European Commission

Moving the Frontier of Macroeconomic Modelling of Research and Innovation Policy

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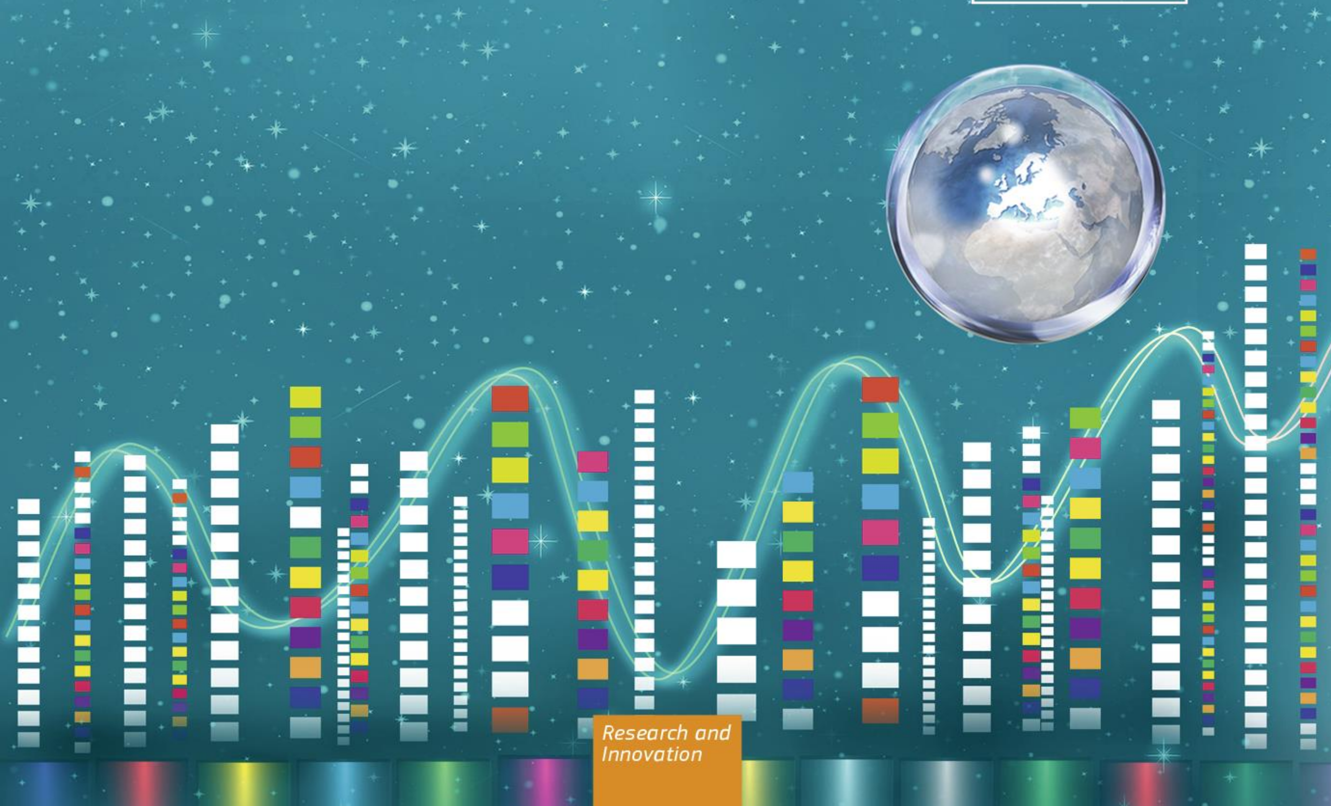

Research and Innovation

Moving the Frontier of Macroeconomic Modelling of Research and Innovation Policy

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Moving the Frontier of Macroeconomic Modelling of Research and Innovation Policy

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2020 Directorate-General for Research and Innovation

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EXECUTIVE SUMMARY

The Directorate General for Research and Innovation of the European Commission (DG R&I) has engaged since 2014 in a medium to long-term agenda to improve the treatment of research and innovation (R&I) in macroeconomic models used to assist policy making.

Since December 2018, an Expert Group has supported the European Commission in the further development of its modelling activities. The Group is chaired by Reinhilde Veugelers (University KU Leuven), with Pierre Mohnen (UNU-Merit) as rapporteur, and Barbara Annicchiarico (University of Rome Tor Vergata), Giovanni Dosi (Sant'Anna School)[1], Omar Licandro (University of Nottingham) and Eva Ortega (Bank of Spain) as members.

MAIN FEATURES AND POLICIES OF R&I FOR MACRO-MODELLING

Based on the existing literature on R&I and innovation policies, mostly the academic macroeconomic literature, Section 2 of this report describes the critical features and enablers of the innovation process needed to appropriately account for its role in economic growth and welfare, as well as the main economic policies oriented to promote innovation, boosting growth and enhancing sustainability. This description of R&I features, enablers and policies can be used to assess applied macro-models on their capacity to study and evaluate innovation and innovation policy.

R&I features

Technological knowledge is the sum of methods and techniques employed in the production of goods and services. It results from the cumulative aggregation of new technological ideas or innovations, resulting from a systematic effort of research and development (R&D) benefiting from multiple forms of knowledge spillovers. It is *non-rival* -it can be used by many agents at the same time- and suffers from *economic obsolescence* -it depreciates in value due to the emergence of subsequent innovations. Non-rivalry and obsolescence prevent private R&D returns from equalizing the corresponding social returns. Technological knowledge is indivisible, tacit and path dependent.

Innovations or new technological ideas are the direct result of *R&D* activities. R&D benefits from *knowledge spillovers*, i.e., unintended knowledge transfers that cannot be appropriated by the innovator. Negative *rent or market spillovers* are also associated with R&D, i.e., the transfer of monopoly rents between firms resulting from the introduction of innovations. They can take the form of *business stealing* when a new, better quality product displaces an existing one, or more generally *obsolescence* referring to the loss in value of an existing product as a result of the reduction in demand that follows from the introduction of innovations in competitive products. The empirical literature finds that knowledge spillovers quantitatively dominate market spillovers making the social return to R&D larger than the private return, which provides a justification for government-supported innovation policy.

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[1] Giovanni Dosi is a member of the Expert Group but not an author of this report.

Firm heterogeneity in products and production processes naturally emerge from the stochastic nature of the innovation process. Well beyond the representative agent model, the literature on *endogenous growth* and *firm dynamics* builds on the fact that R&I shapes the dynamics of heterogeneous firm-level productivity, and the associated creation and destruction of jobs, eventually affecting the evolution of aggregate productivity, GDP growth and people's welfare. In this process, R&D activities are addressed to create new products, improve the quality of existing ones as well as to reduce the associated production costs. This approach provides a sound basis for modern quantitative macro-models of innovation and innovation policy, using macro and micro data to discipline the analysis. Heterogeneity is also an essential feature in the *evolutionary* view of technological progress, and in the literature on *vintage technologies*, studying the embodied nature of technical progress. Other relevant dimensions of heterogeneity like *granularity*, the existing of *superstar firms* and the *network structure of the production process* are also of critical relevance.

Different types of research and innovation can be distinguished. *Basic research* is fundamentally addressed to move the frontier of knowledge, while *applied research* aims at providing solutions to technological problems. Basic research is at the highest level of knowledge spillovers, motivating public support. *Product innovations* result in the introduction of new goods or services. *Process innovations* result in cost reductions. From the perspective of a product, productivity has at least two conceptually different components: the quality of the product and the technical efficiency of the production process. The former is related to product innovation and the latter to process innovation. Innovation may at different degrees be *incremental or drastic*, of a *general-purpose* nature or product/sector specific.

New technological ideas, after discovery, diffuse throughout the economy, affecting the design of products and production processes in different sectors and locations. *Diffusion* may be modelled as an adoption process aiming to catch-up the frontier technology or as the result of adoption delays. In the former approach, adoption rates positively depend on the distance between the frontier and the actual state of technology. In the latter, innovations belong to different *technological vintages* susceptive of long adoption delays. More recently, the literature stresses the role of *production and innovation networks* in the diffusion of firm level innovations, making idiosyncratic shocks to firm's productivity lead to aggregate outcomes.

The report also describes the most commonly used measures of R&I inputs and outputs, and illustrates how these measures are being used in the macroeconomic literature of innovation and growth. It includes a description of the measurement of R&D and intangible capital, the estimation of knowledge and market spillovers, the use of patents information, as well as the measurement of process and product innovation, and firm level productivity.

R&I enablers

Market size. Firms have more incentives to do R&D when there is a large market willingness to pay to recover the fruits of their R&D investment.

Competition and patents. Patents systems grant temporarily monopoly rights to innovators in order to protect them from being copied or imitated. However, *the relationship between competition and innovation is inverted U-shaped*. When competition is low, incumbents do not need to protect their monopoly rents, having little incentives to innovate. When markets become more competitive, technological leaders innovate to escape competition, followers and potential entrants to catch-up or leapfrog the leader. However, when there is too much competition, the gains from innovation dilute to the point that neither incumbents nor potential entrants have incentives to innovate. Moreover, *mark-up dispersion affects the misallocation of resources*, affecting the incentives to innovate. When mark-ups are heterogeneous, relative prices are distorted and resources misallocated, the degree of misallocation increasing with mark-up dispersion.

Human capital. Leading the innovation process requires a highly performing education system able to generate a large body of high human capital scientists and applied researchers dominating and moving the frontier of knowledge.

R&I financing suffers from high risk and large asymmetrical information problems between the innovator and the fund provider. For this reason, small and new innovative firms experience high financial costs and credit scarcity, and large established firms prefer internal funds for financing their R&D investments. Financial frictions have an important negative effect on R&D investment.

R&I policy

Macro-models aimed to evaluate innovation policy should include the main *R&I policy instruments* used in practice, the distortions they are expected to correct and the relevant channels through which they are presumed to operate. In order to be a good laboratory for the quantitative evaluation of R&I policy, macroeconomic models of R&I need to be disaggregated enough and disciplined by the available macro and micro data on those dimensions in which policies are expected to operate.

R&D tax incentives aim at reducing the gap between private and social returns to R&D, and alleviating the financial problems faced by R&I performers. The use of R&D tax incentives is worldwide spread. In principle, R&D tax incentives are neutral -can be claimed automatically as long as some general criteria are fulfilled. But governments can give special tax incentives to specific areas like health or environmental protection or targeted firms, like SMEs.

Direct subsidies. Research grants are another main R&I policy instrument. They are aimed to promote research excellence by supporting projects with the highest expected social return, expected to move the frontier of scientific and technological knowledge. Contrary to tax incentives, research grants are non-neutral. They are granted generally through a competitive process where the best projects are selected by experts.

Public financial support for innovation can also be given via loans, guarantees and venture capital, including the support to startups and highly innovative small and medium size firms. The governments can also directly perform R&D in *public universities or research labs* or engage in *public private partnerships*. Instead of stimulating innovation by lowering R&D costs, *public procurement* can provide a demand for new products, facilitating their diffusion.

Patents are used to protect innovation from copy and imitation, by creating temporary monopoly rents. It does so in exchange for the disclosure of the relevant information behind the innovation, which favours the spread of knowledge spillovers.

Other policy instruments affecting innovation include *corporate taxes. Regulations* and *environmental policies* may direct technical change towards the achievement of socio-economic and environmental challenges, introducing incentives to innovate in the desired direction.

Dimensions of macroeconomic impact of R&I

Several macroeconomic dimensions can be impacted by R&I and R&I policies. A main impact dimension of R&I policies studied with macro-models is *GDP and its growth rate*. As GDP is a common anchor metric used for targeting macroeconomic performance, macroeconomic models are a prime tool to assess the impact of R&I policy interventions on GDP at various horizons.

R&I policies need to be evaluated also by their potential effects on *competitiveness*, i.e., the ability of a firm, sector or country to successfully compete in global markets. Multi-country macro-models of R&I should include channels through which competition in global markets shapes the incentives of firms to innovate, building countries' comparative advantages.

Since innovation creates and destroys jobs and skills, R&I policy needs also to be evaluated by its *labour market* effects, addressing important issues like the skill premium, job polarization and automation, skill obsolescence and structural transformation.

Social exclusion and *inequality* have emerged as major concerns. Inequality across countries or regions requires asymmetric multi-country-region models with *heterogeneity* in firms' innovative capabilities. Inequalities among individuals or across socio-economic groups require the explicit modelling of different categories of workers having different skills.

Macro-models aiming at studying the effects of R&I on *health* should include individual health statuses, life-expectancy and population aging, explicitly modelling health technology.

The importance of the *environment* has been gaining momentum in both policy-making and academic circles. Macroeconomic models for R&I policies evaluation should embody environmental externalities, account for the damage of pollutants, deal with the issue of resource scarcity as well as the creation of new clean technologies.

THE MACROECONOMIC MODELS CURRENTLY USED BY DG R&I FOR R&I POLICY

Section 3 assesses for the 3 macro-models currently used by the European Commission, DG R&I, namely QUEST, RHOMOLO and NEMESIS, whether they contain the basic features, enablers and policies thought to be important for modelling R&I and assessing R&I policy interventions, and, if not, how they could be included.

