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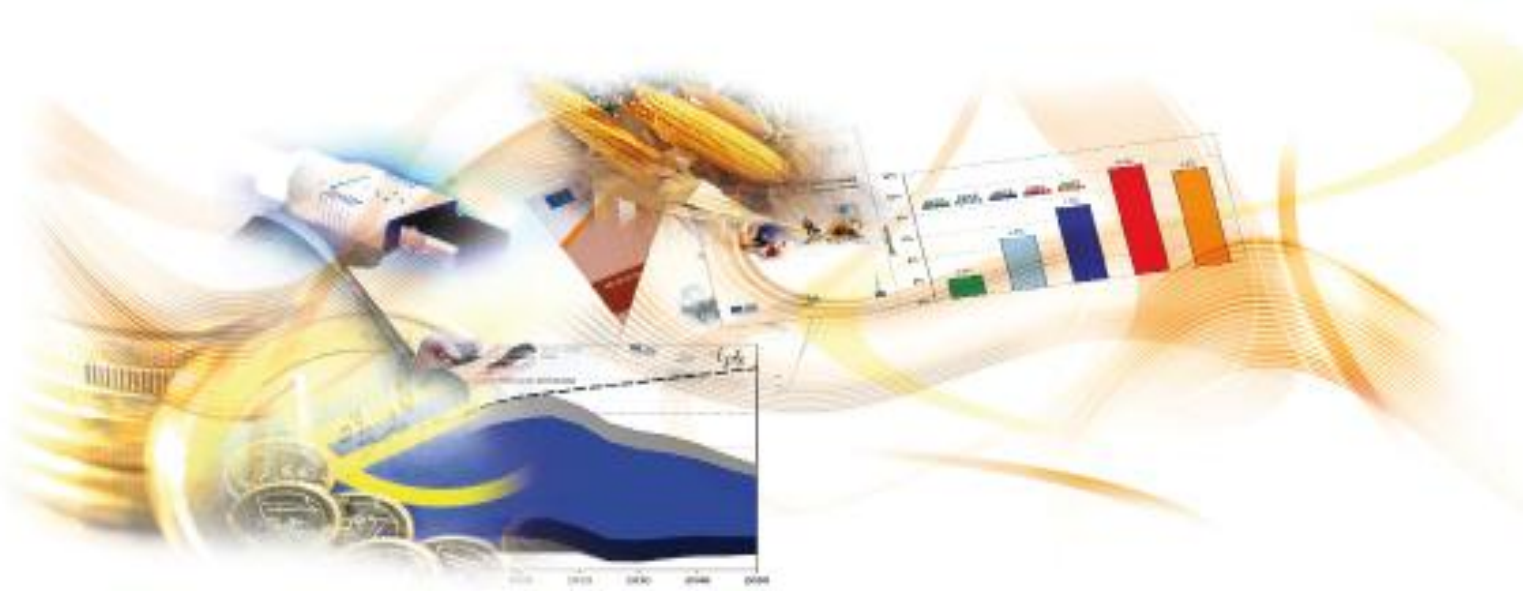

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Macro-Economic Models for R&D and Innovation Policies

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Abstract
This report compares R&D modelling approaches in four macroeconomic models used by the European Commission for ex-ante policy impact assessment: one Dynamic Stochastic General Equilibrium (DSGE) model – QUEST; one Spatial Computable General Equilibrium (SCGE) model – RHOMOLO; one Computable General Equilibrium (CGE) model – GEM-E3; and one macro-econometric model – NEMESIS. The report critically compares particularly those parts of the four models that are relevant to R&D transmission mechanisms and interfaces for implementing policy shocks. Given that R&D investment decisions are inherently dynamic, QUEST appears to be the most suitable model for assessing the impact of R&D and innovation policies over time, as it is the only model with inter-temporal optimisation of economic agents. In order to address questions related to geographic concentration of innovative activities and spatial knowledge spillovers, RHOMOLO has a comparative advantage, as it is the only one which models regional economies and spatial interactions between them explicitly. Due to its detailed treatment of energy sectors and environmental issues, GEM-E3 appears to be the most suitable model for assessing the impact of innovation in clean energy. For a more detailed modelling of different types of innovation measures, NEMESIS can provide valuable insights thanks to its richness in estimating and accounting for specific channels of innovation. We also identify avenues for future research, which in our view could improve the modelling of R&D and innovation policies both from a conceptual and empirical perspective.

JEL codes: C68, D24, D58, H50, O31, O32.

Keywords: RHOMOLO, QUEST, GEM-E3, NEMESIS, Macro-Economic Models, General Equilibrium, R&D Policies.

Macro-Economic Models for R&D and Innovation Policies

A Comparison of QUEST, RHOMOLO, GEM-E3 and NEMESIS

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Abstract: This report compares R&D modelling approaches in four macroeconomic models used by the European Commission for ex-ante policy impact assessment: one Dynamic Stochastic General Equilibrium (DSGE) model – QUEST; one Spatial Computable General Equilibrium (SCGE) model – RHOMOLO; one Computable General Equilibrium (CGE) model – GEM-E3; and one macro-econometric model – NEMESIS. The report critically compares particularly those parts of the four models that are relevant to R&D transmission mechanisms and interfaces for implementing policy shocks. Given that R&D investment decisions are inherently dynamic, QUEST appears to be the most suitable model for assessing the impact of R&D and innovation policies over time, as it is the only model with inter-temporal optimisation of economic agents. In order to address questions related to geographic concentration of innovative activities and spatial knowledge spillovers, RHOMOLO has a comparative advantage, as it is the only one which models regional economies and spatial interactions between them explicitly. Due to its detailed treatment of energy sectors and environmental issues, GEM-E3 appears to be the most suitable model for assessing the impact of innovation in clean energy. For a more detailed modelling of different types of innovation measures, NEMESIS can provide valuable insights thanks to its richness in estimating and accounting for specific channels of innovation. We also identify avenues for future research, which in our view could improve the modelling of R&D and innovation policies both from a conceptual and empirical perspective.

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1. Introduction

There is a general consensus among economists and policymakers that Research and Development (R&D) activities play a decisive role in fostering productivity growth. This relation has been first formalised by Griliches (1973) and Terleckyj (1974) and has widely been accepted since. Yet, markets are likely to underprovide R&D because of the wedge between private returns of the innovators and social returns for the overall economy (Griliches, 1995; Jones and Williams, 1998; Klette et al., 2000; Bye et al., 2011). To address this potential market failure, a wide array of policy interventions has been designed by governments to stimulate innovation and realign public and private interests. The impact assessment of such policies requires the development of adequate modelling frameworks in order to capture the specific characteristics of research and innovation. This paper overviews four models currently used by the European Commission to this end: QUEST, RHOMOLO, GEM-E3 and NEMESIS.

Before turning to the specific characteristics of the four macroeconomic models, a brief literature review is presented in the next section to illustrate the overarching issues that any general equilibrium model dealing with R&D has to face.

1.1 Previous studies

One of the key issues modellers are faced with, when dealing with R&D, is the issue of how to deal with *spillovers*, which are a typical feature of R&D. As noted by Leahy and Neary (2007), any innovative activity has an information component that is almost completely non-appropriable and costless to acquire, an idea dating back to Marshall (1920), Nelson (1959) and Arrow (1962). The introduction of this idea in general equilibrium models, though, is more recent, splitting research activities into an appropriable and non-appropriable knowledge, as for example in Goulder and Schneider (1999) in the context of climate studies, or Diao et al. (1999) based on a theory of endogenous growth, or based on the extension of product varieties (Romer, 1990; Grossmand and Helpman, 1991; Aghion and Howitt, 1992; Jones, 1995).

However, in order for society to enjoy the non-appropriable component of R&D, some specific economic agents have still to incur investment costs which need to be associated with a positive return to be compatible with individual incentives. To this end, every country has deviced mechanisms such as patents to allow agents to privately appropriate parts of the output of their R&D efforts to provide incentives for innovation. As for the modelling of this appropriable part of knowledge, almost all general equilibrium models include a knowledge-creation sector where firms buy and sell ideas, patents, blueprints or any other output of ingenuity produced similarly to any other commodity in the economy. As for the modelling of the non-appropriable part, and its relevance, there is much less agreement among economists (see, for example, Bernstein, 1998). While the existence of spillovers is seldom contested (early empirical overviews can be found in Coe and Helpman, 1995; Park, 1995; Adams, 1997), its general equilibrium modelling requires making bold choices on their sources and functioning. For example, spillovers may be associated with trade, as in Coe and Helpman (1995), Lee (1995) or Ghosh (2007). They can be linked to a global level of knowledge and a firm-specific absorptive capacity (as in Cohen and Levinthal, 1989, who define it

as the ratio of usable to actual rival R&D), which can be developed by firms' investments (Hammerschmidt, 2006) or depend on macroeconomic variables such as the adoption rates of new technologies as in Comin and Hobijn (2010) or Parente and Prescott (1994). Other models relate spillovers to geographic distance, based on papers such as Audretsch and Feldman (1996), showing that spillovers tend to be extremely localised and may even fail to spread across borders, as Branstetter (2001) notices showing that spillovers seem to be more important intra- than internationally.

An empirical complication in modelling R&D is the heterogeneity of activities that can be classified as such. For example, Varga, Pontikakis and Chorafakis (2014) distinguish between market-oriented and science-driven research, finding that agglomeration appears to be more important in fostering the former and interregional scientific networking in strengthening the latter. There are also different kinds of agents that can undertake R&D, as it can be modelled as a private-sector profit-maximising activity or public pursuit aimed at fostering productivity (Nadiria and Mamuneas, 1994; Guellec and De La Potterie, 2001; Bor, Chuang, Lai and Yang, 2010). For example, in Kristkova (2013), the public R&D sector is not involved in the production of capital varieties, but it does produce general knowledge that enters the production processes of both public and private R&D as a specific production factor.

Of course, modelling public intervention in R&D as a free productive input (or equivalently, as a productivity shock) raises questions on the determination of optimal policies, as the role of the policymakers would not be limited to subsidise an activity which may be underprovided by the market because of positive spillovers across firms, but it would allow governments to directly affect the production frontier of the economy, which calls for caution in the determination of the parameters capturing this effect in the economy.

