments, depending on the type of ECP funds. The balanced EU budget is written as:

$$\left(\sum TR_{EU}^r + \sum TR_{EU}^m\right) - \left(\sum TR_r^{EU} + \sum TR_m^{EU}\right) = 0 \qquad (50)$$

7. Discussion on the endogeneity of the knowledge-creation process

In what sense can this model be seen as generating an endogenous knowledge-creation process? And how are changes in the economy going to affect this process? To answer these questions, we should turn to equation (2), describing the regional knowledge production function, and analyse the sources of variation of its inputs: stocks of R&D-embedded capital, knowledge and human capital. For the sake of illustration, we can see the example of what would happen to the determinants of knowledge creation if transport costs are reduced because of an exogenous improvement in transport infrastructures resulting in lower interregional transport costs.

The first order of effects runs through the availability of cheaper intermediates imported from other regions lowering the production cost of new ideas. In fact, the reduction in marginal costs of production will affect prices of ideas, R&D-embedded capital and final goods and trigger reallocation and welfare effects. The second order of effects depends on the geographical knowledge spillovers. If the knowledge spillovers between regions are influenced directly by transport costs (for example, because researchers can travel and meet more often) or indirectly by an increase in trade (assuming that knowledge is embedded in the products and services traded), the impact of a reduction in iceberg transport costs would be associated with more efficient production of ideas, which will momentarily increase the salary of researchers and drive

new researchers in the knowledge-creation activities to re-equilibrate high-skilled wages. This would result in more knowledge produced and lower prices for ideas.

A third order of effects runs through the availability of R&D-embedded capital to rent for producing new ideas. Lower transport costs of intermediate goods imported from other regions make the R&D-embedded capital production process in equation (13) more efficient and thus increase its stock [equation (12)], which is assumed to be on a steady growth path before the shock and thus above the trend after the shock. The impact of an increase in this stock to rent would then lower the prices and increase the quantities rented.

Human capital input is exogenously given in the current version and would therefore not be affected by a reduction in transport costs. However, if a production function is assumed also for the provision of the education service and it uses inputs such as intermediates, then also the human capital stock (the relative number of high-skill workers) would behave similarly to the R&D-embedded capital stock and have the same impact on the knowledge-creation process. In addition, it should be noted that even a temporary increase in knowledge production enhances future productivity for the region experiencing the shock and for its neighbours because an increase in the regionally produced stock knowledge as modelled in equation (1) shifts the knowledge production frontier outwards by increasing the stock of ideas available to researchers. This means that even the temporary shocks may have long-lasting effects, reinforced by the spatial spillovers.

Summing up, conditional on the specific technological parameters of the production functions, the endogenous knowledge-creation process of the model may yield self-sustained endogenous growth and allow us to model permanent effects of temporary shocks such as European Structural Funds.

8. Conclusions

This paper has described in detail how an endogenous knowledge-creation process can be embedded in a spatial CGE model. We described how, in each region, high-skilled researchers leverage the existing stock of ideas, R&D-embedded capital and intermediates to produce ideas which are transformed by local investors into R&D-embedded capital that add up to the existing stock which sustains the economy. This stock is indeed used not only to create new idea and regenerate the stock, but also by firms for producing final goods (for consumers) and intermediate goods (for the physical capital sector and the government) by combining regional R&D-embedded capital with labour, intermediates and public goods and services (provided by local governments). Besides consuming local and imported final goods, households provide both the labour input (low- and high-skilled) and the savings that are used as equity for setting up firms.

The main aim of this extension is to provide an analytical tool to deal with the heterogeneous response of European regions to policy intervention. Indeed, both

persistence in economic disparities and convergence in income levels can be observed looking at the full sample of European regions. The extension proposed can rationalise economic convergence or the lack thereof though the differences in the accumulation of knowledge and R&D-embedded capital stocks. We showed that even temporary policy shocks —for example due to the availability of Cohesion Policy funds— can have long-lasting effects on the regions involved. These results are in line with the innovation literature finding that the socio-economic conditions of regions play a key role in determining that extent of a successful knowledge-for-growth nexus (Veugelers and Mrak, 2009).