QUEST III is a large-scale *Dynamic Stochastic General Equilibrium* (DSGE) model designed as a laboratory for policy analysis of the EU economy. It is a multi-countrymodel calibrated for EU countries and the rest of the world. The explicit modelling of *knowledge creation* and of *technology adoption* allows QUEST III to support questions related to the evaluation of *R&I policies*. QUEST III adopts a *semi-endogenous growth* framework with expanding varieties and incorporates an *endogenous diffusion process of new ideas*. Given the general equilibrium structure of the model several agents are involved in the *innovation process*. *R&D activities* take place in research institutes employing *skilled labour* and making use of the commonly available domestic and trade related international knowledge (*knowledge spillovers*). Technology adopters use *skilled labour* to transform non-adopted technologies (or ideas) into technologies that are then used by intermediate goods producers to produce new varieties. In this sector firms produce intermediate goods using physical capital and the designs of *adopted technologies* licensed from households. In the final good sector, firms produce horizontally differentiated goods employing three types of labour inputs of different skill levels and a composite of intermediate goods.

QUEST III includes several mechanisms and features related to the creation and the diffusion of new technologies (*spillovers*, *basic and applied research*, *absorptive capacity*, *non-rivalry, obsolescence*, *congestion externalities*) and to the *enablers for R&I creation*, *adoption and diffusion* (*market size*, *competition*, *intellectual property rights* and the *skill composition* of the labour force). The general equilibrium framework allows to capture the effects of *R&I policies* on the main macroeconomic aggregates, *inequalities*, *labour markets*, *external competitiveness* and to address the *budgetary and financing issues related to costly R&I policies*. The model presents a rich set of tools and channels through which *R&I activities* and *adoption* can be promoted that range from more direct interventions, such as *tax incentives*, *subsidies* and *patent policies* to policy initiatives that involve the overall economy, such as *public procurement*, *regulation*, *education policies*.

RHOMOLO is a *Spatial Computable General Equilibrium* (SCGE) model covering all the European Union NUTS 2 regions and disaggregating each regional block in ten sectors. The model is based on a large system of simultaneous equations where all sectors are interlinked through input-output relations and interactions are mediated by markets and prices. RHOMOLO is used extensively for impact assessments of *regional policies* and provides sector- and region- specific simulations to support the EU policy making on a wide range of *structural reforms*, *investment policies, including R&I support programs* and of initiatives reinforcing the *internal market*.

In RHOMOLO V3 in each region *scientific and technical activities* take place in a wider sector also embodying other professional services and administrative service activities. In this sector imperfectly competitive firms make use of physical capital, intermediate inputs and labour inputs of different skill levels. An increase in *R&D investments* generates two direct effects on the economy. The first effect is related to the positive effect of innovation on *total factor productivity* (productivity channel). *R&D investment* increases the *stock of knowledge* which through *spillovers* generates a structural positive impact on all the other sectors and regions of the economy. The strengths of these spillovers are sector- and region- specific and depend on estimated elasticities. A higher *R&D intensity* at regional level is a sign of greater *absorptive capacity* of firms located in that region and is associated with a larger elasticity of *total factor productivity* to *R&D investments*. The second effect of *R&D investment* refers to the direct temporary impact on aggregate demand

(demand channel). *R&I spending* is introduced as private investment, so that increases in *innovation activities* give rise to a higher demand for capital goods.

RHOMOLO presents several mechanisms and features related to the *creation and the diffusion of new technologies*, and to the *enablers for R&I creation*, *adoption and diffusion*. Its extreme *granularity* allows to evaluate the impact of *innovation activities* on a vast range of indicators at regional and sectoral level, and to keep track of the potential effects on the geographic distribution of economic activity and population. RHOMOLO can simulate a vast range of policies directly affecting *innovation activities*, especially the impact of *R&I policy initiatives* undertaken at different levels (*EU funding*, *national* and *regional*) and targeting specific sectors.

NEMESIS is a large scale *multisector macroeconometric model* covering all the European Union countries. NEMESIS is mainly used for the impact assessment of *research and innovation policies* carried out at country and EU level. The model belongs to the neo-Keynesian tradition and is based on national accounting with the demand side predominant in the short to medium run, and the supply size driven by *technological change* predominant in the long run. Sectors and countries are interlinked through trade and *international knowledge spillovers*. The main behavioural equations describing consumption, factor demand by firms, wage and price formation, import and export decision are subject to reaction delays reflecting the existence of adjustment costs and of adaptive expectations.

In NEMESIS *innovation activities* take place in each country/sector and are related to investments in three categories of *intangible services*: *R&D*, *ICT* and *other intangibles*. The production of each innovation component is a positive function of the country/sector specific *stock of knowledge* and of the *absorption capabilities* that depend on *innovation intensity*. Each country/sector specific *stock of knowledge* in turn builds on the stocks of *intangible assets* (*R&D*, *ICT* or *other intangibles*) belonging to all sectors and countries of the model economy. This feature allows capturing the existence of *knowledge externalities* across sectors and countries. In each sector services produced by the *stock of knowledge* increase the *productivity* of all the other production factors, resulting in a *Hicks-neutral productivity improvement*. In addition, *innovation services* improve the *quality of products* increasing market demand.

NEMESIS can represent many aspects related to the *creation and the diffusion of new technologies*, and to the *enablers for knowledge creation*. The multi-sector and multi-country structure of the model permits to evaluate the impact of *innovation activities* and of the related *R&I policies* for several key economic indicators.

Comparing the strengths and weaknesses of QUEST III, RHOMOLO and NEMESIS informs that all the three models are able to account for several features related to *R&I* and address a vast range of policy initiatives and reforms falling in the domain of *research and innovation* or in other areas of interventions that may have an impact on *knowledge creation and diffusion*. The presence of *knowledge spillovers* and of several sources of *market imperfections* shapes the scope for *public interventions in R&I*. The modelling of the labour market is differentiated among *different skill categories of workers*, therefore the three models can capture the *social dimension of technological progress* and account for *income inequalities*. The three models have a multi-country structure and can be used to address issues related to the *interactions between national and international R&I policies*, and to evaluate *the impact of technological advancements on trade performance and external competitiveness*.

The distinct strengths of QUEST III, RHOMOLO and NEMESIS are related to the specific modelling approach they are based on. The main strengths of QUEST III refer to its *theoretically consistent micro-founded approach* based on the optimising behaviour of rational agents. Its *general equilibrium* structure allows to disentangle clearly the different *transmission channels of R&I policies* over time and to fully account for reallocation effects and the possibility of *policy trade-offs*. The main strengths of RHOMOLO pertain to its *granular structure* and the detailed modelling of *spatial interactions* across regions. With these features RHOMOLO can effectively address questions related to the *geographic concentration of innovation activities* and to the *interactions between specific R&I policy initiatives and cohesion policies*. The main strengths of NEMESIS are related to its ability to fit the observed data and to its *flexibility*, allowed by its departure from the general equilibrium framework. Also, NEMESIS presents a rich modelling of *innovation activities* that allows to account for several direct links between concrete *R&I policy interventions* and market outcomes.

Although all three models present a vast range of mechanisms and features through which R&I policies can be simulated, all of them have some important limitations and need further developments to better cover key features of the *technological process*. A first weakness is related to the lack of *firm heterogeneity* and the associated *dynamics* of products, firms and markets. None of the models can capture the *complex process of creation and destruction of products and production processes, plants and firms* through which *technological progress* occurs. A second weakness regards the absence of *endogenous financial frictions*. Firms operate under very different market conditions and especially *small and innovative firms* may have limited access to credit. A third weaknesses is that none of the three models can capture the *risk associated to R&I activities* and the randomness in the outcome of the *R&I process*. A fourth weakness is that the role of *human capital* is limited in all three models. There is not any explicit link between *human capital formation*, the *investments in the education system* and the *individual educational choices and training*. Finally, although all the three models have already been extended or used to address *environmental sustainability issues*, *the relationship between environmental regulation and technical change* as well as the effects of *technological progress* on the environment are all aspects that have not yet been systematically incorporated in the core models.

Applying the check-list developed in this report of the key ingredients a macro-model requires to deliver a sound macroeconomic evaluation of innovation policy to the three macroeconomic models, QUEST III, RHOMOLO and NEMESIS, reveals the following lessons:

- All three models present a rich set of mechanisms and parameters through which R&I policies can be simulated.

- Yet, none of the models covers all of the key characteristics of innovation and innovation policy. This implies that none of them can be considered as dominantly better for the modelling of innovation and innovation policies. Each has its own strength and weaknesses. Which model to choose for R&I policy analysis will depend on what the major objectives are of the modelers and their users.

- All models require further developments to better cover key features of innovation and innovation policy. Some key features can be included with minor changes to the models, others would require bigger adjustments.

- All the models struggle with a lack of sufficiently recent and disaggregated data to calibrate/estimate critical parameters. All models can be improved with better data.

CONCLUSIONS AND RECOMMENDATIONS FOR MOVING FORWARD

- **No single macro-model** can simultaneously account for all features, enablers and policy instruments in the checklist provided and used in this report, and still consistently produce the accurate quantitative figures needed for the macro-evaluation of all current R&I policies. Choices have to be made about which features and policies are more relevant, depending on the objectives and the innovation policies being evaluated. In making these choices, a few recommendations should be kept in mind:

    - A good macroeconomic model designed to evaluate innovation policies should ideally include **heterogeneous firms and heterogeneous production and R&I technologies**. This requires, in particular, an important disaggregation at the level of firms, including innovation incentives and performance, as well as the associated dynamics, including the entry of new innovative firms, their development and eventual exit.

    - When the different features of the R&I process, their diffusion channels (the enablers), the different policy instruments and the different dimensions of macroeconomic impact are studied in **different models (or sub-models**), or at different levels of disaggregation, their results should nevertheless remain comparable with a common core.

    - For the **geographic** dimension in the case of the European Union, a macro model designed to evaluate innovation policies ideally has to mimic a multi-country, multi-region Europe trading with the rest of the world, the degree of disaggregation depending on the policy under evaluation.

    - Innovation, by creating and destroying jobs and the value of the associated skills, impacts **social inequality**, deeply affecting the distribution of income and wealth. To evaluate this dimension of R&I, macroeconomic models must be designed to properly account for **heterogeneity** across workers and households and the associated **dynamics**. Modelling skill and education heterogeneity is of fundamental importance to evaluate the labour market and the distributional implications of innovation policies.

    - **Environmental** issues, such as those falling in the domain of climate change, have become pressing in the recent decade. Environmental policies direct technical change towards the development of environmental-friendly technologies. However, the advancement of green and clean energy technologies and the development of abatement technologies require large investments in

R&I. These two dimensions should be addressed together in models integrating environmental aspects with endogenous technical change mechanisms.

- There will never be one perfect or right model. "All models are wrong, but some are useful". The agenda should thus be to help incumbent models becoming more useful for innovation and innovation policy analysis, as well as helping the development of new models which are better able to assess innovation and innovation policy analysis.

    - A lot of progress could already be made from sharing and learning among the currently used models.

    - When contemplating bigger adjustments to the models, a more **modular** approach should be considered, with a stable "core" model that is capable and flexible to link to (new) submodules. Modules can address in more detail key features of innovation or different dimensions of macroeconomic performance and can be activated when needed.

    - Commonly **missing features** in the current models (such as the formation of human capital for the creation and adoption of innovation; the modelling of risk and uncertainty, role of the public R&D sector, the heterogeneity and dynamics of the innovative firms population) require bigger adjustments through **new submodules**. As the features are missing in all of the currently used applied macro-models, efforts to develop new submodules for these features could be shared among the models.

    - To achieve the objectives mentioned above in the development of R&I macro-models for the evaluation of R&I policies the following **families of models** should be seriously considered: endogenous growth models with firm dynamics, models of vintage technologies, models of directed technical change, models of human capital formation and occupational choice, and models of search in the labour market, among others.

    - Beyond further developing currently used models, **new models** should be on the radar as well, such as, models of networks, models of structural transformation, models of bounded rationality, evolutionary game theory and agent-based computational models. New models offer new perspectives for modelling currently missing features.

- Macroeconomic models can only be a good laboratory for the evaluation of economic policy, if they are as close as possible to the available data on those dimensions in which the policy is supposed to operate. This is a basic requirement for any macroeconomic model to provide accurate quantitative figures that help evaluating the contribution of innovation policies. High on the to-do list should be to improve **the data availability** for modelling of the key R&I features and key R&I policy interventions, in particular data on innovation policies in Europe.

- Modern macroeconomic models based on microeconomic foundations should be designed consistently with **microeconomic data** and the institutional framework in which economies operate. This is generally done by an exercise of calibration and/or estimation of behavioral parameters of the model that are reasonable (i.e. consistent with empirical evidence from micro studies on different dimensions of the model) but that also allow the replication of the observed data.

- **Transparency** should be improved for all models to enable a more informed use by policy makers of the results and to enable a more interactive mode of continuous development of the models. Ideally, **a full description of the model, code and dataset should be available on open access**.

Within this overall agenda for moving the macro-modelling of innovation policies forward, **DG R&I** can play a pivotal role through the following actions:

- Providing grants for excellent research at the knowledge frontier of macroeconomic models contributing to the development of the modelling of R&I and R&I policy as well research into new models;

- Procuring research into further developments of currently used models by the EC to improve the modelling of their R&I policy evaluation, with a close involvement of policy modellers and users;

- Full transparency should be a condition (a full description of the model, code and dataset should be open access);

- Improving the provision of common data inputs to macro-models, most notably data on innovation policies;

- Providing a platform for macro-models where research results and best practices can be exchanged, databases can be shared and where open access to models and codes can instigate further (co-)development of existing macro-models or inspire the research on new models;

- Regularly bringing together producers and users of macro-models, improving the transparency of models to users and improving the user friendliness of models for model-users.