1. 2 Overview of features of QUEST, RHOMOLO, GEM-E3 and NEMESIS

The four models presented in this paper pertain to four conceptually different modelling traditions in macroeconomic modelling: macro-econometric models, Computable General Equilibrium (CGE) models, Spatial Computable General Equilibrium (SCGE) models, and Dynamic Stochastic General Equilibrium (DSGE) models. The main characteristic of macro-econometric models is their reliance on long-run time-series data and solid empirical base. Their structural equations are estimated econometrically very rich in economic detail. Following a neo-Keynesian theoretical approach, the economies are characterised by a demand-driven structure with the possibility of under-utilisation of productive capacity, which implies the relaxation of some equilibrium constraints.

Computable General Equilibrium (CGE) models rely instead on Arrow-Debreu framework where markets are always in equilibrium balancing supply and demand through the system of prices. Policies that alter the equilibrium are considered shocks that induce new equilibria in the interaction between consumers and producers in the different markets. Household preferences and production functions are usually described by constant elasticity of substitution (CES) functions.

Spatial Computable General Equilibrium (SCGE) models are similar to CGE models in their structure but, in addition to CGE models, they explicitly model regional economies and spatial linkages

connecting them, such as trade of goods and services, factor mobility, income flows and knowledge spillovers. In addition, SCGE models account for spatial frictions between the regions, such as transportation costs, which typically is not the case in the other three types of macroeconomic models.

Finally, Dynamic Stochastic General Equilibrium (DSGE) models follow the rigorous market equilibrium concept of CGE models, but derive agents' decision rules explicitly from inter-temporal optimisation under technological, institutional and budgetary constraints, which is the main difference with respect to the other two types of model. The internalisation of inter-temporal considerations from economic agents makes DSGE particularly valuable instruments for R&D policy analysis because they can capture phenomena such as anticipation effects from future shocks and consumption smoothing behaviour.

An overview about the key features of the four macro-models is provided in Table 1. As can be seen, QUEST is the only Dynamic Stochastic General Equilibrium (DSGE) model among the four; RHOMOLO is a Spatial Computable General Equilibrium model (SCGE); GEM-E3 is a Computable General Equilibrium models (CGE); and NEMESIS is a macro-econometric model.

Table 1. General characteristics of QUEST, RHOMOLO, GEM-E3 and NEMESIS

	QUEST	**RHOMOLO**	**GEM-E3**	**NEMESIS**
1 – Model type	DSGE	SCGE	CGE	Macro-econometric
2 – Multi-country geo-units	EU-28+RoW / countries	EU-27+RoW / NUTS2 regions	EU+RoW5 / country groups	EU-28+RoW10 / countries
3 – No of sectors / competition	1 monopolistic competition	6 monopolistic competition	38 perfect competition	30 monopolistic competition
4 – Inter temporal optimisation	Yes / fully dynamic	No / recursively dynamic	No / recursively dynamic	No / recursively dynamic
5 – Parameterisation	Stochastically estimated & calibrated	Structurally estimated & calibrated	Structurally estimated & calibrated	Structurally estimated & calibrated

All four macro-models are multi-country (multi-region) models, and capture international (inter-regional) linkages between economies of Member States. All EU-28 Member States are included in QUEST (as 28 countries), GEM-E3 (as 1 country group), RHOMOLO (as 267 NUTS2 regions)[b] and NEMESIS (as 28 countries) (row 2 in Table 1). The QUEST model does not differentiate between industrial sectors. RHOMOLO disaggregates economies into 6 sectors, GEM-E3 into 38 sectors and NEMESIS into 30 industrial sectors (row 3 in Table 1). Whereas QUEST, RHOMOLO and NEMESIS model industrial sectors as monopolistically competitive, in GEM-E3 they are modelled as perfectly competitive. As row 4 in Table 1 confirms, only QUEST is a fully dynamic model with inter-temporal optimisation of economic agents. The other three are recursively dynamic models. As usually in

[b] Croatia will be included in RHOMOLO in the next update of the base year to 2013.

macroeconomic models, all key parameters are estimated econometrically, whereas the rest are calibrated in the model. In addition, QUEST can be also estimated stochastically.

2. The QUEST R&D model

The QUEST model is a global dynamic stochastic general equilibrium (DSGE) model (Roeger, Varga and in 't Veld 2008). There are different variants of the QUEST model, and the version discussed here is the semi-endogenous growth version with an explicit R&D sector. Decision rules are explicitly derived from inter-temporal optimisation under technological, institutional and budgetary constraints. In QUEST the economy is populated by households, final and intermediate goods producing firms, a research industry, a monetary and a fiscal authority. The household sector consists of non-liquidity constrained households, which have full access to financial markets, and liquidity constrained households, which cannot trade on asset markets and consume their entire disposable income each period. In the final goods sector monopolistically competitive firms use a composite of intermediate goods and three types of labour: low-, medium-, and high-skill. The intermediate sector is composed of monopolistically competitive firms producing durables based on patents purchased from the research sector. QUEST is a multi-country model calibrated for the 28 Member States and the rest of the world in which the individual country blocks are interlinked through international trade, financial flows and knowledge spillovers.

2.1. R&D modelling framework in QUEST R&D

Following Romer (1990) and Jones (1995), QUEST models product innovation, i.e. innovation corresponds to discovery of a new variety of innovative intermediate inputs that provides an alternative way of producing final goods. The four main agents involved in the innovation process are: an R&D sector, non-liquidity constrained households, an intermediate sector and high-skill workers (for the latter see section 2.3). Further, government can affect innovation activity through taxes and/or subsidies. In addition, the supply of high skill labour determines innovation capacity of the R&D sector.

In practice, households derive utility from consumption and accumulate stocks of capital and design to smooth their consumption over time. This is achieved by renting out their stocks to firms in the intermediate sector, which are used by the latter to produce innovation.

R&D sector

New ideas are produced by the R&D sector, which is operated by a (virtual) research institute. It employs high-skilled labour, $L_{RD,t}$, at market wage, $W_{H,t}$, and uses the existing stock of knowledge (both domestic, A_t, and foreign, A_t^*) to produce new designs according to the following knowledge production function:

(1.) $$\Delta A_t = v A_{t-1}^{*\bar{\omega}} A_{t-1}^{\phi} L_{A,t}^{\lambda}$$

where ϖ and ϕ measure the foreign and domestic spillover effects from the aggregate international and domestic stock of knowledge, A_t^* and A_t, respectively. Parameter v can be interpreted as the total factor efficiency of knowledge production, while λ measures the elasticity of R&D production with respect to the number of researchers, $L_{RD,t}$.

Non-liquidity constrained households

Non-liquidity constrained households maximise their consumption, given inter-temporal budget constraints, and can smooth their consumption accumulating stock. Additively separable nested inter-temporal CES-Dixit-Stiglitz preferences govern non-liquidity constrained household decisions about consumption, labour supply, the purchases of investment good, the investment in government bonds, the renting of physical capital stock, the purchases of new patents from the R&D sector, and the licensing of existing design stock.

As illustrated in Figure 1, non-liquidity constrained households, in order to smooth consumption over time, buy new patents of designs produced by the R&D sector, $J_t^{A,i}$ to build up a stock, A_t, , rented to intermediate goods producers in period t at rental rate i_t^A:

$$(2.) \quad i_t^A \approx \frac{(1-\tau^A)(i_t-\pi_{t+1}^A+\delta^A)-t_t^K\delta^A)}{(1-t_t^K)} + rp_t^A$$

Where t_t^K is the income tax rate on the return of intangibles in period t, and τ^A is the tax subsidy rate. In equilibrium, the rate of return on intangible capital, i_t^A, is equal to the nominal interest rate (for safe public bonds) minus the rate of change of the value of intangible assets and also covers the cost of economic depreciation plus a risk premium.

The budget constrain is expressed in real terms with the price for consumption, investment and patents and wages divided by the GDP deflator.

Intermediate goods sector

The intermediate sector consists of monopolistically competitive innovative firms, which have entered the market by paying entry cost, FC_A, to overcome the administrative entry barriers. After entering the market, intermediate goods producers rent capital inputs at rental rate i_{t-1}^K, and a license for design, $i_{t-}^A \mathrm{P}_t^A$, from non-liquidity constrained households to produce innovative intermediate output, which represents a second fixed cost. Following a linear technology, each unit of capital (assembled from different sources similarly to final goods firms in the economy) can be transformed into one unit of innovative intermediate input:

(3.) $x_i = k_i$

Product innovation corresponds to the discovery of a new variety of intermediate good that provides an alternative way of producing the final good. In addition, the greater availability of capital leads to a higher quantity of intermediates sold per design turned into an intermediate variety.

2.2. Knowledge spillovers

Knowledge spillovers are governed by parameters ϖ and ϕ in equation (1), which capture the foreign and domestic spillover effects from the aggregate international and domestic stock of

knowledge, A_t^* and A_t, respectively. In the multi-country version of the QUEST model the aggregate international stock of knowledge is the weighted average of the trading partners' knowledge stock (weighted by the bilateral trade shares and the size of the trading partners' economy). In the current version of QUEST the elasticities of knowledge spillovers are taken from the previous literature, e.g., Botazzi and Peri (2007).

2.3. Human capital

R&D sector employs high-skill workers,, L_A, in knowledge production function (1). Hence, the supply of high-skill workers determines the national R&D capacity. The supply of high-skill workers is endogenous – in addition to an exogenous population growth rate, the adjustment takes place through participation and employment channels. This is an important feature of QUEST, as particularly workers' participation is an important channel of adjustment in the EU to macroeconomic chocks, such as financial and economic crisis.

Human capital accumulation in form of endogenous investment in education is not possible in the current version of QUEST. Also labour migration, which could be triggered by an increased demand for high skill workers in a country, is not possible in QUEST. In the current version of QUEST, human capital elasticities with respect to education are taken from the literature.

2.4. Implementation and simulation of R&D policies

The R&D modelling framework of QUEST provides a rich set of channels and parameters, through which innovation policy interventions can be simulated. All policy measures can be implemented either permanently or temporarily.