An exogenous shock in a certain region increasing the efficiency of knowledge production has indeed been shown to increase the number of marketable ideas sold to investors, who are then expected to produce more R&D-embedded capital. This in turn increases the availability of the R&D-embedded capital input in the final goods sector, whose output in terms of intermediate and final consumption goods increases and prices lower. This is as far as each region is concerned individually. However, sources of spatial spillovers have been identified in both the knowledge-creation process and the trade of intermediate goods. For example, the efficiency of knowledge creation in each region is increased by the additional stock of knowledge in neighbouring regions. Similarly, the production of cheaper intermediates and final goods in the regions experiencing the positive shocks in knowledge-creation process benefits neighbouring regions by decreasing their costs of purchasing intermediate inputs (which make researchers, investors and firms more efficient) and final goods (which increases the welfare of citizens).

There are different directions in which the model presented here can be enriched. For example, an obvious simplification has been to take human capital stock as exogenous, but it could as well result from an endogenous accumulation process as the other stocks analysed here. Another obvious subsequent step would be to bring the model to the data and see it can indeed be used to rationalise observed growth patterns and impacts of policy intervention. Its implementation will be data-intensive, partly due to the model's large dimensions (267 EU regions and 6 sectors) and due to the detailed knowledge creation process as described in this paper. For comparison, DG ECFINs model QUEST is developed at a country level and has only one productive sector. The model presented in this paper has described the process of knowledge creation, the production of R&D-embedded capital and final and intermediate goods while keeping in mind its actual implementability and calibration at the regional level with available data, which will be done in subsequent work.

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Annex I: Identifiers (subscripts/superscripts)

$r, q \in R$	Regions
$m \in M$	Countries
$j \in N$	Intermediate firms
$ind \in IND$	Industries
$R\&D$	Knowledge-creation activities
I	R&D-embedded capital creation activities
G	Government
h	Households

Annex II: Variables

ci	Consumption of final goods
D	Ideas adding up to the knowledge stock
$DP_{r,t}$	Ideas created using public regional funding
$E_{G,r}$	Regional government expenditures in intermediates to produce public goods
$E_{G,m}$	National government expenditures in intermediates to produce public goods
F	Total effective financial investments
$f_{i,r}$	Remuneration of financial capital needed to set up a firm
f_i	Total remuneration of financial capital
FC_i	Fixed costs of setting up a final goods firm (in terms of units of financial capital)
$H_{R\&D}$	Researchers' human capital
H_I	Investors' human capital
HP_r	Per capita levels of human capital in region
$I_{h,r}$	National household income
I_h^c	Income spent on consumption
$K_{r,t}$	R&D-embedded capital stock at time
K_I	R&D-embedded capital rented to the investments' sector
K_i	R&D-embedded capital rented to the final goods firms
$K_{R\&D,r}$	R&D-embedded capital stock in region
KP_r	Per capita levels of R&D-embedded capital in region

$l_{R\&D}^{hi}$	High-skilled labour force used in the knowledge-creation sector
L_i	Composite bundle of labour employed for goods firms
l_i^e	Labour force with skill level, (respectively low, high)
MC_i	Marginal costs of firm
N_i	Number of final goods firms
p^D	Price of ideas
$p_{I,r}^z$	Price of new R&D-embedded capital produced by investors
p_I^k	R&D-embedded capital rental price in for investors
P_I^x	Intermediates bundle price index for investors
p_I^x	Intermediates' price for investors
P_i^x	Intermediates bundle price index for goods firms
p_i	Price of final goods
p_i^k	Capital rental price for goods firms
p_i^x	Price of intermediates for goods firms
P_r^c	Price index of final goods in consumption bundle in region
GS_r	Public goods and services provided by regional governments
GS_m	Public goods and services provided by regional governments
$P_{G,r}^x$	Intermediates bundle price index for producing public goods and services in region
P_r^c	Price index of final goods in region
Pop	Population
$PR\&D_r$	Regional budget for public research
$PR\&D_m$	National budget for public research
$R\&D_r$	Stock of knowledge in region
ρ_r	Regionally available stock of knowledge
r_i	Remuneration of a unit of financial capital
S^f	Total financial savings stock
TR_h^m	Transfers from countries to households
TR_h^r	Transfers from regions to households
TR_m^r	Transfers from regions to countries
TR_r^m	Transfers from countries to regions
TR_{EU}^m	Transfers from countries to the EU (contribution to EU budget)
TR_m^{EU}	Transfers from the EU to the countries (ECP funds)