1. INTRODUCTION

The Directorate General for Research and Innovation of the European Commission (DG R&I) has engaged since 2014 in a medium to long-term agenda to improve the treatment of research and innovation (R&I) in macroeconomic models used to assist policy making.

In December 2018, an Expert Group was set up to produce a report that policy makers and practitioners can use as guideline for this agenda and to help identifying potential future strands of work in its support.

The aim of the report is double. First, it aims to identify those characteristics and properties of R&I that should ideally be included in macro-models, i.e., those that would help to understand the behaviour of innovation and to produce sound evaluations of R&I policies. Second, it aims at identifying the main R&I policies used in practice, those that macro-models need to include in order to produce well-founded assessments.

Section 2 identifies those critical properties and policies of the R&I process that ought to be included in macro-models. Since our focus is on moving the frontier of macro-modelling R&I, this section will rely mostly on the state-of-the-art academic literature on macro-modelling R&I and the current state of experience with quantitative macro-models, leaving some relevant contributions of the R&I literature, especially from the micro literature, left uncovered.

The critical properties and policies of the R&I process may affect the incentives on doing research and development (R&D) and the probability of innovating, how much is or ought to be spent on R&I and the effects of R&I investments on various measures of economic performance, especially productivity and economic growth, but also other dimensions of relevance for policy makers, like environmental and socio-economic sustainability. For each of these properties and policies, the report aims at explaining why it would be worth to include them in the modelling, what effects their inclusion is expected to have on the performance of the model and the scope for R&I policy evaluation. The report will also discuss what is required in order to include these properties and policies in the modelling, both in terms of model design and empirical implementation.

In Section 3, we check whether and how such properties and policies are accounted for in the macro-models used by the European Commission. In particular, we will look at the three models currently most commonly used by DG-R&I, namely QUEST, RHOMOLO and NEMESIS. We assess whether they contain the basic features and policies identified in Section 2 as important for modelling R&I and assessing R&I policy interventions, and, if not, how they could be included.

The report closes with some conclusions and recommendations on how to move forward the medium-long term agenda on the development and use of macroeconomic models to inform and advice research and innovation policy making.

2. MAIN FEATURES AND POLICIES OF R&I

Based on the existing literature on R&I and innovation policies, mostly the academic macroeconomic literature, this section describes and analyses the critical features of the innovation process needed to appropriately account for its role on economic growth and welfare, as well as the main policies to promote innovation, boosting growth and enhancing sustainability. This description and analysis of innovation features and policies is addressed to illuminate the design of macro-models for evaluating innovation and innovation policy. This is clearly not an exhaustive account of all there is to know about R&I and innovation policy, as the focus is on what we can learn for the macroeconomic assessment of R&I policies

2.1. Main features of R&I

Our journey starts by describing the main features of technological knowledge, the process of knowledge creation, the innovation process and its diffusion, to finally refer to its measurement.

2.1.1. Technological knowledge

***Technological knowledge* is the sum of techniques employed in the production of goods and services.** It results from the **cumulative** aggregation of new technological ideas or innovations, resulting from a systematic effort of research and development (**R&D**) benefiting from multiple forms of knowledge **spillovers**. Like for physical and human capital, R&D is a form of investment that cumulates in the stock of *technological knowledge*. In macro-models, technological knowledge is generally represented by a state variable that cumulates previous R&D effort,[2] but can also include other mechanisms such as learning-by-doing[3] and adoption of technologies developed by others[4].

The stock of technological knowledge also relates to ***intangible capital***, which includes computerised information, innovative property and economic competencies [5] Technological knowledge has some specific properties that to a great degree differentiate it from other forms of capital. The specific features of

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2 See the seminal contributions of Romer (1990), Aghion and Howitt (1992) and Grossman and Helpman (1992).

3 See the seminal contribution of Arrow (1962). Irwin and Klenow (1994), among others, provide empirical evidence supporting the existence of learning-by-doing in the innovation process.

4 See Comin and Gertler (2006) and the documents supporting the FRAME (2019) project.

5 Corrado et al. (2005) and (2009) extend, in the framework of the economic growth literature, the definition of a production technology to include the stock of intangible capital. They find for the US that the growth rate of output per worker increases more rapidly when intangible capital is included, that capital deepening (on physical and intangible capital) becomes the unambiguously dominant source of growth, diminishing the role of total factor productivity, and find that the labour income share has significantly decreased over the last 50 years due to the rise of intangible capital

technological knowledge include, first of all, its **non-rival nature,** i.e. it can be used by many agents at the same time.[6] In this sense, it entails high generation costs but can be easily reproduced by those that have the needed *absorptive capacity*.[7] To some extent, it is ***indivisible***.[8] Last but not least, it suffers from ***economic obsolescence***: it may depreciate in value but not in essence, due to the emergence of subsequent innovations.[9]

Technological knowledge typically will have a **social value** that is **different from its private value**. On one hand, since innovations are non-rival, part of their return is appropriated by others. On the other hand, the negative effect that innovations have on existing technologies is not paid by the innovator, but by the owners of the existing technologies.

However, technological knowledge does not get transmitted as easily as sharing a simple piece of information such as the latest result of a soccer match. First, technological knowledge is partially **tacit**, that is, it cannot be entirely explained in a manual by means of words, symbols or graphs, as opposed to codified knowledge. Second, it is **cumulative**, meaning that it cannot be understood without grasping prior knowledge. Third, it cannot be assimilated, adopted and reproduced without incurring substantial costs, those related to building the needed ***absorptive capacity***. It bears the cost of learning, adaptation and reproduction.

Technological knowledge is therefore not a free good that falls like manna from heaven for economic actors wishing to use it, but it requires a deliberate effort on the part of the actors to generate, adopt and use it. We can distinguish different stages in this process, starting from the Schumpeterian distinction between invention, innovation, adoption and diffusion, although some scholars would consider this subdivision to be already reductionist because it looks like a linear process without possible feedbacks.[10]

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6 The fundamental role of non-rivalry on innovation and economic growth was pointed out by the seminal contribution of Romer (1990). Referring to Romer, Jones (2019) says "he pinpointed that the nonrivalry of ideas is ultimately responsible for the rise in living standards over time."

7 For Cohen and Levinthal (1990), absorptive capacity is the "firm's ability to recognize the value of new, external information, assimilate it, and apply it to commercial ends." In more precise terms, Leahy and Neary (2007) define firm's absorptive capacity as "its ability to absorb spillovers from other firms." Cohen and Levinthal (1989) "suggest that R&D not only generates new information, but also enhances the firm's ability to assimilate and exploit existing information."

8 To quote Dosi and Nelson (2010) "half a statement about whatever property of the world or of a technology is not worth half of the full one; most likely it is worth zero."

9 The business stealing effect in Aghion and Howitt (1992) is a form of economic obsolescence. See also Boucekkine et al. (2009).

10 See Schumpeter (1934). For a reminder of the basics of the economics of information and references to the prior literature, see Dosi and Nelson (2010).

2.1.2. Innovations and the creation of new technological knowledge

Innovations represent additions to the stock of technological knowledge which result from the use of R&D (internal or external to the firm) as an input in the innovation process. Innovations modify the economic environment by introducing novel final consumption goods (like the washing machine, the TV or the smartphone), by developing new materials (like plastics or graphene) and drugs (like penicillin, aspirin or AIDS drugs), new sources of energy (like electricity, solar panels or hydrogen), new ways of processing information (like the printing press, or quantum computers), new means of transportation (the sailing boat or electric cars), new services (like on-line dating) among many others.

Creating new technological knowledge requires a systematic effort of research and development (R&D), and benefits from multiple forms of knowledge spillovers. In this sense, R&D can be seen as the main input in the generation of those innovations that cumulate into the stock of technological knowledge.

In this subsection we review the features of R&D and knowledge spillovers in creating innovations, while considering firm heterogeneity, uncertainty and path-dependency, as well as different classifications of innovations: basic vs applied, product vs process, and drastic vs incremental.

R&D

***R&D* refers to those economic activities undertaken with the purpose of improving the actual state of technology**. In the Frascati manual (OECD, 2015), R&D efforts are subdivided into basic, applied and experimental developmental. *Basic research* is addressed to the advancement of knowledge without any explicit intention of solving a particular practical problem. *Applied research*, by contrast, aims to solve technological problems. *Experimental development* is that stage in the R&D process where experiments are made to adjust the initial idea for a more successful product or process. Invention can come from the efforts of individual researchers doing informal R&D, or from R&D efforts done in an organized way in scientific research labs of the private or public sectors. In line with Griliches (1979) and Mansfield (1980), the cumulative aggregation of past R&D effort into basic and applied research (including experimental developments) gives rise to a stock of basic or scientific knowledge and a stock of applied knowledge, respectively.[11] The relation between basic and applied research, and the associated market failures, are discussed in more detail in Section 2.1.3.

In a world of competition, firms may imitate each other to the extent that intellectual property rights allow it. The *imitation* effort usually enters as part of the diffusion process of technologies

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[11] Comin and Gertler (2006) develop a macro-model of innovation and adoption aimed to better understand the relation between the stock of basic and applied knowledge, and the associated spillovers, as well as their effects on output growth in the short, medium and long run. The FRAME (2019) project uses Comin and Gertler (2006)'s framework to evaluate the economic and socio-economic effects of basic and applied research, as well as the role of innovation policy in this framework. See https://www.h2020frame.eu/frame/home.html

In a world of open innovation, firms may collaborate in their research efforts, exploiting knowledge complementarities.[12] Firms may also benefit from scientific progress, coming from universities or public research labs. Instead of searching themselves for new ideas, firms may prefer to buy technological knowledge on the market for technology, by investing in new machines that incorporate the latest technology, or by licensing. Finally, an important element in knowledge building is *learning-by-doing* and learning-by-using.[13]

The recent macroeconomic literature on R&I follows the pioneer work by Romer (1990), Aghion and Howitt (1992) and Grossman and Helpman (1992). In this literature, R&D activities are undertaken with the purpose of improving the actual state of technology, which in Romer (1990) takes the form a new product and in the *Schumpeterian* framework a better-quality version of an existing product -see Aghion and Howitt (1992) and in Grossman and Helpman (1992).

Spillovers

The process of building technological knowledge considerably benefits from ***knowledge spillovers***, i.e., unintended knowledge transfers. Knowledge spillovers result from the non-rivalry nature of technological knowledge and it is constrained by partial excludability.[14] The creation of new technological knowledge helps the development of subsequent inventions through knowledge spillovers. As stated by Bloom et al. (2019) "the literature on spillovers has consistently estimated that social returns to R&D are much higher than private returns."

In order to benefit from R&D spillovers, firms have to develop their own ***absorptive capacity****.* The absorptive capacity of a firm positively depends on the accumulation of its previous R&D investments. It helps understanding why private R&D and knowledge spillovers are likely to be complements in the creation of new technologies. Griffith et al. (2003) implement empirically the concept of absorptive capacity in the framework of the Schumpeterian model to conclude that previous studies underestimate the social return to R&D by neglecting absorptive capacity.[15]

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12 Belderbos et al. (2004) study the determinants of firms to engage in R&D cooperation.

13 The role of learning-by-doing in the growth process was first studied by Arrow (1962).

14 Walsh et al. (2007) provide an interesting example of partial excludability in relation with academic biomedical research.

15 See also Aghion and Jaravel (2015).

Besides knowledge spillovers, the literature also identifies different forms of ***rent or market spillovers***, referring to the transfer of monopoly rents between firms or sectors.[16] Innovations have the negative side effect of destroying value of current technologies, which is the case of a new product reducing the market share of an old product. Rent spillovers may take the form of business stealing or, more generally, technological obsolescence. In the framework of the Schumpeterian model of Aghion and Howitt (1992), *business stealing* refers to the case of a new, better quality product displacing partially or completely an existing one, as typewriters were substituted by computers. *Obsolescence* or *product market spillovers* refer to the loss in value of an existing product as a result of the reduction in demand resulting from the emergence of new products or better versions of existing products.[17]

Bloom et al. (2013) develop a general framework to empirically evaluate the relative importance of the two countervailing spillovers referred above: the positive effect emerging from knowledge spillovers and the negative effect of business stealing/obsolescence. They find, using US firm-level panel data, that knowledge spillovers quantitatively dominate market spillovers, "so that the gross social returns to R&D are at least twice as high as the private returns."[18]

Whether spillovers are localized remains a contentious issue. Bottazzi and Peri (2003) use regional R&D and patent data for Europe to find that "spillovers are very **localized** and exist only within a distance of 300 km." Bottazzi and Peri (2007) use OECD data to study the dynamic relationship between R&D employment and patent applications. They report large spillover effects: "A 1% positive shock to R&D in US increases the knowledge creation in other countries by an average of 0.35% within ten years. The same shock generates a maximum 6% effect on the US stock of knowledge after five to ten years."

Firm heterogeneity and uncertainty

Modelling the innovation process has to consider ***firm heterogeneity*** and the associated differences in the dynamics of products, firms and markets induced by R&I. Heterogeneity of individual firms can be reflected in many dimensions: differences in their production and R&D technologies, vintages of capital, their

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[16] Comin and Gertler (2006) develop a macro-model of innovation and adoption aimed to better understand the relation between the stock of basic and applied knowledge, and the associated spillovers, as well as their effects on output growth in the short, medium and long run. The FRAME (2019) project uses Comin and Gertler (2006)'s framework to evaluate the economic and socio-economic effects of basic and applied research, as well as the role of innovation policy in this framework. See https://www.h2020frame.eu/frame/home.html

[17] The issue of measuring the obsolescence rate of technological knowledge was raised in 70's by Bosworth (1978) and Pakes and Schankerman (1984). The macroeconomic effects of obsolescence have been studied in the vintage capital literature by Boucekkine et al. (1997) and Bambi et al. (2014), among others. See also Chapter 3 of Aghion and Howitt (1998) for a discussion of the effects of rent spillovers in endogenous growth models.