- *Tax credit.* Governments can provide R&D subsidy in form of a tax credit, τ^A, to non-liquidity households on their income from intangible capital (patents) – financed through an increase in taxes (eg. lump-sum, or labour taxes) to households. Tax credit works as follows: higher τ^A → lower rental rate for patents → reduction in fix cost of intermediates → raises demand of blueprints → stimulates R&D and reallocates high skilled workers to R&D sector.
- *Tax reduction.* Governments can affect investment decisions in intangible capital by lowering the tax rate on the return from patents $t_K \delta_A$.
- *Wage subsidy.* Governments can pay a subsidy s_H^ω to high-skilled workers wage in the R&D sector.
- *Fixed cost reduction.* An alternative way of boosting innovation is the reduction of fixed costs, FC^A, faced by the intermediate goods firms.
- *Risk premium reduction:* Similarly, governments can boost innovation activity by reducing risk premium, rp^A, in the intermediate sector.

2.5. Strengths and limitations[c]

Strengths

The QUEST model provides a theoretically consistent micro-founded approach for modelling the innovative activities of firms, as well as the impact of innovation policies. All behavioural equations, including the supply and demand equations of R&D services, are derived from maximisation/minimisation of objective functions of the respective agents, no ad hoc specifications of behavioural equations are present in the model.

QUEST is a general equilibrium model, implying that in the model every single transaction triggers a proportional relocation of resources, which enter the national accounts with the opposite signs: one negative (demander) and one positive (supplier). This implies that no resources can disappear from the economy without benefiting someone, as no agent / production factor can enjoy free manna from heaven. This feature is particularly important for comparing alternative R&D policy options and/or for calculating fiscal multipliers. For example, in order to boost innovation through R&D subsidies, additional tax income must be collected through higher tax rates. Higher tax rates in turn affect production, consumption and saving behaviour of economic agents, which in turn would affect the innovative activity itself.

In the context of modelling R&D policies, an important feature of QUEST is that economic agents are forward-looking. The model relies on strong inter-temporal micro-foundations: growth arises as a result of innovation by rational, forward-looking, profit maximising agents. This feature is crucial to model research and innovation, as decisions on R&D investments are inevitably forward-looking. In addition, the model can also account for the anticipatory effect of (announced) reforms.

High-skill workers in the model are only those who have tertiary education degree in science & technology fields, this gives a realistic labour supply constraint on the production of new knowledge. Another strength of the approach is that it provides a rich set of channels and parameters, through which innovation policy interventions can be simulated (see section 2.4).

Limitations

One limitation of the QUEST R&D model is that the approach does not distinguish between private and public R&D investments. All R&D activities are carried out by a (virtual) R&D sector.

The underlying approach assumes that there is only one type of innovation – which can be interpreted as product innovation (as new varieties of intermediate goods are produced) or process innovation (as this variety increases the efficiency of capital). Productivity-enhancing organisational and marketing innovations are exogenous to the model.

No endogenous skill accumulation through education is currently included in the model, in the sense that the share of high-skill workers does not increase endogenously after a demand shock to knowledge production. It is influenced exogenously via government policies, though.

[c] See Tables 2-4 for a summary of QUEST R&D strengths and limitations for modelling of R&D and innovation policies.

The current version of QUEST cannot account for reforms in the R&D system that support higher quality investments. However, the quality aspect of R&D investment is at least as important as the amount of R&D expenditures invested in innovation.

Technology diffusion between countries is not modelled explicitly. However, according to Comin et al. (2012) and Comin and Mestieri (2014), the speed and pattern of diffusion of new technologies between countries is endogenous, and depends on various factors, most notably on market conditions, institutions, human capital and various measures of distance or similarity between innovators/early adopters and late adopters.

The empirical foundation of R&D-related parameters can be improved in the future versions of QUEST. Given that the elasticities of knowledge spillovers are taken from the previous literature, which are estimated on outdated pre-crisis data and for non-EU countries, e.g., Botazzi and Peri (2007), they are not Member State-specific. Similarly, human capital elasticities with respect to education are taken from the literature, which are not Member State-specific.

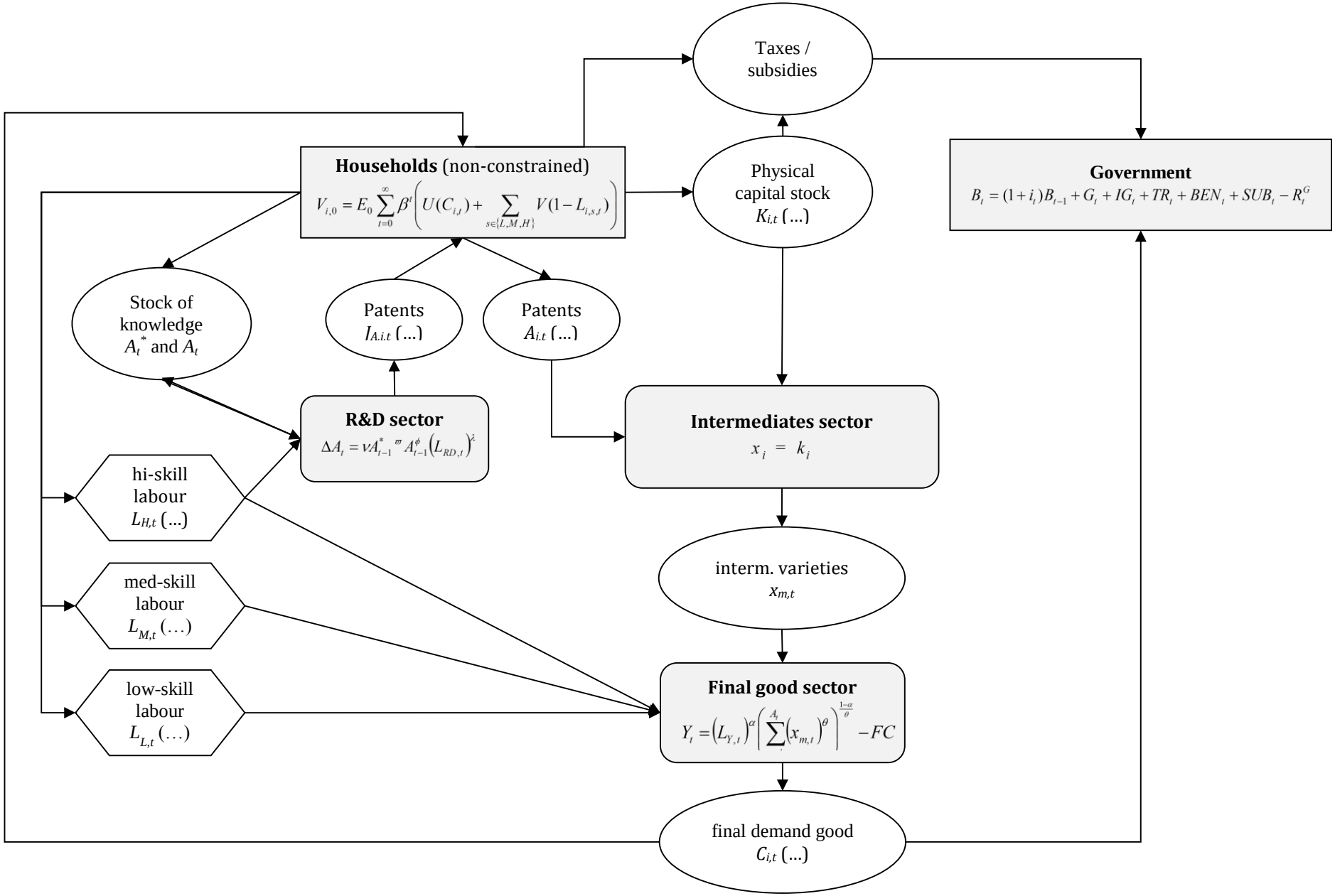

Figure 1: R&D treatment in QUEST.

3. The RHOMOLO model

RHOMOLO is a recursive-dynamic Spatial Computable General Equilibrium (SCGE) model covering the whole EU at the regional level. The current version of RHOMOLO covers 267 NUTS2 regions of the EU27,[4] and each regional economy is disaggregated into six industrial sectors. Goods and services produced within regional economies are consumed by households, government and firms. Households receive income from the supply of labour, capital and government transfers. Spatial interactions between regions are captured through trade of goods and services (which is subject to trade costs), factor mobility and knowledge spillovers.

The extensive regional disaggregation of RHOMOLO requires that the dynamics is kept relatively simple. In contrast to QUEST, which is a fully dynamic model with inter-temporal optimisation of economic agents, RHOMOLO is solved recursively, implying that the optimisation problems in RHOMOLO are inherently static, the different periods being linked to each other through the accumulation of stocks in the economy. In each period the households make decisions about consumption, savings and labour supply in order to maximise their utility subject to budget constraint.

3.1. R&D modelling framework in RHOMOLO

RHOMOLO models R&D as one additional sector of the economy producing innovation. The three main agents involved in the innovation process are: an R&D sector, high-skill workers and final (intermediate) demand firms. The national R&D sector sells R&D services to firms in the six sectors located in the same country and uses a specific high-skill labour factor. Government can affect innovation activity through taxes and/or subsidies. In addition, the supply of high skill labour determines innovation capacity of the R&D sector.

National R&D sector

There are *M(=27)* national R&D sectors which produce new knowledge using a bundle of high-skill labour rented from the different regions of the country. Since R&D services are one of the productive inputs of the economy, their demand in each region of the country depends on the relative price of R&D with respect to the other production factors. The production (and purchase) of R&D services are associated with a positive externality to all the sectors and regions in the country by raising total factor productivity:

(4.) $$TFP_{t,region,sec} = TFP_{t-1,region,sec} * \left[\frac{KnowK_{t,country}}{KnowK_{t-1,country}}\right]^{\kappa_{region,sec}},$$

Where $\mathrm{KnowK_{t,country}}$ is the national stock of knowledge accumulated at time t; the elasticity $\kappa_{\mathrm{region;sec}}$ allows the spillovers generated by the increase in the national stock of knowledge to be differentiated by region and sector. The accumulation of knowledge capital (assuming for simplicity no depreciation from year to year) is formalized as follows:

[4] As noted in Section 1, Croatian regions will be included in the RHOMOLO model in the next update of the base year to 2013.