TR_r^{EU}	Transfers from the EU to the regions (ECP funds)
$U(C_r)$	Utility of the representative consumer in region r
u_r	Efficiency of public research of region
V_I	Number of ideas successfully turned into new R&D-embedded capital.
$w_{i,r}^e$	Wage of e-skilled labour employed in goods firms, e=lo,hi (low, high)
W_i	Wage index of labour bundle for goods firms
w_I^{hi}	Wages (high-skill) of investors
$X_{R\&D}$	Intermediates' bundle consumption by researchers
$x_{R\&D}$	Intermediates purchased by researchers to produce ideas
X_I	Intermediates' bundle consumption by investors
x_I	Intermediates purchased by investors to produce R&D-embedded capital
X_i	Intermediates' bundle consumption used by goods firms
X_m	Intermediates' bundle consumption used by the national government
X_r	Intermediates' bundle consumption used by the regional government
x_G	Intermediates used by government to produce public goods
x_j	Intermediates used by firms to produce goods
y_i	Output of goods firms
Z	New R&D-embedded capital produced
$\tau_{q,r,ind}$	Trade cost from q to r in industry ind
Π_i	Goods firm 's profits in the sector
ϕ_{FC}	Transformation parameter for savings into financial capital/equity
ϕ_r	Rate of success in turning ideas into R&D-embedded capital

Annex III: Taxes

$t_{r,R\&D}^w$	Regional subsidies or taxes on researchers' wages
t_r^D	Regional taxes or subsidies on ideas' sales
$t_{I,r}^w$	Regional subsidies or taxes on investors' wages
$t_{I,r}^k$	Regional subsidies or taxes on R&D-embedded capital rented by investors
$t_{I,r}^x$	Regional subsidies or taxes on intermediates purchased by investors
$t_{i,r}^w$	Regional subsidies or taxes on employees' wages in the goods sector
$t_{i,r}^k$	Regional subsidies or taxes on R&D-embedded capital rented by goods firms
$t_{i,r}^x$	Regional subsidies or taxes on intermediates purchased by goods firms

t_r^c	Regional subsidies or taxes on goods sales
t_m^f	National subsidies or taxes on rental of financial capital
t_r^f	Regional subsidies or taxes on rental of financial capital

Annex IV: Parameters

$d_{r,r*}$	Measure of distance between region and
s_r	Savings rate in region r
β	Preference parameter
γ_e	Relative skill e(=lo,me,hi) weight in the labour bundle for final goods production
δ	Depreciation rate
$\delta_{R\&D}$	Depreciation rate of knowledge stock
δ_K	Depreciation rate of R&D-embedded capital stock
δ_s	Depreciation rate of savings stock
$\in_{H_{R\&D}}$	High-skill human capital share in ideas' production function
$\in_{K_{R\&D}}$	Rented capital share in ideas' production function
$\in_{X_{R\&D}}$	Intermediate consumption share in ideas' production function
$\in_{H_I}$	High-skill human capital intensity in R&D-embedded capital's production function
$\in_{K_I}$	R&D-embedded capital intensity in R&D-embedded capital' production function
$\in_{H_i}$	R&D-embedded capital intensity in final goods production function
$\in_{G_i}$	Relative importance of public goods in goods production function
$\in_{L_i}$	Labour intensity in goods production function
$\in_{X_I}$	Intermediates consumption's intensity in R&D-embedded capital production
$\in_{X_i}$	Intermediates consumption's intensity in goods production function
$\zeta_{R\&D,r}$	Region-specific productivity parameter in the knowledge creation process
$\zeta_{I,r}$	Region-specific productivity parameter in R&D-embedded capital production
$\zeta_{i,r}$	Region-specific productivity parameter in the goods manufacturing process
$\zeta_{G,r}$	Region-specific efficiency in the production of public goods and services
θ	Level of substitutability between varieties
λ	Relative importance of R&D-embedded capital and human capital for innovation capability
σ	Substitution parameter
$\omega_{R\&D}$	Knowledge absorption capacity in the knowledge-creation process