[18] In the same line, Jones and Williams (1998) claim that conservative estimates suggest that optimal R&D investment is at least two to four times actual investment, which implies that in fact there is too little R&D.

expectations and information sets, and their market situation among others. These differences will not only matter ex ante, but they will also shape the **dynamics.** Given some initial states (e.g. technology and its distribution), at each period heterogeneous agents update their choices, depending on their own history and the state of the whole economy, and interact through markets to determine the states for the subsequent period. Heterogeneity is therefore an essential feature of macroeconomic models, particularly those using quantitative and computational methods.

It is also important to emphasize the **stochastic** nature of technological progress. The probability of making and succeeding in the right investments may be different across firms, even drawn from the same probability distributions. There may be even uncertainty and asymmetric information on the exact shape of the distribution of R&D returns, since firms face different technological trajectories and past experience.

The literature on ***endogenous growth***, following the seminal contributions by Aghion and Howitt (1992) and Grossman and Helpman (1992) among others, stresses the fact that firms produce differentiated products by means of heterogeneous technologies with R&I shaping the dynamics of firm's productivity. Following the seminal contributions of Hopenhayn (1992) and Jovanovic (1982), the literature on ***firm dynamics*** represents firm heterogeneity by assuming that firms' productivity evolves over time following some random processes with high persistence.[19] These random processes are affected by the R&D activities of firms.[20] An equilibrium is then characterised by a distribution of productivity across products, plants and firms.[21] Endogenous growth theory and the theory of firm dynamics converged to a common framework of R&I and heterogeneous firms well beyond the representative agent model -see Klette and Kortum (2004).

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[19] See Aghion et al (2015) for a discussion of the relation between the Schumpeterian approach and the theory and empirics of firm dynamics (including the size distribution of firms, the relation between size and age, and the behaviour of small firms).

[20] It is important to notice that the literature on firm dynamics in models of monopolistic competition, inspired by Melitz (2003), implicitly requires a notion of innovation too. New firms in Melitz produce a new differentiated good, meaning that the fixed entry cost in Melitz (2003) may be interpreted as the research cost of producing a new variety. See the survey by Licandro (2018) published in the forthcoming book by Akcigit et al. (2020).

[21] Under some general aggregation conditions, general equilibrium models of firm dynamics share common properties with the Neoclassical growth model. Collard and Licandro (2020) provided a simplified version of the Hopenhayn model which dynamics collapses to the dynamics of the Neoclassical growth model. The same aggregation conditions apply to models of endogenous growth.

All this to point out that every firm is in a different position and may act differently depending on its characteristics, its history, its particular needs and its expectations. This individual heterogeneity is an essential feature in the ***evolutionary* view of technological progress** and the associated agent based computational models **(ACE)**.[22] In this strand of the literature, heterogeneity shows up at all levels of aggregation (Dosi 1988)[23]. Dosi et al. (2010) is a representative example of this literature. Their agent-based model has a machine-producing sector where firms do R&D and/or imitate in order to produce more advanced machines to the customer goods sector. Their success in coming up with better machines depends partly on luck, but partly on their heterogeneous search capabilities.

Neary (2010) stresses the importance of considering ***granularity*** when modelling firm heterogeneity. He claims that "it is unsatisfactory … to view large firms as more productive clones of small ones." Consequently, he suggests three alternative ways of modelling imperfect competition: heterogeneous industries, natural oligopoly, and superstar firms.[24]

Path dependency

During the R&D stage, researchers benefit from their past experience and are conditioned by their state of knowledge and their past technological choices. This is where **path dependency** or **technological cumulativeness** comes into the picture. To quote Dosi and Nelson (2010), "… advances are likely to occur in the neighbourhood of the techniques already in use within the firm." Following Griliches (1979), one way of modelling the cumulative nature of R&D is to consider not the flow of R&D expenditure but the accumulated stock of past and present R&D expenditure as the appropriate variable to affect productivity or to enter as an input in an extended production function. But it is not only the total past R&D but also of the direction in which past research has been conducted that determines the future technological trajectory.

Path dependency may trap countries into bad outcomes. Models of path dependency and **poverty traps** are surveyed by Azariadis and Stachurski (2005). An example is Acemoglu (1997) where multiplicity of steady state equilibria results from labour market frictions. In this framework, poor technology adoption and low investment in human capital are self-reinforcing, generating a shortage of skilled labour that makes technology adoption unprofitable. Economies with strong labour market

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22 The evolutionary approach follows Nelson and Winter (1982). See also Nelson (2009) and Dosi and Nelson (1994) and (2010).

23 Agent-based computational economics (ACE), defined as the computational study of economies considered as complex evolving systems ACE provides an alternative methodology to the representative agent models to build macroeconomic models from the bottom up based on assumptions about the way agents behave and interact, which are rooted in the actual empirical microeconomic evidence (Tesfatsion 2006). According to Tesfatsion (2006), complex systems are characterized by interacting agents who through their interactions lead to emergent properties of the system that are not those of the agents.

24 See Gabaix (2011) on the role of granularity for the aggregate effect of idiosyncratic firm shocks, and Dorn et al. (2020) and Veugelers (2018) on superstar firms.

frictions and a history of low human capital are trapped in an equilibrium of low technology adoption and low human capital. More recently, Benigno and Fornaro (2018) rationalize the Great Recession that followed the 2007 financial crisis as a *stagnation trap*, i.e., an equilibrium with high unemployment and weak growth. They generate this result in a Schumpeterian growth model interacting with a Keynesian growth theory in which pessimistic expectations can lead to very persistent, or even permanent stagnation trap.

Path dependency is also a fundamental property of macro-models with **vintage technology**. In these models, medium term fluctuations critically depend on the past of R&D investments following the so-called *echoes principle*. Bambi et al. (2014) claim that the type of wave-like fluctuations previously described by Schumpeter (1934) help to replicate the medium-term fluctuations of the US economy studied by Comin and Gertler (2006).[25]

2.1.3. Innovation typology

Basic and applied research

Basic research is fundamentally addressed to move the frontier of knowledge, without necessarily intended to solve any practical problem. In Nelson (1959)'s words "scientific research is the human activity directed toward the advancement of knowledge", while ***applied research*** is more likely to provide solutions to practical problems (see also Oslo Manual (OECD, 2018)).

It is difficult to imagine the current state of technology and welfare in our modern society without the development of modern sciences. As a fundamental principle, the scope of applied research is limited by the development of basic research. As pointed out above, innovation, in particular drastic innovation, requires new knowledge which critically depends on new scientific knowledge. This makes basic research to be a high source of knowledge spillovers. One of the main policy implications in Nelson (1959) is that if applied research may stimulate private industry to spend close to the social optimum, "the social benefits of basic research are not adequately reflected in opportunities for private profits." Public support for basic research is consequently critical.

Most of the literature on endogenous growth is addressed to model applied research. The study of the economic impact of basic research, pioneered by Nelson (1959) and Arrow (1972), has been recently embodied in the endogenous growth literature by Akcigit et al. (2020).

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[25] In Bambi et al. (2014) "waves of innovations arrive *en masse*, moving the economy to a boom; the associated increase in productivity raises purchasing power all over the business sphere, inducing research activities to flourish; but, the new products will take a while to develop; when the new wave of innovations is eventually implemented, the new products enter the market producing a second boom, which will generate a third, then a fourth and so on and so for."

Process and product innovation

The latest version of the Oslo Manual (OECD, 2018) recognizes two kinds of innovation. On the one hand, you have ***product innovations***, which could be completely new goods or services or goods and services that have undergone significant improvements in one or the other functional characteristic, be it quality, affordability, or durability. On the other hand, you have ***process innovations***, which refer to improvements in the business functions, such as increased efficiency, meeting regulatory requirements or cost reductions. Process innovations are generally modelled as **cost-reducing** whereas product innovations are modelled as **demand shifting.**[26] Some innovations may play dual roles, being a product innovation for some firms but a process innovation for others (a new robot will be a product innovation for the firm producing it, but a process innovation for the firm using it in its production process).

From the perspective of a product, productivity has at least two conceptually different components: the quality of the product (as perceived by consumers) and the technical efficiency of the production process (in transforming inputs into output). The former is related to product innovation and the latter to process innovation. The empirical literature on firm level productivity, following the seminal contribution of Foster et al. (2008), developed methods to decompose these two components of firm's productivity (see Section 2.1.5 below).

Romer (1990), Aghion and Howitt (1992) and Grossman and Helpman (1992), and the large literature that followed, developed *macro-models of product innovation*, in which researchers succeed in generating new products or in improving the quality of the existing ones. They feature well the type of innovation generated by startups, but also by incumbent firms, that undertake product innovation.[27] Klette and Kortum (2004) extend the Schumpeterian model to allow for multiproduct firms, in which incumbent firms invest in R&D to generate better quality versions of existing products produced by other firms. In Acemoglu and Cao (2015) or Impullitti and Licandro (2018), firms invest in *process innovation* aiming at reducing their production costs. Akcigit and Kerr (2018) combine both product and process innovation in line with the literature just cited above. In the vintage capital literature new technologies are embodied in new capital (tangible or intangible). Dosi et al. (2010) model innovation in terms of new machines that will be used by the consumption goods sector.

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[26] Huergo and Jamandreu (2004) use Spanish data to study the relation between process innovation and productivity growth concluding that process innovation lead to extra productivity growth.

[27] This is the case in the model of step-by-step innovation suggested by Aghion et al. (2001).

Drastic versus incremental innovations

Innovation may be at different degrees ***incremental or drastic***,[28] and they may vary in their ***general-purpose nature***. At the very extreme of the innovation process are those innovations that drastically change the environment by introducing new technological paradigms that affect production and innovation in several sectors. These innovations are referred in the growth literature as *general-purpose technologies* (GPT). Examples of general-purpose technologies are the introduction of the steam engine, electricity power, information and communication technology. Bresnahan and Trajtenberg (1995) stressed the fact that a decentralized economy will have difficulty in fully exploiting the growth opportunities of GPT's, lowering the rate of technical progress.[29]

In the first family of *endogenous growth models*, innovation is the intended result of applied R&D activities undertaken by potential **entrants** (or inventors), which is more likely but not necessarily of the drastic type. Subsequent research also explored the effects on growth of R&D activities and innovation developed by existing firms, being referred by the notion of innovation-by-**incumbents**, which is more likely but not necessarily to be of the incremental type

2.1.4. Diffusion of new technologies

New technological ideas, after discovery, diffuse throughout the economy by affecting the design of products and production process of firms in different industrial sectors and geographical locations. This process is referred as the **diffusion of new technologies**.[30] Extensive empirical work was undertaken by Comin et al. (2008) and Comin and Hobijn (2004) and (2010), among others, describing the long process of diffusion of new technologies across time and countries.

The diffusion of technologies can take place through the various mechanisms by which knowledge spills over across space and time: trade relationships, foreign direct investment, mergers and acquisitions, movement of personnel, patents, patent citations, publications, research collaborations, and networks.[31] The process of diffusion is itself subject to path dependency, network externalities and the presence of complementary products or services. A new product or process is more

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28 In the Community Innovation Surveys (Eurostat), there is the distinction between a product new to the firm and a product new to the market, the latter being more drastic than the former.

29 See also Jovanovic and Rousseau (2005).

30 For more on diffusion see Adams (1990), Jovanovich and Lach (1997) and Stoneman and Battisti (2010), a.o.

31 See Cai and Li (2019) and Zacchia (2019), Acemoglu et al. (2012b), Carvalho and Draca (2017) on networks, Keller (2004) on trade.

likely to be widely and/or faster adopted if it uses existing or familiar technologies, or if complementary goods or services already exist.[32]

Nelson and Phelps (1966) suggested two alternative approaches of technological diffusion highly suitable for macroeconomic modelling. In their framework, the technological frontier exogenously moves at a constant positive rate. In the first approach, adoption rates are assumed to positively depend on the **distance from the technological frontier** of the actual state of technology: the further a firm is from the technological frontier, the larger its margin to improve, the more likely it will adopt. The second is **a *vintage technology* approach**, where discoveries are adopted with a delay.[33]

Comin and Gertler (2006) embody the first approach in a dynamic stochastic general equilibrium (DSGE) model with both innovation and adoption. It has the additional feature, when compared to Nelson and Phelps (1966), that innovation moves the technological frontier instead of it being exogenously driven. As pointed out by Comin (2009), this adoption mechanism is pro-cyclical, which allows the Comin and Gertler (2006) model to match the observed pattern of short-, medium- and long-term output fluctuations of developed economies. Using the same framework, Anzoategui et al. (2019) find that the slowdown in productivity that followed the Great Recession was an endogenous response of innovation and adoption to the contraction in demand induced by the downturn, explaining a significant fraction of the fall in productivity that followed. Recoveries from financial crises are slow due to the long delays associated to the adoption process.