(5.) $KnowK_{t,country} = KnowK_{t-1,country} + Z_{t,country;R\&D}$.

Where $Z_{t,country;R\&D}$ is the country's yearly production of R&D services.

The knowledge production function of the national R&D sector displays constant returns to scale and perfect competition. The wage of high skill workers employed in R&D sector is equalised across regions of the same country and the high-skill workers employed in the R&D sector are specific to that sector.

Firms and technology

Monopolistically competitive firms of each sector buy national R&D services at the same national price. There are no trade costs for R&D services, which are traded within countries, but not internationally. The value added production technology in the other sectors is described by:

(6.) $Q_{t,region,sec} = TFP_{t,region,sec} * Q\left(K_{t,region,sec}, L_{t,region,sec},\right),$

where $Q_{t,region,sec}$ is value added; $TFP_{t,region,sec}$ is the total factor productivity; $K_{t,region,sec}$ is capital service input; $L_{t,region,sec}$ is the labour rental.

3.2. Knowledge spillovers

In RHOMOLO there are spatial technological spill-overs in the sense that the national R&D sector affects total factor productivity of the regions with each country, which results in inter-regional knowledge spillovers from the stock of national accumulated knowledge captured by the parameter $TFP_{t,country}$, which shifts the production functions of all the sectors.

3.3. Human capital

High-skill workers constitute an integral part of the region-specific human capital and contribute importantly to the creation of knowledge. RHOMOLO contains several channels how human capital in a region can be accumulated. First, the regional stock of human capital can be augmented through investment in education (Torfs and Persyn, 2015). Although, education is costly, if the skill premium is high enough, low- and medium-skill workers may find it profitable to invest in education and become highly skilled. Second, the regional stock of human capital can be augmented through labour migration from other regions. High-skill workers may find it beneficial to migrate to a particular region, if the net (of migration costs) wage difference between the origin and destination regions is large enough (Brandsma, Kancs and Persyn, 2014). Finally, the supply of high-skill workers is affected also by participation and employment decisions, which are endogenous in RHOMOLO (Persyn, Torfs and Kancs, 2014). In the current version of RHOMOLO, human capital elasticities with respect to education are taken from the literature, however, they are being estimated econometrically using micro-data and will be included in the future versions of RHOMOLO, as documented on https://ec.europa.eu/jrc/rhomolo.

3.4. Implementation and simulation of R&D policies

The R&D modelling framework of RHOMOLO provides a rich set of channels and parameters, through which innovation policy interventions can be simulated. All policy measures can be implemented either permanently or temporarily and their impact will depend on the elasticity of supply of the specific R&D labour, which can be assumed exogenously fixed or endogenous:

- *Subsidies to the national R&D sector:* The national R&D sector can be supported by the national government and the EU interventions, which provide subsidies;
- *Wage subsidy:* Governments can pay a subsidy on the wage paid to high-skilled workers in R&D sector;
- *Fixed cost reduction:* An alternative way of boosting innovation is the reduction of fixed costs of final (intermediate) goods firms. This would trigger entry of new firms, resulting in higher demand for R&D services;
- *Education cost reduction:* Many EU policies on human capital are aimed at targeted education programmes and job-specific trainings more accessible to (lower) skill workers.
- *Exogenous increase in R&D workers supply:* An alternative way of boosting innovation is for the government to stimulate innovation by exogenously increasing the number of national R&D workers in the country.

3.5. Strengths and limitations[5]

Strengths

The RHOMOLO model provides a theoretically consistent micro-founded approach for modelling the innovative activities of firms, as well as the impact of innovation policies. As in QUEST, all behavioural equations are derived from maximisation/minimisation of objective functions of the respective agents, no ad hoc specifications of behavioural equations are present in the model.

RHOMOLO is a general equilibrium model, implying that in the model every single transaction triggers a proportional relocation of resources, which enter the national accounts with the opposite signs: one negative (demander) and one positive (supplier). This implies that no resources can disappear from the economy without benefiting someone, as no agent / production factor can enjoy free manna from heaven. This is particularly important for comparing alternative R&D policy options and/or for calculating fiscal multipliers. For example, in order to boost innovation through subsidies, additional tax income must be collect through higher tax rates. Higher tax rates in turn affect production, consumption and saving behaviour of economic agents, which in turn would affect the innovation activity itself.

Region- and country-specific human capital plays a key role in the knowledge creation process in the model. This can be seen in equation (4), where labour demand, L, captures R&D sector's demand for high-skill labour. Human capital stocks in RHOMOLO can be altered through investments in

[5] See Tables 2-4 for a summary of RHOMOLO strengths and limitations for modelling of R&D and innovation policies.

education and labour migration from other regions. In addition, also participation and employment decisions are endogenous in RHOMOLO.

An important strength of the approach is that it provides a rich set of channels and parameters, through which innovation policy interventions can be simulated, the most important of which are highlighted in section 3.4.

Finally, the spatial dimension of the model allows RHOMOLO to model geographical spillovers and complex interactions between different levels of policy (EU, national and regional). Given that R&D activities are highly concentrated in geographical space, and knowledge spillovers are significant only locally (Jaffe, Trajtenberg and Henderson 1993; Lychagin et al 2010), the detailed spatial dimension of RHOMOLO can be used to address questions related to geographic concentration of innovative activities and spatial knowledge spillovers.

Limitations

One limitation of the R&D modelling approach taken in RHOMOLO is that it does not explicitly distinguish between private and public R&D investments. All R&D activities are carried out by a national R&D sector.

Further, the dynamics is captured in a rather simple way in RHOMOLO. All minimisation/maximisation problems of objective functions of economic agents are inherently static. In the context of R&D and human capital this is a clear limitation, because both innovation and education decisions have inter-temporal consequences, and they can change not only the level but also the rate of growth of regional economies.

The underlying approach assumes that there is only one type of endogenous innovation, which can be interpreted as product or process innovation, but marketing and organisational innovations are exogenous.

As in QUEST, the current version of RHOMOLO cannot account for reforms in the R&D system that support higher quality investments, even if the quality aspect of R&D investment is at least as important as the amount of R&D expenditure invested in innovation and will be accounted for in the future.

Similarly to QUEST, technology diffusion between regions is not modelled explicitly in RHOMOLO. In contrast to QUEST, there are spillovers across regions within the same country, reflecting a high intra-national speed of diffusion of innovations.

As in QUEST, the empirical foundation of R&D-related parameters can be improved in the future versions of RHOMOLO. Given that both the elasticities of knowledge spillovers and human capital elasticities with respect to education are taken from the previous literature, they are neither region- nor sector-specific, which may bias simulation results of R&D and innovation policies considerably.

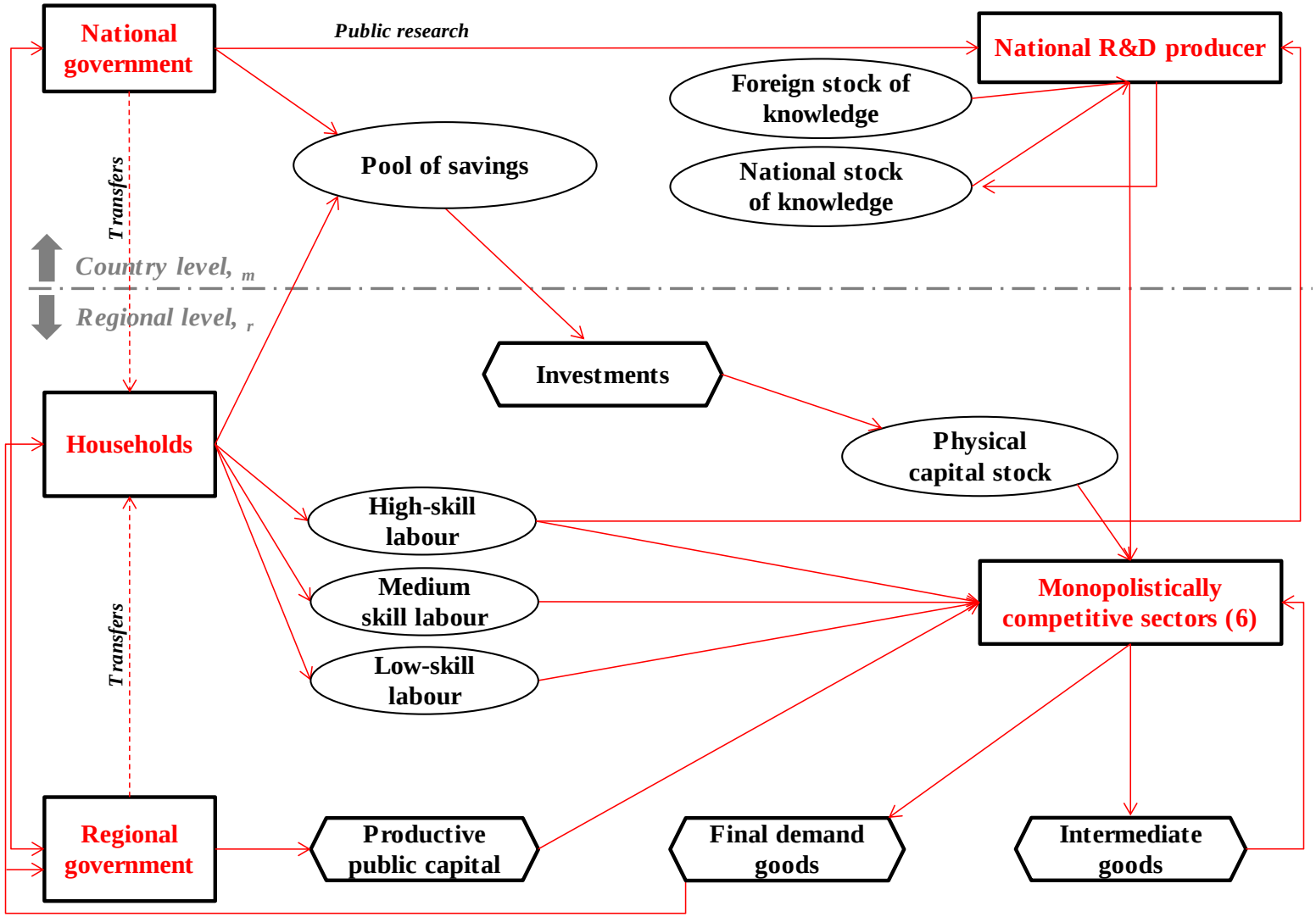

Figure 2: R&D treatment in RHOMOLO.