In the framework of the endogenous growth theory and based on Boucekkine et al. (1997), Bambi et al. (2014) adopt the **vintage technology** approach. From the Schumpeterian perspective, they stress the fundamental role of the history of R&D investments (path dependency) on the endogeneity of medium-term fluctuations according to the so-called *echoes effect* principle. More recently, Sedlacek (2020) uses a DSGE model of vintage technologies to study the counter-cyclical behaviour of uncertainty, measured as the dispersion of firm-level productivity shocks, relating the diffusion of innovation with the business cycles.

More recently, a new literature emerged stressing the role of ***production and innovation networks*** in the propagation of firm level productivity shocks. Acemoglu et al. (2012b) show that under some general conditions the network structure of production and the associated input-output links make idiosyncratic shocks to firm’s productivity lead to aggregate fluctuations. The occurrence of such an event depends on the structure of the production network with upstream and downstream interconnections capturing the possibility of “cascade effects” affecting not only immediate downstream customers, but also the rest of the economy. The diffusion of micro innovations is expected to propagate through the production network, depending on its structure, to eventually affect the structure of the network itself. Acemoglu et al. (2016b) use U.S. patents and their citations to map the American innovation network. They study the evolution of citation patterns

[32] It is not always the superior technology that gets adopted. See David’s (1985) story of the adoption of the QWERTY typewriter as an example.

[33] Endogenous adoption delays in vintage capital models and their business cycle properties are studied by Caballero and Hammour (1994), Boucekkine et al. (1997) and Gilchrist and Williams (2000), among others.

across technology classes to measure the structure of the innovation network and find that the interaction of pre-existing network structures with patent growth has strong predictive power on future innovation.

The dynamics which drives the rate of diffusion of capital-embodied innovation are described in Dosi et al (2010). Their model includes firms producing consumption goods employing capital (composed of different vintages) and labour under constant returns to scale. Desired production is fixed according to adaptive demand expectations. Given the actual stock of inventories, if the capital stock is not sufficient to produce the desired production level, consumption-good firms invest in new machines in order to expand their production capacity. They also invest to replace old and obsolete machines according to a payback period rule and according to the prices of new machines. As new machines embed state-of-the-art technologies, the labour productivity of consumption-good firms increases over time according to the vintages of machine present in their capital stock.

2.1.5. Measuring inputs and outputs

As a general principle, a macroeconomic model is a good laboratory for the evaluation of economic policy if it is as close as possible to the available macro and micro data on those dimensions in which the policy is supposed to operate. In other words, models designed to evaluate innovation policy in practice have to be quantitatively relevant, i.e. subject to quantitative evaluation consistently with both macro and micro evidence, and providing quantitative figures concerning the effects of innovation policy.

This section describes the most commonly used measures of R&I inputs and outputs in the macroeconomic and applied microeconomic literature of innovation and growth. The references to the literature here are not exhaustive. They just aim to provide examples of use of these measures in macro-models. For more elaborate discussions on measuring innovative inputs and outputs, see a.o. Gault (2013), Hall and Jaffe (2018) and Mohnen (2019).

Measurement of R&D

R&D statistics are available annually for most countries and for many years and are collected in a harmonized way. They are supposed to cover all R&D performers, i.e., the business enterprise sector, government, higher education and private non-profit organizations, but are unequally able to capture the whole population of performers across countries (different response rates, different sampling below a certain size cut-off point).[34] When stocks rather than flows of R&D are used as building blocks, they may differ depending on the assumed depreciation rate and construction of the initial capital stock. These depreciation rates may vary across sectors -see Li and Hall (2018). Moreover, some firms might conduct informal R&D, which is not reported in the R&D surveys. That R&D statistics may differ depending on whether they are extracted from R&D surveys or from Innovation surveys is indicative of the measurement problems.

[34] See the Frascati Manual (OECD, 2015).

R&D data are frequently used in the macroeconomic literature of innovation. The approach adopted by the FRAME (2019) project, partially based on Anzoategui et al. (2019), is an example35. Another interesting example is in Akcigit et al. (2020). They use firm level French data on basic and applied R&D to measure the basic/applied research intensity of firms that they use to estimate a macro-model with basic and applied R&D.

Measurement of spillovers

As reported by Bloom et al. (2019), two main methods have been used in the empirical literature on R&I to measure knowledge spillovers: the *production function approach* and the *patent citation approach*. In the first approach, knowledge spillovers are measured as the effect of some aggregate (industry, regional, national or international) R&D stock on the productivity of the firm -see Griliches (1979). In the second approach, patent citations are used to relate an innovation to the preceding ones.[36] R&D stocks are generally calculated as the weighted sum of various industry specific R&D stocks measured at the regional, sectorial, country specific (domestic and/or foreign) levels. The weights can be proportional to potential inter-industry knowledge flows (such as purchases or sales of intermediate inputs, investment goods, flows of labour, or patent citations) or proportional to the proximity of locations in the geographical or technological space (e.g. the space of patent classes, research areas, product classes, qualifications of R&D personnel). Foreign spillovers can be proportional to international trade, foreign direct investment, trade in technology, patent citations, international collaborations, etc.[37]

Patent citations have the advantage of directly identifying the path that spillovers follow from one innovator to the next, but are based on patent counts with all patents having the same weight independently of their economic value. The production function method, in contrast, measures spillovers in terms of their economic value as measured by their contribution to firm's productivity, but is uninformative on the channels through which spillovers operate. Different measures of distance have been used in the production function approach to help disentangling different channels, like geographical proximity, sector/industry, product class and technological distances, among others.

As discussed above, firms may also face a negative externality generally referred as product market spillovers. Bloom et al. (2013) use firm level information on the distribution of patenting across technology fields, and sales across four-digit industries to determine the firm's position in technology and product market spaces, which allows them to construct distinct measures of the distance between firms in

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[35] Anzoategui et al. (2019) use US R&D data to estimate the elasticity of R&D in the innovation technology, getting an estimated value in line with the estimates reported by Griliches (1990).

[36] See Trajtenberg (1990) and Jaffe et al. (1993). The importance of this measure is highlighted by Hall et al. (2005). To give an idea of the magnitude of knowledge spillovers, they find that an extra citation per patent increase the market value of the firm by 3%.

[37] For a discussion on the measurement of domestic and international R&D spillovers, see Belderbos and Mohnen (2013)

the technology and product market dimensions. They use this information to distinguish empirically between technology and product market spillovers.

Measurement of intangibles

Since the pathbreaking work by Corrado et al. (2005), statistical offices have made considerable efforts to incorporate intangible investments to the measurement of Gross Domestic Product (GDP) in National Accounts. Investment in intangible capital covers three types of assets: computerized information (software, databases), innovative property (R&D, mineral exploitation, copyright and license costs and other product development, design and research expenses), and economic competences (brand equity, firm-specific human capital and organizational structure). Since then, intangible investments have been added to Gross Fixed Capital Formation, instead of being considered as intermediate inputs (as it was the case in the past). Some data on these intangibles have been collected in the *Innodrive* and *Intan* projects funded by the European Commission, but they are not systematically updated -see for instance Corrado et al. (2013).

Measurement of patenting

Many studies have resorted to patent data as a mean to measuring innovation output -see Griliches (1990). Patents however are well known to be an imperfect measure for innovation output. Nevertheless, patents are widely used as measures of the output of innovation.

Patent data have the advantage that they are easily available, for long periods of time, and that they contain lots of information: content of the patented invention, timing of introduction, renewals and termination, name and the location of the assignee and references to prior knowledge. All these pieces of information can be useful to infer the private and social value of a patent.

The weakness of patent data is the unequal propensity of patenting across firms and sectors, and the difficulty of merging patent data with other firm- or sector-level data (technology classification versus industry classifications, disambiguation for matching on the basis of firm names). It is also well known that patents are of unequal value, rendering the simple counting of patents an imperfect measure for innovation output. One way to correct for that is to weigh patents by their forward citations.[38] As patents are essentially formal ways to protect intellectual property, they can also be used as strategic weapons of competition (patent thickets), as signals to attract venture capital or as means to acquire new technology through cross-licensing. If they are not used to protect the patented idea, but used more as a strategic tool of competition, patents are not necessarily realizations of innovation.

An example of a macro-model of heterogenous firms using patent data is Akcigit et al. (2020), which is aimed to evaluate the public policy support to both basic and applied R&D.

Measurement of licensing

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[38] For a more detailed discussion of patents as an innovation indicator, see Nagaoka et al. (2010)

Data on licensing of patents are scarce. The European and Japanese Patent Offices (EPO and JPO) organised a survey of licensing among patent holders in 2007 (Zuniga and Guellec, 2009). They observe that licensing is quite common among patenting firms, as one company in five (four) in Europe (Japan) licenses patents to non-affiliated partners, and the relationship between firm size and probability to licensing is U-shaped. Arqué-Castells and Spulber (2018) use data on patent trades from USPTO, licensing deals from the Securities and Exchange Commission filings and cross-licensing data from the SEC forms. Abrams et al. (2019) use data on licensing revenues from a large non-practicing entity to estimate some key micro parameters of their macro-model.

Measurement of innovation expenditure (other than R&D)

Besides R&D, innovating firms must incur a range of other expenditure to bring a new product on the market or to introduce a new process. The innovation surveys that follow the Oslo Manual (OECD, 2018) collect the following costs: engineering, design and other creative activities, marketing and brand equity activities, IP-related activities, employee training activities, software developments and database activities, activities related to the acquisition or lease of tangible assets, and innovation management activities. Unfortunately, many of these items are not (yet) collected regularly by all firms, and are therefore difficult to quantify and very likely subject to substantial measurement errors. For instance, firms report training activities in general but not necessarily specifically those for the production of new products or the use of new machines.

Measurement of innovation output

Innovation output measures are provided in the innovation surveys, which by and large follow the guidelines of the Oslo Manual (OECD, 2018) in the form of product and process innovations. Innovation surveys are supposed to be representative regarding size, industry, and in some countries regional distribution, based on stratified random sampling, above a certain minimal size threshold. They are currently conducted every two years in EU countries and on a more irregular basis in many other countries. A few countries have yearly data (Germany since 1993,[39] Spain since 1990,[40] U.S. since 2009). As opposed to patent data, innovation output data are to a large extent subjective (hence subject to measurement errors), qualitative (binary or categorical variables), refer to a three-year interval (the Spanish data are annual), they are biased towards large firms, less internationally comparable than patents, and not as easily accessible for reasons of confidentiality. It is therefore difficult to merge innovation survey data from different countries to conduct international comparisons, unlike what can be done with business register data like ORBIS/AMADEUS from Bureau van Dijk, the Business Environment and Enterprise Performance Survey (BEEPS) database from the World Bank and the European Bank for Reconstruction and Development or the EU Industrial R&D

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[39] The German Mannheim Innovation Panel is managed by the ZEW-Leibniz Centre for European Economic Research.

[40] The Spanish ESEE (Encuesta sobre Estrategias Empresariales) Survey on Business Strategies has been conducted since 1990 by the Ministry of Industry and the SEPI Foundation. https://www.fundacionsepi.es/investigacion/esee/en/spresentacion.asp

Investment Scoreboard database managed by the DG Joint Research Centre of the European Commission.[41]

A critical issue on the measurement of innovation output relates to the contribution of new products to GDP and GDP growth. Alternative methodologies have been recently suggested to estimate the gains from increasing product variety. Broda and Weinstein (2006) use customs data to measure the contribution of the raise in product variety of imported goods to US output and welfare.

Measurement of productivity

The productivity of a firm has at least three conceptually different dimensions: the quality of those products offered by the firm or *product value* (as perceived by consumers or by firms using them as inputs in their production process), the *technical efficiency* of firm's production process (in the transformation of inputs into output), usually referred as total factor productivity (TFP), and the *quality and price of inputs* (including labour) used in the production process. The literature has been mainly concentrated in measuring firm's *total factor or multi-factor productivity*. Different techniques have been developed in recent years to estimate the product value of firms (usually referred as *demand shocks* in the literature, since an increase in product value raises the demand of the firm) the production efficiency of the firm (usually referred as total factor productivity measured in physical quantities or *TFPQ*) and the quality adjustments of the inputs. For a recent survey of the interpretation and the measurement of productivity, see Syverson (2011).[42]

For a description of the aggregate and sectorial measurement of productivity see the OECD (2011) manual.

Other measures for innovation output

Some other technological indicators exist but are not available on a systematic basis and therefore not often used in macro-models. As an alternative to questionnaire-based surveys or patents, other measures of innovation output have been constructed based on literature-based announcements of new products, scientific or technical journals, invention counts, and user innovations. Big data allow for the examination of innovation from different angles and may encompass the limits related to the lack of granularity, coverage and timeliness of other sources. For instance, web mining allows to extract innovation-related information from the websites of a large number of businesses, differentiating between sectors and regions. On the use of web mining techniques for the measurement of innovation see e.g. Katz and Cothey (2006), Gök et al. (2015) and Kinne and Axenbeck (2018). With progress in digital technologies the literature on text and web mining search methods is growing rapidly in different macroeconomic research areas. Aggregated news indexes and indicators of economic policy uncertainty, market sentiment and

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[41] For a critical discussion of the quality and the use that has been made of data from the innovation surveys, see Mairesse and Mohnen (2010).