4. The GEM-E3 R&D model

GEM-E3 R&D is a computable general equilibrium model with a particular focus on energy and environmental issues, covering the all key interactions between the economy, the energy system and the environment. The model allows for the evaluation of the welfare and distributional effects of various environmental policy scenarios, including different burden sharing scenarios, environmental instruments and revenue recycling scenarios. GEM-E3 R&D distinguishes between six country groups, including both developed (the EU-28, North America, OECD Pacific) and developing economies (China, Energy Exporters, rest of the world). The model splits the entire economy in 38 production sectors (10 of which are power generation sectors, given the energy focus of the model).

The model is recursively dynamic, driven by the accumulation of capital and equipment. Technological progress is represented in the production functions. The amount of capital is fixed within each period. The investment decisions of companies in one period affect the stock of capital in the next period. The allocation of investment across sectors and country groups is based on their respective profitability. The model allows for a certain degree of capital mobility (across sectors or country groups), implying that firms can close down and start up in another sector (capital mobility across sectors) or in another country group (capital mobility across country groups).

As shown in Figure 4 at the end of the section, the economic agents optimise their objective function and determine the supply or demand of capital, energy, environment, labour and final demand goods. Firms use capital, labour, energy and intermediate goods from all sectors to produce output. For each country group, a representative consumer allocates his total expected income between consumption of goods and services (both durables and non-durables) and savings and allocates time to work supply and leisure depending on the wages and leisure opportunity net costs.

4.1. The modelling of R&D

R&D- and non-R&D-driven innovation in clean energy sectors is modelled through three different channels: the use of the R&D services sector as an input in other sectors, learning-by-searching based on R&D expenditures and learning-by-doing based on total production.

As for the first channel, the standard GEM-E3 production nest, whose first nest involving capital (K), labour (L), energy (E) and materials (M) assuming CES functions in each nest, is augmented by adding the purchase of R&D services.

The demand for R&D depends on the relative unit price of R&D with respect to unit prices of other production factors. The represented nests are all modelled through CES functions, multiplied by a total factor productivity term which is country-group and time-specific.

The production (and purchase) of R&D services produces a positive externality to all the sectors in the country group, which is captured by a learning-by-searching function that interacts with the learning-by-doing function in determining changes in total factor productivity in country group r at time t ($tfp_{r,t}$). In the clean-energy industries, the general specification is then as follows:

$$(7.)\quad \frac{tfp_{r,t+\tau}}{tfp_{r,t}} = \left[\frac{Stock\ production_{r,t+\tau}}{Stock\ production_{r,t}}\right]^{\epsilon_1} \left[\frac{Knowledge\ R\&D\ stock_{r,t+\tau}}{Knowledge\ R\&D\ stock_{r,t}}\right]^{\epsilon_2}.$$

Equation (8) states that any change in the total factor productivity in country group r between period (t) and period $t+\tau$ (τ is the duration of a model period, 5 years) depends on the increases in cumulative production (with elasticity ϵ_1) and in the R&D knowledge stock (with elasticity ϵ_2) over the same period.

Practically, learning-by-doing curves measure how much the capital costs of a given technology will be reduced due to its increased adoption (i.e., cost reductions achieved for doubling the capacity). Learning-by-research curves will instead measure how much the capital cost of clean technologies will be reduced due to increased R&D expenditures (i.e. cost reductions achieved for doubling the cumulative stock of knowledge).

GEM-E3 R&D adopts sector-specific learning rates for the different sectors, looking at both power generation and energy efficiency in production. This is done because every sector is different and estimates of the learning rates are shown to vary substantially (not only across sectors, but also between different studies of the same sector). The available R&D data and their use for calibration od GEM-E3 R&D is explained in Figure 3.

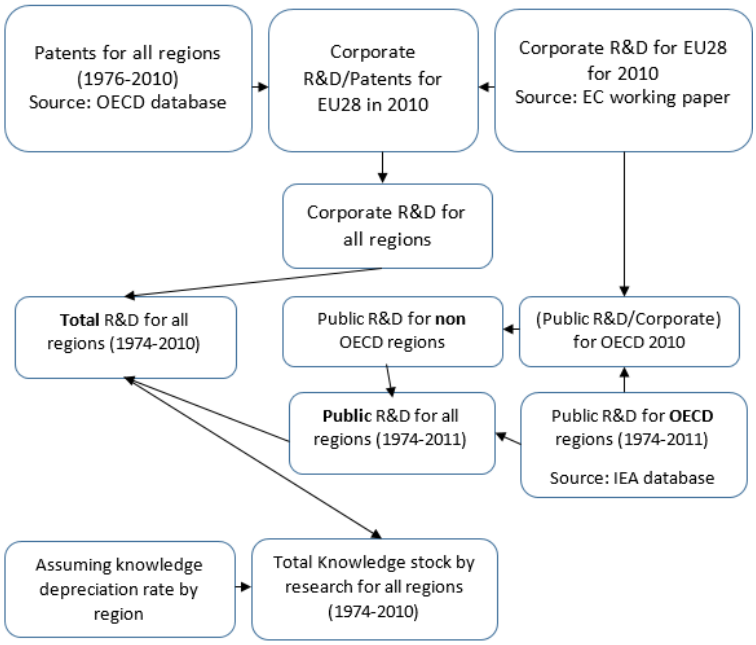

Figure 3: Data used for calibration of the R&D module in GEM-E3.

4.2. Knowledge spillovers

In GEM-E3 R&D, spillovers are included as a component of the overall effect on competitiveness and adoption of clean technologies. They are both international and inter-sectorial, taking into account the indirect productivity effects induced by the purchases of intermediate goods. Spillovers are cost-free and their magnitude is differentiated by time and country groups. In particular, when production costs decrease through learning by doing, spillovers are very low. The spillovers induced

by learning by research are assumed to occur with a lag of 5 years.

In order to take into account the impact of spillovers and knowledge depreciation on technological learning, the total-factor-productivity growth specification reported in the previous subsection can be rewritten in a more comprehensive way as follows:

$$(8.)\quad \frac{tfp_{r,t+\tau}}{tfp_{r,t}} = \left[\frac{CSales_{r,t}(1-\delta_1)^{\tau}+XD_{r,t}\frac{1-(1-\delta_1)^{\tau}}{\delta_1}+\sum_{c\neq r}CSales_{c,t}(1-\delta_1)^{\tau}(1-\delta_3)}{CSales_{r,t}+\sum_{c\neq r}CSales_{c,t-\tau}(1-\delta_1)^{\tau}(1-\delta_3)}\right]^{\epsilon_1} \cdot$$

$$\cdot \left[\frac{RD_{r,t}(1-\delta_2)^{\tau}+IRDE_{r,t}\frac{1-(1-\delta_2)^{\tau}}{\delta_2}+\sum_{c\neq r}RD_{c,t}\,(1-\delta_2)^{\tau}(1-\delta_4)}{RD_{r,t}+\sum_{c\neq r}RD_{c,t-\tau}\,(1-\delta_2)^{\tau}(1-\delta_4)}\right]^{\epsilon_2}.$$

The two parts of the equation describe the learning-by-doing and the learning-by-research mechanisms for the clean energy producing sectors. The variables used are: $CSales_{r,t}$ representing the cumulative stock of production in country group r (stock variable); $D_{r,t}$, is the production of equipment in country group r in time t (flow variable); $RD_{r,t}(1-\delta_2)^{\tau}$, is the stock of R&D in each country group r (stock variable); and $IRDE_{r,t}$ represents the R&D expenditures realised by country group r in time t (flow variable).

Knowledge depreciation rates are included in the above specification as follows: δ_1 is the annual depreciation rate of accumulated production stock in country group $(CSales_{r,t})$; and δ_2 is the annual depreciation rate of accumulated R&D stock in country group r $(RD_{r,t})$.

The rates for technological spillovers within country groups are included (with a five-year lag) as follows: δ_3 is the spillover rate for the learning by doing component; and δ_4 is the spillover rate for the learning by research component.

Parameters ϵ_1 and ϵ_2 represent the elasticies of learning by doing and learning by research components respectively. They are calibrated in order to reproduce the learning rates assumed in the GEME3-RD model following the previous literature.

Notice also that since the R&D service sector is modelled as one of the sectors of the economy, it employs all the inputs used in the other sectors of the economy (i.e. capital, labour and intermediates). Therefore, an additional, indirect channel for international spillovers can be identified through the trade in intermediates sales between country groups (the cheaper the intermediates, the more efficient the R&D service production process).

4.3. Human capital

Human capital accumulation is not modelled endogenously in GEM-E3. The production function in the model takes labour into account and calibrates it, by differentiating high-skill and low-skill, but no mechanism to accumulate skills or affect labour productivity is possible. Similarly, no mechanisms to adjust labour supply through employment or labour migration are present in the model.

4.4. Implementation and simulation of R&D policies

- *Research output of high-tech sectors*. The simulation of R&D policies in GEM-E3 R&D is built upon the cost advantages that can be obtained by scaling up research and production of high-tech sectors in order to exploit the two learning curves and obtain first-mover cost advantages.
- *Tax rate*. Government behaviour and policy is considered as exogenous. Policy shocks can be modelled through changes in eight categories of revenues and expenditures, including indirect taxes, environmental taxes, direct taxes, value added taxes, product ion subsidies, social security contributions, import duties, and foreign transfers.

4.5. Strengths and limitations[6]

Strengths

The main strength of the GEM-E3 R&D model is its granular disaggregation of energy sectors. Indeed, although the model is global, the sectors, the structural features of energy/environment and the policy instruments are very disaggregated. Hence, the economic and distributional effects of environmental and energy policies for sectors, agents and country groups can be analysed, while ensuring that the world economy remains in equilibrium.

The three channels used to model innovation (product/process innovation, learning-by-searching, learning-by-doing) provide a great flexibility in terms of policy modelling: governments can subsidise production, the R&D sector or the purchase of R&D from final goods firms to generate long-lasting increases in total factor productivity.