[42] The main methodological issues on estimating TFP at the firm level has been discussed by Olley and Pakes (1996), Levinsohn and Petrin (2003), De Loecker (2011) and Ackerberg, Caves and Frazer (2015).

communication transparency are often used in vector autoregressive models to study macroeconomic fluctuations. Examples in this direction include Baker et al. (2016), Hansen and McMahon (2016), and Larsen and Thorsrud (2019), among others.[43] An early example of web data used for policy analysis is the Billion Prices Project.[44]

2.1.6. Linking inputs and output: knowledge production functions

In macro-models of R&I, innovation is assumed to be produced by means of an R&D technology using as inputs labour, capital (tangible and intangible, like research infrastructure, computers and software) and other intermediate inputs (like research materials such as protein structures). R&D labour is to a large extent comprised of scientists and technicians, i.e. highly skilled and specialized labour, where research skills are acquired by specific R&D education (typically PhD degrees) and training.

The productivity of firm specific R&D technologies benefit from multiple knowledge spillovers, the assimilation of which may require some form of absorptive capacity

Variable returns to R&D[45]

Empirical studies estimating knowledge production functions typically obtain higher rates of social return on **basic R&D** than on applied R&D, the reason being the longer lasting effect of basic R&D. Griliches (1986), for example, reports a significant premium to basic research. Social returns are generally found to be lower for **public R&D** (be it financed or executed) than for private R&D, due to the so-called *ivory tower* effect -see a.o. Aghion et al. (2008). Yet public R&D might be justified for reasons of high externalities, indivisibilities, high uncertainty, gigantic costs and low immediate returns, as for instance for national defence, atomic energy and generally for mission-oriented R&D, areas where the private sector typically does not find it profitable to invest[46]. Akcigit et al. (2020) use a quantitative macro-model of endogenous growth with both basic vs applied research and public vs private research. They find that standard innovation policies (like a uniform R&D tax credit) can accentuate dynamic misallocation by oversubsidising applied research, concluding that "Policies geared towards public basic research and its interaction with the private sector are significantly welfare-improving."

The returns to R&D may also depend on the existence of complementarities, between R&D and innovation and communication technologies (ICT) that allow

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[43] Big data are used for business cycle analysis and forecasting. See e.g. Choi and Varian (2012) and D'Amuri and Marcucci (2017). For a survey on nowcasting, see Buono et al. (2017).

[44] The project was launched by the MIT in 2008. See http://www.thebillionpricesproject.com/.

[45] For more details on the literature of returns to R&D, see Hall et al. (2010). Donselaar and Koopmans (2016) provide a meta-analysis of the rate of return to R&D.

[46] See also Archibugi and Philippetti (2018) and Mazzucato (2013).

productivity gains in doing research -see Mohnen et al. (2018), or between in-house research and purchased technology –see Cassiman and Veugelers (2006), or between process and organizational innovation -see Bresnahan et al. (2002).

There is an old debate among macroeconomists whether **returns to R&D are constant** or not. Endogenous growth theory assumes that returns to R&D are constant, which in the original Romer (1990) model generates the undesirable property known as *scale effect*: since returns are constant, the growth rate of the economy positively depends on the economy size. Jones (1999), among others, argues that scale effects are counterfactual since large countries don't grow on average faster than small countries. This controversy gave rise to the so-called semi-endogenous growth models, under the assumption of **decreasing returns to R&D**. Any form of congestion externality that makes spillovers operate in per capita terms, easily destroys scale effects under constant returns. These congestion externalities may be related to adoption and learning. Many mechanisms have been proposed in the literature to remove scale effects in fully endogenous growth models. Early works include e.g. Smulders and Van de Klundert (1995), Peretto (1998), Young (1998), Dinopoulos and Thompson (1999) and Howitt (1999). Consistent with the evidence reported in Griliches (1990), the creation of technologies seems to be subject to diminishing returns at the aggregate and sectorial level. More recently, Bloom et al. (2017) claim that *ideas are getting harder to get*, pointing out that research effort is rising sharply while research productivity is declining substantially in a wide range of sectors. By contrast, returns may also increase because of intertemporal R&D spillovers which again may differ across sectors; the so-called *standing on the giant's shoulders* argument -see Scotchmer (1991) and Caballero and Jaffe (1993). Knowledge accumulated today may lead to new inventions in the future.

2.2. Enablers for R&I creation, adoption and diffusion

2.2.1. Size of the market

Firms may be more willing to do R&D when there is a large market in order to quickly be able to recover their R&D investment expenditure. The market can be national or international depending on the presence or not of trade and non-trade barriers. Acemoglu and Linn (2004) find for the pharmaceutical industry a large effect of potential market size on the entry of non-generic drugs and new molecular entities. Moreover, as pointed out by Impullitti and Licandro (2018), when innovation is addressed to reduce production costs, the incentives for investing in R&D are larger the larger the size of the market. Trade openness enhances innovation and productivity growth by increasing the size of the market faced by exporters. See the discussion on Competitiveness and globalization, Section 2.4.3. As discussed in Section 2.3.1, public procurement operates through this channel too.

2.2.2. Competition and intellectual property right protection

Patents systems grant temporarily monopoly rights to innovators in order to protect them from being copied or imitated. By restricting competition, the patent system aims at solving the market distortion generated by the non-rivalry feature of technological knowledge; patents are expected to promote innovation restoring the incentives to innovate. Consequently, patents systems relate to the argument invoked by Schumpeter (1942) that **monopoly rents are the desired reward for**

innovation. Since Romer (1990), Aghion and Howitt (1992) and Grossman and Helpman (1992), macroeconomic models of R&I assume that innovations are patented, crediting monopoly rents to innovators.

Competition, however, can be **beneficial to innovation** too, since in competitive environments firms innovate with the hope of *escaping competition* -see Aghion et al. (2001). This argument relates to the so-called *Arrow replacement effect*: entrant firms have more incentives to innovate than incumbents since innovation allows them to steal at least partially the monopoly rents of incumbents -see Arrow (1962b). In the extreme case when the prospect of entry is very low, incumbents have little incentives to innovate. However, under the prospect of their monopoly rents being stolen, incumbents innovate to escape competition from potential entrants. Competition may also promote innovation through the type of market size effect described supra, if it results in increasing the size of the market by lowering prices.

Theoretical and empirical research has been developed asserting that the relationship between competition and innovation follows an inverted **U-shape**. When competition is low, incumbents do not need to protect their monopoly rents, having little incentives to innovate (*replacement effect*). When markets become more competitive, incumbent firms innovate more to escape competition (*escape competition effect*). However, when there is too much competition, the gains from innovation dilute to the point that neither incumbents nor potential entrants have incentives to innovate (*Schumpeter's argument*). Aghion et al. (2005) find strong evidence of an inverted U-shape relation between product market competition and innovation, and develop an endogenous growth model to understand this evidence. Aghion et al. (2009b), using micro data, find that "the threat of technologically advanced entry spurs innovation incentives in sectors close to the technology frontier, where successful innovation allows incumbents to survive the threat, but discourages innovation in laggard sectors, where the threat reduces incumbents' expected rents from innovating."

It is not just competition within the industry that matters for innovation, but lack of competition in the upstream industries may also harm innovation in the downstream industries, as shown by Bourles et al. (2013).

Besides the incentives of firms to innovate to escape competition or to catch up with the industry leaders, there is an indirect aspect of competition that is emphasized by evolutionary economists -see Dosi et al. (2010). Market shares expand (shrink) as firms are more (less) competitive than the sector average. Hence markup pricing increases profits but may reduce the market share. Exogenous limits on the achievable market shares (antitrust policies) give newcomers the chance to enter the market via a search process for new technologies, the success of which depends on their search capabilities and the level of technological opportunities.

Different **measures** may be used to identify competition. **Markups** is one of them, since the degree of competition of a market negatively relates to the average markup that firms charge over their marginal costs. The literature on *misallocation*, indeed, stresses the importance of **markup dispersion**. In a framework of heterogeneous, oligopolistic competitive firms, markups are heterogeneous implying that relative prices are distorted, and allocations are not efficient. The degree of misallocation increases with the variance of markups. Edmond et al. (2015) study the procompetitive gains from international trade in a quantitative macro-model with endogenous variable markups. Using Taiwan data, they find that trade openness reduces markup distortions significantly lowering productivity losses due to misallocation.

2.2.3. Human Capital

Innovation requires an education system able to generate a large enough body of scientists and applied researchers capable of moving the frontier of knowledge. The adoption of new technologies also requires a large body of highly qualified workers able to easily understand and operate the frontier technology, as well as an important effort of making the frontier technology user-friendly.

Human capital and skills formation are endogenously determined by **educational choices and training**. The role of human capital formation for economic development has been emphasized by Lucas (1988), based on the theory of human capital first developed by Becker (1962) and Schultz (1961).[47] In this view, individual education cumulates into a stock of individual human capital, that makes different cohorts of workers more productive over time. Like intangible capital, human capital benefits from knowledge spillovers.

Human capital, like tangible and intangible capital, is heterogeneous inter- and intra-generationally. Phenomena like the skill premium and job polarization are analysed by means of occupational choice models stressing the role of **intra-generational heterogeneity** and heterogenous education -see Acemoglu and Autor (2011) and Autor and Dorn (2013). **Inter-generational heterogeneity** is studied in models of vintage human capital -see Chari and Hopenhayn (1991) and Boucekkine et al. (2002).

2.2.4. Financing of R&D

Innovation financing faces in a world of imperfect information a problem of **asymmetric information** between the innovator and the fund provider. Because of the non-rival nature of knowledge, the innovator has no interest in sharing with the fund provider some of the information the latter would need to justify the funding.[48] Therefore, R&D is as much as possible financed through **internal funds**. In the absence of sufficient self-funding possibilities, **external funding** will have to be accessed. This external funding can be private or public. Major sources of **private funding** include bank financing, capital markets and venture capital. Major sources of **public funding** include grants, subsidies, tax incentives and public venture capital.

In their survey of empirical evidence, Hall and Lerner (2010) conclude "that while **small and new innovative firms** experience high costs of capital … the evidence for high costs of R&D capital for large firms is mixed. Nevertheless, **large established firms** do appear to prefer internal funds for financing such investments and they manage their cashflow to ensure this."

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47 Lucas (1988) acknowledges the previous contribution of Uzawa (1965). See also Barro (2001).

48 See Lee et al (2015) on the difficulties of using intangible collateral for risky projects.

In the macroeconomic literature, there has been a surge of research on the role of **financial constraints** in the aftermath of the 2007 financial crisis. In a multi-country Schumpeterian growth model, Aghion et al. (2005b) introduce imperfect creditor protection. They show that there is a critical level of financial development below which countries converge to a low level long-run growth rate, compared to the growth rate of countries with a level of financial development larger than the critical one. They provide crosscountry evidence supporting their main finding. Aghion et al. (2012), using French microdata, find strong evidence on the negative effect of credit constraints on R&D. They conclude that firm R&D investment is pro-cyclical for firms that face tight financial constraints, particularly in sectors that strongly depend upon external finance. Buera et al. (2011) develop a quantitative framework to explain the relationship between total factor productivity (TFP) and financial development. Financial frictions distort the allocation of capital and entrepreneurial talent across firms, adversely affecting aggregate productivity. Their quantitative analysis shows that financial frictions account for a substantial part of the observed crosscountry differences in output per worker, aggregate TFP, sector-level relative productivity, and capital-to-output ratios. Christiano et al. (2014) introduce financial constraints in a standard DSGE model and find that fluctuations in entrepreneurial idiosyncratic risk are the main source of business cycle fluctuations. In this framework, Vinci and Licandro (2020) relate the Great Recession with the destruction of the assets' value (tangible and intangible) generated by a surge of entrepreneurial risk during the financial crisis, and the associated reduction in the incentives to invest on these assets. In the K+S model - see Dosi et al. (2010), firms need external financing and capital markets are imperfect, implying that the firms may be rationed, cutting their investment and then downscale their production plans.

2.3. R&I Policy

Following the academic literature on R&I, this section reviews and assesses the main R&I policy instruments used in practice, the distortions they are expected to correct and the relevant channels through which they are presumed to operate. The main features of R&I identified in Section 2.1 serve to identify the channels and frictions that macro-models should ideally include to better understand and evaluate the working of R&I policies. This is singularly true when the aim is to evaluate the different programmes, legislations, and policies that constitute the EU innovation strategy, since particular attention should be paid to the different types of market failures and channels that policy makers and experts had in mind when designing it. Box 1 in Appendix on "R&I policies in the EU and its member states" provides a brief description of the main innovation policy instruments deployed in the EU. Finally, particular attention will be paid to the empirical evidence on the effects of innovation policies, and the macroeconomic modelling of these policies, frictions and channels.

Innovation policies are usually designed to address the potential market failures and distortions discussed supra, such as non-rivalry of ideas, knowledge and market spillovers (positive and negative), asymmetric information between innovators and providers of finance, coordination failures, and uncertainty, among others. Innovation policies can also lead to direct technological change to meet societal challenges like climate change, health or population aging.[49] Innovation policies also

[49] See Mazzucato (2013).

come at a cost, including the cost of administering the policies and the cost of failure to reach the aimed targets. Some of the policy instruments designed to protect and promote innovation may generate other distortions. Patents, being designed to solve the non-rivalry problem, promote non-competitive behaviour. Tax incentives may cause deadweight losses.[50]

In a recent survey of the **empirical literature on R&I policies**, Bloom et al. (2019) synthetize the evidence into what they refer as a *toolkit for innovation policy makers*. They rank R&I policies in terms of their overall impact from a social cost-benefit perspective and in terms of their distributional effects, conditional on the strength and quality of the evidence and the magnitude of the estimated effects. In their view, "In the short run, research and development tax credits and direct public funding seem the most effective, whereas increasing the supply of human capital (for example, through expanding university admissions in the areas of science, technology, engineering, and mathematics) is more effective in the long run." Competition and trade policies seem to have small benefits for innovation but they are inexpensive for the public budget. R&D tax credits and trade policies tend to increase inequality, as they boost the relative demand of skilled labour, while human capital policies have the opposite effect.

Macroeconomic models aimed to evaluate the EU innovation policy have to include these key channels, in order to provide figures that help to quantitatively assess their contribution to innovation, productivity and economic growth. The innovation process needs then to be detailed enough for a model to be able to evaluate the different policies, their objectives and the channels through which they are expected to operate. Correctly representing these policies and the channels through which they are expected to affect productivity and GDP growth, as well as other socio-economic and environmental variables, will be critical. In order to identify the key aggregate channels through which innovation policy may affect productivity and growth, the use of relevant micro and macro data is paramount. Such a quantitative effort has to be undertaken in the framework of macroeconomic models of innovation and growth with heterogeneous agents.

2.3.1. Major R&I policy instruments

This section discusses the major R&I policy instruments used in practice, which include R&D tax incentives (like R&D tax credits), R&D subsidies (like research grants), research loans and public venture capital, public R&D and public-private partnership, public procurement and patents.

R&D tax incentives

R&D tax incentives are designed to promote innovation, aiming at reducing the gap between private and social returns to R&D, and alleviating the financial problems faced by R&I performers. They are directed towards lowering R&D costs by means of R&D tax-credits, R&D tax allowances, accelerated depreciation of investment in research equipment, or reduced tax rates on corporate revenues from R&D,

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[50] For a more comprehensive discussion of various innovation policies and an analysis of their effectiveness, see Edler et al. (2016). See Feldstein (1999) for an analysis of the deadweight losses associated to income taxes.

innovation or patents (patent box/innovation box).[51] The use of R&D tax incentives is worldwide spread and represents a sensible contribution to the reduction of R&D costs incurred by firms. The OECD (2018c) report is a comprehensive study of the extent and deepness of this type of policies[52].

In their design, R&D tax-credits can be in proportion of R&D levels or in excess of R&D relative to a certain base. As small firms and startups suffer more from the asymmetric information related to R&D financing, they benefit generally from higher R&D tax credit rates. In principle, R&D tax incentives are neutral letting the private sector choose the projects in which to invest. But government can also take a more directive approach and give special tax incentives to areas considered of prime importance like health, environmental protection or defence, or incentives to do R&D in collaboration with universities. To allow firms benefit from the tax incentives even if they have no taxes to pay (absence of profits) the tax-credits can be made refundable, carried back or forward, or they can be deducted from social security contributions.

Mohnen (2018) discusses the effectiveness of R&D tax incentives. Besides the stimulating marginal effect, tax incentives, especially when they are proportional to R&D volume and benefit mainly large R&D performers, may lead to deadweight losses by supporting R&D that would be done anyway. The R&D tax-credits involve administration costs for government and implementation costs for receivers, in addition to the tax distortions related to raising tax revenues. Besides the cost/benefit calculations, it is also important to keep in mind that R&D tax policies, if they are stable and reliable, reduce the cost and the uncertainty related to R&D. Some studies have found that they can also raise the wages of R&D labour if there is a lack of researchers with the required qualifications. And finally, it must be kept in mind that the effectiveness of R&D tax-credits can be substantially reduced by R&D tax competition.

Most empirical studies show that R&D tax incentives are quite effective in reaching the objective of raising R&D expenditure. However, no firm conclusion can yet be reached on the degree of effectiveness: the estimated elasticities are below or above 1 depending on the time horizon considered and the presence or not of negative externalities, and the bang for the buck is often lower than 1 -see Ientile and Mairesse (2009), European Commission (2014), Bloom et al. (2019).

Concerning the heterogeneity of R&D tax credits, Busom et al. (2014) report that in Spain financially constrained firms and new entrants prefer direct subsidies over R&D tax credits because they are not able to fully benefit from R&D tax credits, and

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[51] Bloom et al. (2019) strongly argue against patent boxes, i.e., special tax regimes that apply lower taxes to patent revenues. Patent boxes give to multinationals considerable freedom in deciding where to book taxable income from patents, but have little effect on the real location of R&D. In this sense, they claim "patent boxes are an example of a harmful form of tax competition that distorts the tax system under the guise of being a pro-innovation policy."

[52] It does assert that "As of 2017, 30 of the 35 OECD countries, 21 of 28 EU countries and a number of non-OECD economies provide tax relief on R&D expenditures." It does also report that in countries like France, Portugal and Spain, R&D tax incentives reduce the R&D costs in at least 30%. See also Appelt et al. (2019).

that small firms contrary to large firms prefer tax credits over direct support because they are easier to get without having to reveal any information about the amount and the kind of research that is being performed. Many countries have introduced ways to recover the R&D tax credits even in the absence of profits, the so-called refundability of R&D tax credits. As shown by Agarwal et al. (2020), in Canada small firms without tax liability are more responsive to R&D tax credits than small firms with tax liability. In the same vein, Dechezleprêtre et al. (2016) show that in the UK the young firms among the small firms are more responsive to R&D tax credits because they are credit constrained. A higher additionality for small firms than for large firms is also reported in Lokshin and Mohnen (2012) for the Netherlands and Hægeland and Moen (2007) for Norway. Not only do small firms receive higher R&D tax credits, but they are also more responsive to the tax incentives.

In the macroeconomic literature, the aggregate effects of non-neutral (size dependent) R&D tax credits is an important, but still open question.[53] Benedetti-Fasil et al. (2020) find that R&D tax credits directly increase technology adoption and productivity of incumbent firms (intensive margin), while the general equilibrium effects raise firms' survival rates (extensive margin), which has the counterbalancing effect of reducing adoption and the average productivity of the economy.

At the EU, R&D tax incentives are under national jurisdiction -see Box 1. *R&I policies in the EU and its member states*. It raises the issue of **tax competition** within the Union. An ideal macro-model designed to evaluate this dimension of the EU innovation strategy should ideally include knowledge spillovers and be multi-country with heterogenous tax credit policies able to analyse, among other issues, tax competition.

Direct subsidies

Another way of lowering the cost of R&D, reduce the gap between private and social returns to R&D and alleviate financial frictions is through **direct support in the form of grants and subsidies.** Certain types of R&D, collaboration partners or research areas are targeted to receive (partial) support from the government usually in the form of grants. The idea is to support the projects with the highest estimated social return. It also goes in the direction of addressing specific social challenges like environmental sustainability and digital transformation. Generally, direct subsidies are aimed to move the frontier of knowledge by promoting excellence in basic research; promote the emergency of new technological paradigms (like robotics); promoting research cooperation between top universities/research centres and the leaders in the private sector; promote research in areas of fundamental relevance for society (environment, digitalization, health) through mission-oriented objectives.

The major conceptual difference between direct R&D support (like grants) and indirect support (like tax-credits) is with respect to the **neutrality of policy instruments**. Whereas tax incentives can be claimed automatically as long as a

[53] Gunner et al. (2008) study the macroeconomic effects of size-dependent policies in models of exogenous growth.

firm does R&D (sometimes under some additional restrictions), grants and subsidies are granted generally through a competitive process where the "best" projects are selected by experts. The EC Framework Programme grants are examples of direct R&D support. Direct subsidies are used by every single country in the EU as one of their major innovation policy instruments -see Box 1. *R&I policies in the EU and its member states*.

The issue of *additionality* is as the heart of the justification for R&I policies and for government intervention. Additionality has to do with how much a policy can generate in addition to what would have been the case without the policy.[54] There are different dimensions of additionality, namely input additionality, output additionality and behavioural additionality. Input additionality refers to the effects that R&I policy interventions may have on private R&D expenditure. Output additionality is related to increases in the proportion of innovation outputs that would not have been achieved without the public intervention (e.g. number of patents, new products, enhanced productivity etc..) as a result of the policy. Finally, behavioural additionality refers to the changes that occur in firms' behaviour and strategy as a result of a policy. In the presence of behavioural additionalities, the traditional input- and output additionality concepts may not adequately capture the impact of public R&I policies on the innovation process itself.[55]

Acemoglu et al. (2018), in the framework of a macro-model with firm heterogeneity, find that in the US economy there is large room for policy intervention, but that neutral R&D subsidies are not very effective.[56] Subsidies should be non-neutral but oriented to support research projects with the highest social return. As pointed out by Bloom et al. (2019): "A disadvantage of tax-based support for research and development is that tax policies are difficult to target at the R&D that creates the most knowledge spillovers and avoids business-stealing. In contrast, government-directed grants can more naturally do this type of targeting." In this direction, Akcigit et al. (2016) suggest a methodology to study the optimal design of corporate taxation and R&D subsidies in a macroeconomic framework of heterogeneous innovation capacity and private information. They find that linear corporate taxes combined with a nonlinear R&D subsidy can do almost as well as full unrestricted optimal policies. To provide a sound evaluation of R&D direct subsidies, macroeconomic models are expected to deal with the complex structure of R&D grants, the associated selection process, its efficiency on selecting the best projects and the associated effects on the variance of the productivity distribution of firms. The FRAME (2019) project developed a framework to study the role of R&D subsidies in DSGE models with homogeneous firms, being able to identify the

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[54] For examples of studies evaluating the additionality of subsidies, see Lach (2002), Takalo et al. (2013) and Gonzalez et al. (2005), among others. Lach (2002) finds evidence of partial additionality. For Israel manufacturing in the 90's, he estimates that an extra dollar of R&D subsidies increases long-run company financed R&D expenditures by 41 cents (total R&D expenditures increase by 1.41 dollars). He claims that "the magnitude of this effect is large enough to justify the existence of the subsidy program."

[55] See for example Buisseret et al. (1995).

[56] See also Benedetti-Fasil et al. (2020).

distinct effects of supporting basic and applied R&D on the diffusion of innovation, productivity and output, and some relevant redistribute effects.

Loans and public venture capital

Public financial support for innovation can also be given via **cheap loans, loan guarantees** or a **guaranteed financing from government.** Such government financial support schemes to R&D vary along three main dimensions: (i) the interest rate charged on loans; (ii) whether repayment is conditional on the project's outcome; (iii) the co-financing requirements applicants must comply with.

An alternative way is for the public sector to provide financing by participating in the capital of startup firms, the so-called public venture capital. In that case, not only financing is provided but also management guidance and network connections to give the innovative projects the best chances to succeed. After a few years, typically, the public sector sells its participation, sometimes with a gain, sometimes with a loss.

Public financial support for innovation is a dimension of innovation policy that macro-models should incorporate. Particular attention should be given to the relevant dimensions of firm heterogeneity, including the support to startups and highly innovative small and medium size firms, and the treatment of zombie firms, among others.

Public R&D and public-private partnerships

Instead of just subsidising or participating in the financing of R&D, governments can also decide **to perform the R&D itself in public universities or public research labs.** This would be the case for projects too basic, too large, expensive or risky to be undertaken by a private company, like space exploration or the production of nuclear energy. Examples of publicly funded research labs would be the German Max Planck Institute, the CNRS in France, the US Manhattan project. Bloom et al. (2019) in their *toolkit for innovation policy makers* rank direct public funding at the very top.

Public R&D can also be done joint with the private sector, where both sides co-finance projects, share knowledge and research facilities. The Fraunhofer Institutes in Germany or TNO in the Netherlands are examples of such public-private partnerships, where the private and the public sector join forces in research topics in the public and private interest.[57] Akcigit et al. (2020) find that policies promoting basic research and its interaction with the private sector are welfare-improving.

Public procurement

Instead of stimulating innovation on the supply side by lowering the cost of innovation, an alternative way for the government is to provide demand for innovations. Through innovative public procurement, innovators can more quickly recover the investment costs and at the same time increase the diffusion of

57 See Comin et al. (2019b) for a recent study of the contribution of Fraunhofer Institute to innovation in Germany.

innovations. Public procurement can also be used to define the functional requirements of innovations. Shaping markets for innovations decreases the risk of investing in R&D. Demand can also be encouraged by giving subsidies to private consumers of new products (e.g. photovoltaic panels) or by encouraging the adoption of new products through information campaigns or by regulations.

Cozzi and Impullitti (2010) argue that government spending played a significant role in stimulating the wave of innovation in U.S. economy in the late 1970s and 1980s. Using a quality-ladders endogenous growth model with heterogeneous industries and endogenous supply of skills, they show that a change towards a larger technological content of public spending stimulates R&D, raises the wage of skilled workers and stimulates human capital accumulation.

Carvalho and Draca (2017) stress the role of the US Department of Defense spending in funding corporate innovation in the US. They estimated that defence procurement had a positive direct and indirect market size effect on private patenting and R&D investment.

Patents

Patents are the instrument generally used to protect innovation from copy and imitation, thus enhancing the incentives to innovate**.** Patents provide temporary **monopoly rents** that are expected to let firms recover their R&D investments. By doing this, patents distort the static allocation of resources, eventually affecting the diffusion of innovations and knowledge. Given the complexity of the problem, various dimensions of patents can be adjusted to make monopoly rents close to its optimal level (length, breadth, height, renewal fees, etc…). This monopoly position, which conflicts with competition policy, is seen as the price to pay to stimulate private R&D.[58] Patents can also be more or less strongly implemented, depending on how much patent infringement can be defended by the patent holders. Moreover, various strategies exist to make patents even more anti-competitive (patent trolls, patent thickets).[59]

An important property of patents is that they grant property rights protection to innovators in exchange for the **disclosure** of the relevant information behind the innovation being patented. Disclosure favours the spread of knowledge spillovers**.**[60] Secrecy is a mutually exclusive alternative strategy to patents, also creating monopoly rents when successful, with the additional social cost of reducing

58 For a historical analysis of patent protection, see Lerner (2002). Boldrin and Levine (2013) argue against patent protection. In the same direction, Bessen and Maskin (2009) argue that when innovations are sequential (so that each successive invention builds in an essential way on its predecessors) and complementary (so that each potential innovator benefits from the discoveries of others), the prospective profits of inventors may actually be enhanced by competition and imitation rather than patent protection.