In addition, the GEM-E3 R&D model treats the R&D sector as any other sector of the economy, which means that it includes all the inputs used in the other sectors of the economy and uses all the information that can be extracted from the Social Accounting Matrices on the capital, labour and intermediates employed to produce R&D services. Therefore, through intermediates sales between country groups, an additional, indirect channel for international spillovers can be identified.

Limitations

Dynamics in GEM-E3 R&D are recursive-dynamic, similarly to RHOMOLO, which means that the optimisation problems of economic agents are inherently static. This can be a limitation in the context of assessment of R&D and human capital policies because it is difficult to fully capture the inter-temporal dimensions of such policies.

The main limitation of the current version of the GEM-E3 R&D model is that the innovation process is modelled only in the domain of clean energy production, which is in line with the scope and aim of the model, but it implicitly assumes no innovation occurring in the manufacturing sectors and services. In addition, while the R&D sector is modelled consistently with the general equilibrium nature of the model, the spillovers within country groups from R&D spending result directly into higher productivity. This feature is not consistent with the underlying general equilibrium framework

[6] See Tables 2-4 for a summary of GEM-E3 R&D strengths and limitations for modelling of R&D and innovation policies.

and does not take into account how the spending is used (for example, R&D outputs in the R&D sector would be a better proxy than simply R&D spending).

In addition, the macro focus of the model (consisting of only 6 aggregate country groups) reduces the scope for a meaningful international modelling of knowledge spillovers or technology diffusion, which would require a more detailed geographical resolution to be parameterised using the existing empirical literature.

Finally, since GEM-E3 R&D covers both developed and developing country groups, there are important data issues that the model has to deal with when dealing with the calibration for non-OECD countries. This is an issue, for example, for the ratio between public and private R&D in low-carbon technologies.

As for QUEST and RHOMOLO, the current version of GEM-E3 R&D cannot account for reforms in the R&D system that support higher quality investments. Similarly to QUEST and RHOMOLO, also GEM-E3 cannot differentiate between public and private R&D activities.

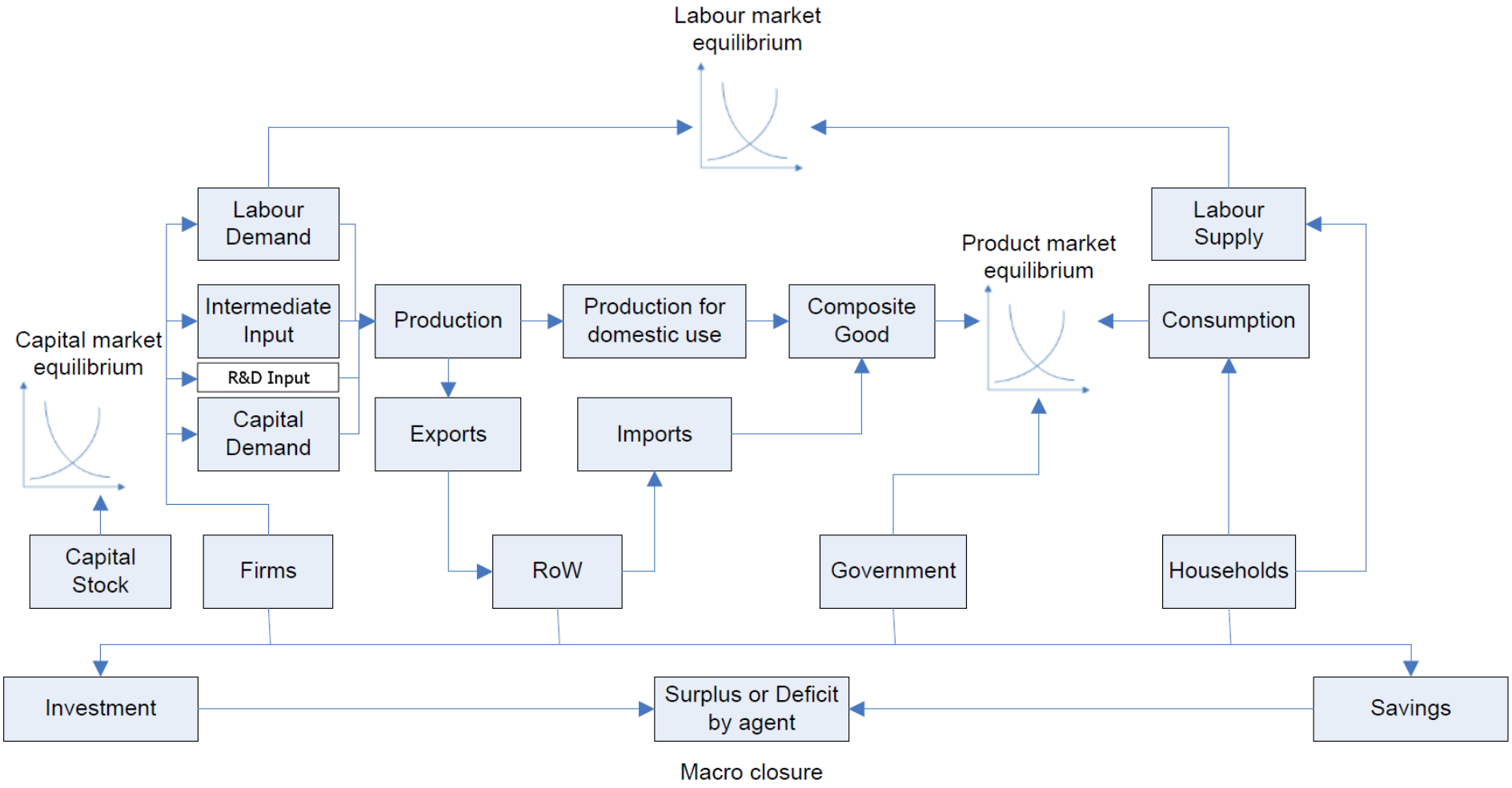

Figure 4: Overview of the GEM-E3 model.

5. The NEMESIS model

The NEMESIS model is a macro-econometric model, and has the following particularities with respect to the other three models presented here: (1) There are no utility functions for households and then the consumption functions are not derived directly from a maximisation of utility. (2) The prices are "sticky" and do not lead to a general equilibrium on all markets. (3) The departure from a micro-economically founded optimisation allows for more flexibility in behavioural functions, but is less consistent theoretically. (4) The expectation systems are adaptive and therefore recursively dynamic. (5) The model is not derived from the microeconomic theory.

NEMESIS is a macro-econometric model estimated for EU-28 and ROW-10. It distinguishes between 30 sectors and 6 factors of production combined in five-level nested-CES functions: material (M), energy (E), high skill labour $(\mathrm{L_{HS}})$, low skill labour $(\mathrm{L_{LS}})$, stock of capital (K) and innovations (A). The model covers both the supply and demand sides of the economy, and incorporates endogenous technical change. The conversion matrices of the model for final consumption, investment goods, intermediate consumption, energy/environment and technological transfers, capture the interdependencies between production sectors, with one representative firm per sector, and between the producers and the other agents of the economy: Households, Government and Foreign Countries. NEMESIS is partially "calibrated" and, in the long-run, the supply side properties replace the demand based equilibrium.

The current version of NEMESIS distinguishes between process and product innovations, the novelty being the introduction of innovation complementarities between investments in R&D, investments in ICT and investment in Other Intangibles (OI). It is particularly well adapted to represent innovation in service sectors that have intensive investments in ICT and OI, but not in R&D. This new version encompasses the former one, with R&D only, and the same general methodology extended to ICT and OI. The description of the different versions of the model is based on Brécard et al. (2006), Fougeyrollas et al. (2014a), Zagamé et al. (2010).

5.1. R&D modelling framework in NEMESIS

In NEMESIS, the investments in R&D, ICT and OI by private firms produce innovation services that impact on the economic performance of firms through two channels: the improvement in total factor productivity, and the increase in demand (taste for novelty). The resulting endogenous growth comes from the increasing returns provoked by the accumulation of knowledge stocks that are specific to countries and sectors, and to the type of investment: R&D, ICT or OI.

Final (intermediate) goods sector

The production function has a CES-nesting structure combining at the first level innovation services, A, to the set of traditional production factors, regrouped in the compound input X = KLEM, that includes physical capital (K), high and low skilled labour (L), energy (E) and intermediate consumptions (M).

The production of final output (Y) in every production sector and every country is expressed as:

(9.) $\mathrm{Y_t = F(A_t, X_t)}$,

with F a CES constant returns to scale production function. The impact of innovation services, A, on the use of production factors included in X is consequently Hick's neutral.

Demand of innovation services

In NEMESIS, the economic performance of innovation services pass through two channels: A total Factors Productivity (TFP) effect (process innovations), with an elasticity α, and a demand effect, (product innovations) with an elasticity α':

(10.) $\alpha = \frac{\partial \ln(X_t)}{\partial \ln(A_t)}$, and (4) $\alpha' = \frac{\partial \ln(D_t)}{\partial \ln(A_t)}$,

with D the demand addressed to the representative firm that has a monopoly power.

The innovation services produce two distinct effects, their demand cannot be solved analytically, and therefore is solved numerically by the model from the optimality conditions of the firm, that operates in imperfect competition with a CES constant returns to scale technology.

Supply of innovation services

The innovation services, A_t, are also produced with a constant returns to scale CES function, combining three innovation components A_{jt}, with j = RD, ICT and OI:

(11.) $A_t = G(A_{RDt}; A_{ICTt}; A_{OIt})$,

where the innovation components have the following evolution in time:

(12.) $\frac{dA_{jt}}{dt} = \lambda_j . \frac{j_t}{Y_t} . \frac{dKNOW_{jt}}{dt}$.

The growth of innovation components is a positive function of the growth of knowledge, and of the sector's ability to absorb knowledge, $\lambda_j . \frac{j_t}{Y_t}$, with λ_j a positive parameter, and $\frac{j_t}{Y_t}$ the investment intensity in j, in percentage of production.

The demands for innovation components are obtained from the minimisation of the cost of innovation services, under the technological constraint given by equation (1); then the demand for R&D, ICT and OI are obtained by inverting equation (2), expressed in level.

5.2. Knowledge spillovers

The knowledge variables, $KNOWj_{cit}$, are modeled as a weighted sum of the stock of assets, R&D, ICT or OI, belonging to all sectors and countries.

For R&D, the knowledge variables of the sector i in country c , $KNOWj_{cit}$, is defined by the sum of R&D capital stock $SR_{p,s,t-\Delta}$ in all countries/sectors (p,s) (wheighted by a coefficient of diffusion $\Phi R_{p,s\to c,i}$ reflecting the relative propensity of the knowledge of a sector s in country p to be useful for innovating in sector i in country c:

(13.) $KNOWR_{cit} = \sum_{p,s} \Phi R_{p,s\to c,i} \times SR_{p,s,t-\Delta}$

The same methodology is applied to the ICT capital and to other intangibles capital where, the coefficient of diffusion is $\Theta j_{p,s\to c,i}$ with, for ICT capital and for OI capital, respectively:

(14.) $KNOWT_{cit} = \sum_{p,s} \Theta T_{p,s\to c,i} \times ST_{p,s,t-\Delta}$,

(15.) $\mathrm{KNOWI_{cit}} = \sum_{p,s} \Theta \mathrm{I_{p,s \to c,i}} \times \mathrm{SI_{p,s,t-\Delta}}$.

The diffusion parameters are calibrated using matrices based on patent citations between sectors and countries developed by MERIT. These matrices combine the citations between patents allocated by technology classes and country with the OECD concordance table, in order to allocate these citations between sectors.

Two ways can be adopted for the sectorial allocation: one considers the sectors that produce the technology related to the patents (Industry Of Manufacturing), the other considers the sectors that use this technology (Sector Of Use). The assumptions underlying the choices of the method for the construction of the coefficient matrices were the following:

1. The sectors that produce the considered technology are the sectors that paid the R&D related to this technology and they receive knowledge spillovers coming from inventions by sectors that produce other technologies. From this perspective, patents allocated to their Industry Of Manufacturing (IOM) reflect the output of the R&D efforts realised by these sectors and the citations between patents belonging to IOM may be considered as indicators of the knowledge spillovers between sectors as IOM.
2. The externalities related to the use of ICT and of OI may reflect network externalities or, if we consider that ICT and OI are important inputs of organisational changes, these externalities may also reflect the diffusion of organisational innovations (the development of a new online distribution channel for instance). As these types of invention are not really patentable, we cannot use the same matrix than for R&D externalities. Nevertheless these inventions are assumed here to be strongly related to the use of technical innovations. The assumption is that sectors using the same type of technologies should have similar production methods and therefore similar organisational problems and their intangible investments as well as their ICT investments may be highly related. The matrices defined by patent citations allocated by SOU are thus retained. According to this approach, the more two SOU cite each other, the more they are using the same technology and, therefore, the more one sector can benefit from the innovation of the other in that field.

5.3. Human capital

In NEMESIS the supply of skills is exogenous, and is based on IIASA projections on the structure of skills in European countries at the horizon 2050. These projections mix extrapolations of the structure of population, and of the investment of Member States in education. The two categories of labour present in the model regroups respectively the ISCED 0 to 4 for Low Skilled Labour, and 5and 6, for High Skilled Labour. The repartition of skills is particularly important concerning innovation policies that can be hampered importantly is case of shortage of high skilled labour.

Exogenously, the supply of human capital can be adjusted in the model through the participation rates of the working age population by age, gender and skill categories. Whenever the employment increases in a simulation, the tensions on the labour market are traduced in the model through the Phillips effect, which provokes a general increase of prices. In the new version of the model with multidimensional innovations combining investment in R&D, in ICT and in OI, NEMESIS has also an

endogenous representation of the investments of private firms in education that are included in the variable OI.

5.4. Implementation and simulation of R&D policies

The mechanisms used in the modelling of research policies can be synthesised a as follows:

- *Rate of return of R&D expenditures*. The R&D decision is endogenous in the sense that it is at the sector level that the maximisation of profits induces the choice to invest in R&D (or in other assets). The rate of return of R&D expenditures is then an important variable, and all the policy measures that modify its value (or the returns of other assets) will modify the innovation decision of firms. It is the case for subsidies or tax credits to R&D expenditures, and of all the other measures that modify the returns, for instance the ERA policies that increase the knowledge spillovers.
- *Tax rate*. The funding of private R&D expenditures is realised by firms and impacts on production costs, while the funding of public R&D is financed by an increase of taxation (direct or indirect) or by a slight increase, at the beginning of the period, in deficits. These financing induce additional costs that lead to inflationary pressures during the beginning of the process (before innovations deployment).
- *Elasticity of the supply of high-skill workers*. The research and innovation activities need high skill labour. The demand for high skill labour increases their wages, and then the inflationary pressures that diffuse in the whole economy.
- *Elasticity of wages increase to unemployment reduction*. This elasticity can be used to affect unemployment and hence the supply of high-skill workers.

5.5. Strengths and limitations[7]

Strengths

Three types of innovation activities: investments in R&D, investments in ICT and in Other Intangibles (Formation and Softwares) are captured in NEMESIS. Hence, in terms of innovation types, NEMESIS is the richest among the four models analysed.

There are three categories of knowledge stocks reflecting knowledge externalities for R&D, and network externalities for ICT and OI.

Process and product innovations are present, with distinct impacts on economic growth and employment that are calibrated from the results of previous studies.

Due to its departure from the general equilibrium framework, NEMESIS can be specified such that it fits the observed data very well. The econometric estimation of empirically specified NEMESIS equations ensures sound empirical foundation.

Limitations

[7] See Tables 2-4 for a summary of NEMESIS strengths and limitations for modelling of R&D and innovation policies.

The model is based on ad hoc empirically observed relationships and departs from the most recent developments of macroeconomic theory, which rely on micro-founded optimisation decisions by consumers and firms under rational expectations. This can be a source of bias in the simulation results.

The model does not incorporate forward looking expectations, but only adaptive ones. Hence NEMESIS simulations related to R&D investment may yield different results, than in models with forward looking expectations, such as QUEST.

The representation and the role of human capital are limited in the model with no explicit link between the human capital accumulation and the investments in the educational system.

As for QUEST and RHOMOLO, the current version of GEM-E3 R&D cannot account for reforms in the R&D system that supports higher quality investments The three models also do not differentiate between public and private R&D activities, differently from NEMESIS, where private and public R&D investments are associated with different impacts on knowledge formation and on economic performance.

6. Avenues for future research

In this section we summarise the key findings from the previous sections and present them in a condensed form in Tables 2-4. Based on the identified strengths and limitations of the current versions of the four macro-models, we propose avenues for future research, which in our view could significantly improve both the theoretical basis and empirical foundations for modelling of R&D and innovation policies.

6.1. R&D investment: private, public and spillovers

Endogenous knowledge production: private R&D (row 1 in Table 2). In all four analysed macro-models – QUEST, RHOMOLO, GEM-E3 and NEMESIS – private investments in R&D and related innovative activities are undertaken by firms to develop and introduce product, process or other types of innovations. As outlined in introduction, these investments in knowledge enhance firm productivity and improve their competitive position relative to that of other firms.

Econometrically estimated elasticities: private R&D (row 2 in Table 2). Productivity elasticities with respect to R&D are estimated econometrically only in the NEMESIS model. In the current versions of QUEST, RHOMOLO and GEM-E3 they are taken from the literature. The major limitations of these elasticities are that they are derived from non-EU data, they are neither Member State- nor sector-specific, nor do they consider the key heterogeneities found in the previous literature (Griliches, 1973; Terleckyj, 1974). Hence, the fact that there is large heterogeneity in the way how and the extent to which R&D investments affect firm productivity is neglected in all four analysed macro-models. For example, the impact of R&D investments on firm productivity varies according to the level of R&D intensity; the relationship between the stock of existing knowledge and productivity growth is non-linear, and only after a certain critical mass of knowledge is accumulated,

productivity growth becomes significantly positive; there are important inter-sectoral differences with respect to R&D investment and firm productivity – high-tech sectors' firms not only invest more in R&D, but also achieve more in terms of productivity gains connected with research activities (Hall et al 2009; Kancs and Siliverstovs, 2015). Therefore, a country-sector specific econometric estimation would improve the reliability of the model simulated impacts.

Quality of research activities (row 3 in Table 2). One limitation that all the models share is that the parameters determining the impact of research on productivity are fixed and therefore cannot account for reforms in the system that support higher quality investments, which is often an explicit objective of policy-makers.[8] The patent data mentioned above could be used together with data on expenditures in research activities or other inputs in the knowledge production process to determine an efficiency parameter in knowledge production and investigate how it relates to other economic variables or policies.

Endogenous interactions between public-private R&D (row 4 in Table 2). In the current versions of the four macro-models the interaction between public and private investment in R&D is not modelled endogenously. Hence, the fact that the investment in R&D may have a differentiated impact on firm productivity, depending on the source of investment: public vs. private (Cox and Gagliardi, 2009), is neglected in all four analysed models. Previous literature points to two channels of countervailing effects of public R&D investment that affect private R&D. On the one hand, through higher stock of locally available knowledge, public R&D activities increase private R&D productivity. As a result, private firms have higher incentives to innovate, which yields higher economic growth (Guellec and Van Pottelsberghe De La Potterie, 2003). On the other hand, public R&D investments may 'crowd out' private R&D investments (David et al, 2000). In order to consistently account for the impact of R&D investment on firm productivity, both channels of public R&D need to be modelled endogenously.

Knowledge spillovers (row 5 in Table 2). In all four analysed macro-models knowledge spillovers are modelled as an important form of externality associated with innovative activities. However, previous literature points that they are not the only form of R&D externalities. The positive effects deriving from technology spillovers counterbalance the negative business-stealing effects derived from increased productivity of competitors (Bloom, Schankerman and Van Reenen, 2013). The two effects can be modelled endogenously, in order to capture the overall knowledge spillover effect in an unbiased and consistent way.

Econometrically estimated spillover elasticities (row 6 in Table 2). Only in the NEMESIS model elasticities of knowledge spillovers are estimated econometrically. In the current versions of the other three macro-models – QUEST, RHOMOLO and GEM-E3 – the elasticities of knowledge spillovers are assumed either ad-hoc or taken from the previous literature, e.g. Botazzi and Peri (2007), which however are neither country- nor region-specific. Moreover, they are estimated on outdated pre-crisis data and for non-EU countries.

[8] Notice, however, that NEMESIS has a research program for evaluating the impacts of reform in the EU innovation system, for example for the "European Research Area" (ERA) priorities and other innovation commitments which can be used for this purpose by altering some key innovation-related parameters of the models.

In order to better align the four macro-models with the recent empirical evidence that (i) knowledge spillovers are large, and (ii) knowledge spillovers are localised/geographically concentrated, knowledge spillovers can be estimated econometrically by region and Member State using the most recent data for the EU. Based on these estimates, the corresponding knowledge spillovers elasticities can then be calculated, which can be used in the four macro-models.

6.2 Skills, education and human capital accumulation

Skill levels (row 1 in Table 3). In order to model differences in human capital between countries, a distinction needs to be made between different skill levels of workers. Three skill levels (low-, medium, and high-skill) are modelled in QUEST and RHOMOLO. NEMESIS captures 2 different skill levels, whereas GEM-E3 does not differentiate between worker skills.

Endogenous human capital accumulation (row 2 in Table 3). Workers' decision to invest into education to accumulate skills is not modelled endogenously in QUEST, GEM-E3 and NEMESIS, and only semi-endogenously in the current version of RHOMOLO. This shuts down one of the most important channels of human capital adjustment, and hence of economic growth.

According to previous literature (Becker, 1975; Romer, 1989; Benhabib and Spiegel, 1994), education is considered as one of the most significant human capital investments, it plays a vital role in the process of economic growth. The previous literature suggests that, generally, the returns to education are large (Schultz, 1961). However, they are found to be heterogeneous between individuals, regions and countries. A second well-established empirical fact is that the return to education is non-linear in the existing stock of human capital. For example, 'upgrading' from low-skill to medium-skill increases individual productivity differently than 'upgrading' from medium-skill to high-skill. Moreover, it depends on the previously accumulated human capital which is available locally.

Endogenous human capital accumulation can be introduced to better align the four models with the empirical evidence that (i) the returns to education are large but heterogeneous between individuals, regions and countries, and (ii) the return to education is non-linear in the existing stock of human capital.

Endogenous human capital adjustment (row 3 in Table 3). In addition to education and training, the stock of human capital can be enhanced also through population growth, participation, employment and migration channels. Such endogenous human capital adjustments take place in all four analysed macro-models.

Econometrically estimated elasticities of human capital (row 4 in Table 3). In the current versions of the four macro-models, human capital elasticities with respect to education are taken from the literature, which are neither region- nor country-specific. In future versions of the four macro-models, human capital elasticities with respect to education can be estimated by skill level and by Member State, so that they can be readily used in the four macro-models.

6.3 Spatial diffusion of technology

Endogenous diffusion of technology (row 1 in Table 4). Individual adoption decisions, which would yield to the accumulation of knowledge across adopters and over time, are not modelled endogenously in any of the four macro-models. Hence, technology diffusion as the dynamic consequence of adoption is exogenous.

As noted by Comin and Mestieri (2014), countries/regions have different levels of productivity not only because they differ in terms of their investment in R&D, but also because of their differences in the extent to which they benefit from research done elsewhere. While spatial diffusion of knowledge may be a powerful engine of growth, in the same time, it is also a crucial factor in explaining growth differences between countries and regions (Comin and Mestieri, 2014).

As noted by Griliches (1960), despite of being non-rival in nature, and involving no direct transport costs, technology diffuses slowly across space. These slow technology flows result in significant lags between the time of invention at the technological frontier and the time when a technology is initially used in a country/region. Even when a technology has arrived in a country/region, it takes time before it has been accumulated to the point of having a significant impact on productivity.

A second empirical observation is that the majority of R&D investments are undertaken by few large firms, which are spatially clustered: top 2500 world-wide innovating companies undertake more than 90% of the global R&D investment (R&D Innovation Scoreboard, 2014). The overwhelming majority of companies around the world do not engage in any significant R&D activities. Instead, most companies in the vast majority of regions are well behind the technological frontier. The fundamental concern of these firms, when upgrading their technology, is to get closer to the technological frontier (Slivko and Theilen, 2014).

In order to better align the four macro-models with the empirical evidence that (i) diffusion of new technology is slow and heterogeneous across regions and countries; and (ii) only few firms innovate and they are geographically concentrated (the majority of firms in most regions around the world imitate), conceptual framework can be adopted that accounts endogenously for differences in the speed of technology diffusion between regions and countries.

Econometrically estimated elasticities of technology diffusion (row 2 in Table 4). In the current versions of QUEST and GEM-E3 elasticities of technology diffusion are taken from the literature. In the current versions of RHOMOLO and NEMESIS no elasticities of technology diffusion are present, as technology diffusion is not accounted for in these two macro-models.

According to Comin et al (2012) and Comin and Mestieri (2014), the speed and pattern of diffusion of new technologies between countries and regions is endogenous, and depends on local amenities, most notably on market conditions, institutions, human capital and various measures of distance or similarity between innovators/early adopters and late adopters.

In the future versions of the four macro-models, technology adoption patterns can be estimated across regions and countries for the whole EU. Understanding the determinants of technology diffusion will allow to better identify "who is getting what from whom" (Eaton and Kortum, 1999), and develop appropriate EU policies for innovation and growth.

Table 2. Comparisons of modelling of R&D investment: private, public and spillovers in QUEST, RHOMOLO, GEM-E3 and NEMESIS

	QUEST	RHOMOLO	GEM-E3	NEMESIS
R&D investment: private, public and knowledge spillovers				
1 - Endogenous knowledge production: private R&D	Yes	Yes	Yes	Yes
2 - Econometrically estimated elasticities: private R&D	No	No	No	Yes
3 - Quality of research activities	No	No	No	Yes
4 - Endogenous interactions between public-private R&D	No	No	No	No
5 - Econometrically estimated elasticities: public R&D	No	No	No	No
6 - Knowledge spillovers (international)	Yes	Yes	Yes	Yes
7 - Econometrically estimated spillover elasticities	No	No	No	Yes

Table 3. Comparisons of modelling of skills, education and human capital accumulation in QUEST, RHOMOLO, GEM-E3 and NEMESIS

	QUEST	RHOMOLO	GEM-E3	NEMESIS
Skills, education and human capital accumulation				
1 - Skill levels of labour	3	3	1	2
2 - Endogenous human capital accumulation	No	Yes	No	No
3 - Endogenous human capital adjustment	Yes	Yes	Yes	Yes
4 - Econometrically estimated elasticities of human capital	No	No	No	No

Table 4. Comparisons of modelling of spatial diffusion of technology in QUEST, RHOMOLO, GEM-E3 and NEMESIS

	QUEST	RHOMOLO	GEM-E3	NEMESIS
Spatial diffusion of technology				
1 - Endogenous diffusion of technology	No	No	No	No
2 - Econometrically estimated elasticities of technology diffusion	No	No	No	No

7. Conclusions

Usually, R&D impact on productivity has been studied econometrically (see e.g., Hall et al 2009). While being very useful tools for the ex-post evaluation of R&D effects, econometric models cannot be employed for ex-ante impact assessment of innovation policies. Instead, macroeconomic models need to be used for simulation of R&D and innovation policies, and comparing the results to the baseline (without policy). In this report we have compared how R&D investments and innovation policies are modelled in four macroeconomic models used by the European Commission for ex-ante R&D policy impact assessment: QUEST, RHOMOLO, GEM-E3 and NEMESIS.

For each of them, strengths and weaknesses have been highlighted, in addition to their main features and properties. In the final section a direct comparison of the four models is proposed, highlighting some of the key aspects that we considered particularly relevant for R&D modelling and how important we judge each item. In this way, we hope the reader will also be able to make up his mind and decide which model to refer to, based on the specific policy question at hand.

Given that R&D investment decisions are inherently dynamic, QUEST R&D appears to be the most suitable model for assessing the impact of R&D and innovation policies over time, as it is the only model with inter-temporal optimisation of economic agents. As discussed in section 6, R&D activities are highly concentrated in geographical space, and knowledge spillovers are significant only locally. In order to address questions related to geographic concentration of innovative activities and spatial knowledge spillovers, RHOMOLO appears to be the most suitable model, as it is the only one which models regional economies and spatial interactions between them explicitly.

The role of energy and environmental policies is growing continuously, e.g. due to factors such as climate change, and advancement of clean and green energy technologies requires large investments in R&D. Due to its detailed treatment of energy sectors and environmental issues, GEM-E3 R&D appears to be the most suitable model for assessing the impact of innovation in clean energy. For those policy questions, which do not require a general equilibrium context, NEMESIS could be an appealing modelling alternative. In addition, the set of policy elasticities which are estimated econometrically in NEMESIS is richer than in the other three macro-models.

Despite our efforts attempting to compare the four macroeconomic models as objectively as possible, it should be kept in mind that large macro-economic models such as the ones presented here are continuous "work in progress", where the availability of new data, improved theoretical foundations, new evidence or better estimates of elasticities and exogenous parameters are always associated with incremental improvements. We are therefore taking a snapshot of the state of the art of these four models in this particular moment of time, but for future reference to the specific properties of each of them, it would always be advisable to look for the latest updates of the models before using or referring to them.

Of course, given the unlimited possibilities of evolution of these models (such as income distribution, different sources of firm and consumer heterogeneity, non-homothetic utility functions, environmental impact), a few guiding principles, such as scientific credibility, saliency and legitimacy, have to be followed to focus the efforts and narrow down the scope of additional modules and variations. The constant efforts of maintaining and fine-tuning these models stem from the need to follow these principles while at the same time exploring new possibilities.

Notwithstanding the different modelling choices and specific mechanisms identified, all the models presented in this report share this common effort towards their own refinement. Even if this continuous evolution may sometimes bemuse the end users of models' results, it should be understood as an integral part of the process of having a general equilibrium model ready to be deployed to answer new policy questions and support policymaking.

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