59 See Abrams et al. (2019b) on patent trolls**.**

60 Kultti et al. (2006) discuss the virtues of patents vs secrecy by means of disclosure theory. The paper rationalises the optimal use of patents in a framework of simultaneous innovations.

knowledge spillovers. Arundel (2001) studies the relative importance of secrecy vs. patents using the European Community Innovation Survey (CIS). He finds that the probability that a firm rates secrecy as more valuable than patents declines with firm size for product innovation, while there is no relationship for process innovations.

Most macro models of innovation work under the assumption that innovation is protected by patent law. Grossman and Lai (2004) analyse strategic intellectual property rights policy in a multi-country endogenous growth model.

2.3.2. Other policy areas affecting R&I

A whole range of policy interventions may affect the incentives to R&D investment and can therefore impact R&I. This section looks at the effect on R&I of corporate taxes, regulations and environmental policies.

Corporate taxes

An excessive burden of the tax system may impede innovation. From a macro-modelling perspective, Ferraro et al. (2011) take Peretto (2003) and (2007) to the data and find that cutting taxes on capital gains increases long-run growth. Cutting corporate income and dividends has the opposite effect, since these policies induce more entry, reducing the per firm innovation rate. More recently, Benedetti-Fasil et al. (2020) study corporate tax reforms in a macro-model with firm heterogeneity and business cycle. They find that corporate taxation not only affect the number but also the size distribution of firms having important implications for innovation. Finally, Ates and Saffie (2018a) analyse corporate taxation in a Schumpeterian model with financial frictions and heterogeneity in R&D technology. In this framework, high corporate taxes are associated with low entry, which implies low growth.

Regulations

The relationship between regulation and innovation is multi-faceted, depending on the nature and the quality of the regulation itself, on the sectors involved and the time horizon considered[61]. At times tight regulations tend to exert pressure on companies forcing them to innovate. Specific regulations addressing negative environmental externalities or dealing with health and safety of citizens may affect the direction of technical change and act as a powerful stimulus to innovation. On the other hand, more prescriptive regulations envisaging high compliance costs and red-tape burdens may hinder innovation activities.

Environmental policies

Macroeconomic models integrating environmental constraints and the negative externalities of pollution may be used to study the impact of a wide range of environmental policies on economic performances and innovation activities. A key insight from the environmental economics literature is that tightened pollution targets induce environmental innovation: appropriately designed environmental

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[61] See Pelkmans and Renda (2014) and Blind (2016).

policies can promote the development and the adoption of advanced abatement technology, and can affect technological progress and the diffusion of clean technologies.[62] Models with directed technical change can capture the transition towards green technologies induced by these policies.[63] As shown by Aghion et al. (2016) firms in a laissez-faire economy may be induced to innovate in the "wrong direction", because of a strong "path dependence" phenomenon in favour of dirty innovations.[64] However, the link between innovation and environmental policies can be bi-directional. Environmental policies may not only push and direct innovation, environmental policies may also respond to innovation.[65]

In modelling environmental policies economists distinguish between two classes of pollution control instruments: command & control versus market-based instruments. The **command & control** approach is essentially a regulatory approach whereby a regulatory authority "commands" emission reduction by directly prescribing emission ceilings (e.g. firms are bound by an upper emission level or by a cap on the ratio of emissions per output or per hour;) or by imposing technological standards (e.g., firms must adopt the best available technology). The "control" step involves verifying how pollution reductions are achieved, standards are met, and enforcement tools such as fines are specified. **Market based instruments** instead consist of incentives to reduce pollutant emissions. The most common market-based instruments are emissions taxes (e.g. carbon tax), cap-and-trade schemes, abatement subsidies, subsidies for the adoption of clean technology and for the use of renewable energy.

For a discussion on the effectiveness of different environmental policy instruments for the adoption and the development of clean technology, see e.g. Requate and Unold (2003) and Requate (2005). Moreover, public authorities can directly steer the development of green technologies, either through public R&D or through targeted financing of private R&D. For further discussion on the macroeconomic modelling of environmental externalities, see Section 2.4.6.

2.3.3. Policy mix

Some innovation policies may work well in some situations and less in others. Governments must also be careful to avoid that some of the policies stand in the way of each other. As already mentioned, intellectual property rights may collide

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62 See e.g. Jaffe et al. (2002) for a survey.

63 See e.g. Peretto (2009), Acemoglu et al. (2012) and Hémous (2016).

64 The economic literature points to an overestimation of the costs of environmental regulation when directed technical change, R&D and learning-by-doing mechanisms are not considered. See e.g. Buonanno et al. (2003) and Manne and Richles (2004). On the role of learning-by-doing mechanism in the abatement process of pollution see Brock and Taylor (2003).

65 See e.g. Carrión-Flores and Innes (2010).

with antitrust policies. Budget-neutral expansionary R&I policies may entail higher taxes and/or undesirable spending cuts on other items. When lumpsum taxation is not available, financing public R&D and other expansionary R&D policies may require the increase of distortionary taxation thereby raising the opportunity cost of using public funds for R&D. Debt financing of public R&D may be limited by balanced budget constraints. Innovation policy is often intertwined with industrial policy i.e. supporting certain champion sectors, firms or technologies.

The potential interactions between policies implemented at different governance levels represent another important dimension that needs to be considered. Nationwide innovation policies are likely to influence the performance of self-contained regional innovation plans and of R&D policies targeted at regional strengths, such as cluster policies, smart specialization strategies or cohesion funds. Similarly, the goals pursed by supranational R&I policies and the instruments used for these purposes may not always be consistent with national and regional innovation policies.

Building further on Klette and Kortum (2004),[66] Acemoglu et al. (2018) quantitatively study the role of innovation policy. They compare optimal social allocations with second-best policy allocations (those resulting from an optimal use of the individual different instruments available for innovation policy). In this literature, innovation policy is modelled by means of simple policy instruments like R&D subsidy or R&D tax-credits, which can be uniform (a common subsidy or tax-credit rate for all firms) or state-dependent (i.e. depending on observable characteristics, like firm size or past R&I performance). These innovation policy instruments are also compared with other, generic policy instruments that also affect innovation, like corporate taxes. While this approach allows to compare various instruments, it does not look at policy mixes.

How then study the policy mix in macro-models? Akcigit et al. (2016) give an important step in this direction by studying the optimal design of corporate taxation and R&D subsidies in an endogenous growth framework of heterogeneous firms with heterogeneous innovation capacity, knowledge spillovers and private information. The optimal policy-mix here is modelled as a dynamic mechanism design problem with spillovers. The model is estimated using firm-level data matched to patent data. In this framework, they show that very simple innovation policies, such as linear corporate taxes combined with a nonlinear R&D subsidy – that provides lower marginal subsidies at higher R&D levels – can do almost as well as full unrestricted optimal policies.

Aghion et al. (2001), in the context of a Schumpeterian growth model with step-by-step innovations and where laggards imitate to catch-up the leader, point out the complementary role for antitrust policy and patent policy. In this context, (a) product market competition has a positive effect on growth, and (b) some imitation is growth enhancing but too much imitation is growth reducing.

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[66] Klette and Kortum (2004) develop a general equilibrium model of innovation and technological change that replicates the dynamics of heterogeneous firms, including entry and exit. Within this framework, they are able to account for the persistence of firms' R&D investment, the concentration of R&D among incumbents, the link between R&D and patenting, and the positive correlation between the R&D to revenue ratio and firm's productivity but not with firm size or growth.

2.3.4. Costs of policy interventions: administrative burdens

An excessive complexity of regulatory procedures and/or a heavy administrative burden on existing businesses and on startups may constitute severe barriers to entry, hinder firms' expansion and undermine R&D incentives. In models with endogenous growth, for instance, impediments introduced by administrative burdens may be seen as increasing the cost of introducing an innovation. Clearly, the reduction of administrative burden through administrative simplification is beneficial for firms since it reduces average production costs.

However, when it comes to understand the relationship between administrative burdens and innovation, there are contrasting forces that should be considered. In models where monopolistic profits represent the crucial incentives for innovation a reduction of rents generated, for instance, by an alleviation of the administrative burden on new businesses, may, in principle, reduce the pace of innovation. Rents of the incumbents may in fact be eroded by the entry of new firms. On the other hand, in models exhibiting scale effects, administrative simplification provisions may induce faster growth.

In macroeconomic models for R&I policy evaluation, administrative burdens may be introduced in the form of overhead labour, entry barriers or fixed costs (see e.g. Roeger et al. 2008).

2.4. Dimensions of macroeconomic impact of R&I

Innovation and innovation policies affect the evolution of technology, which reflects in aggregate productivity gains, economic growth, developing comparative advantages and improving competitiveness in a globalized world. Despite its direct effect on people's income and consumption/investment opportunities, technical progress also shapes human life in other dimensions by transforming the labour market (creating and destroying jobs and skills), modifying the (un)equal distribution of income and wealth, potentially degrading the environment, but also a source of new clean technologies, affecting people's health.

2.4.1. GDP

A main impact dimension of R&I policies is GDP and its growth rate (GDP level, GDP per worker, GDP per capita). GDP is a common anchor metric used for targeting macroeconomic performance. As such, macroeconomic models are a prime tool to assess the impact of R&I policy interventions on GDP at various horizons (short-, medium- and long-term).

As a discipline device, macroeconomic models are targeted to replicate the observed behaviour of GDP and its main components as measured by National Accounts. The bases of modern macroeconomics were developed in the fifties and sixties, with the so-called **Neoclassical growth theory**, by assuming a single final good, directly associated to GDP in the data, a *representative firm* operating an aggregate technology, and a *representative household* taking consumption/ saving decisions - see Solow (1956). This small set of assumption was enough to replicate the so-called Kaldor facts that emerged from the recently created national accounts -see Kaldor (1961).[67]

[68] Following the Neoclassical tradition, the dynamic and stochastic general equilibrium (**DSGE)** model, inspired in the seminal contribution by Kydland and Prescott (1982), developed in the nineties aiming at the study of macroeconomic fluctuations and stabilization policies -see Clarida et al. (1999) and Woodford (2011). In our days, the DSGE framework is the standard instrument for macro policy evaluation used by most Central Banks and Ministries of Finance all around the globe. QUEST, developed by the DG ECFIN for the EU, is a good example -see Section 3.2.

In the Neoclassical growth framework, and the subsequent developments that gave rise to the DSGE model, the growth rate of productivity is assumed to be exogenous. The introduction of R&I in **models of endogenous growth**, pioneered by Romer (1990) and Aghion and Howitt (1992), among others, improved over the Neoclassical growth model by endogenizing the growth rate of productivity. This is an evolution of the macroeconomic literature of fundamental importance for the macro-modelling of R&I and R&I policy evaluation.

Macro-models of heterogeneous firms and households were developed during the last two decades, allowing DSGE models to go beyond the representative firm and household assumptions -see the discussion on firm heterogeneity at Section 2.1.2 and all along Section 2.2. Macro-models of *heterogenous firms* follow the traditions initiated by the *firm dynamics*' framework -see Jovanovic (1982) and Hopenhayn (1992), and the *Schumpeterian* framework -Aghion and Howitt (1992). Instead of a representative firm, the production side of the economy is populated by a mass of heterogenous perfectly competitive (Hopenhayn, 1992) or monopolistically competitive (Aghion and Howitt, 1992) firms.[69] In the tradition of Bewley (1977) and Aiyagari (1994), Krusell and Smith (1998) develop a stochastic growth model of *heterogeneous households* with partially uninsurable risk to study the interaction between income and wealth inequality with the main macroeconomic variables. **Models of heterogeneous firms and households** use micro data, on top of

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[67] In the US, National and Income and Product Accounts (NIPA) were developed in the thirties and forties -see Kuznets (1934) and Carson (1975). The publication of the NIPA officially statistics started in 1947.

[68] Kaldor (1957) states that, over long periods of time, the following variables are roughly constant, 1) the labour and capital shares of national income; 2) the rate of growth of the capital stock per worker; 3) the rate of growth of output per worker; 4) the capital/output ratio; 5) the rate of return on investment.

[69] In Hopenhayn (1992), firm's technology is assumed to have decreasing returns to labour, like in the *span of control model* suggested by Lucas (1978). Following the seminal contribution by Dixit and Stiglitz (1977), models of monopolistic competition alternatively assume that heterogeneous firms produce a large variety of differentiated products under constant returns. This framework has been extended to alternative forms of imperfect competition like in Melitz and Ottaviano (2008) and Impullitti and Licandro (2018). Collard and Licandro (2020) study the general conditions for aggregation that makes heterogeneous firm economies to share similar aggregation properties as the Neoclassical growth model.

macro data, to discipline the analysis. A critical aspect remains: How do heterogenous behaviours aggregate in GDP and its components? Consistently with the aggregation theory in Solow (1962), Collard and Licandro (2020), show that macro-models based on Hopenhayn (1992) show aggregate properties similar to the Neoclassical model, making the selection process play a fundamental role in determining aggregate productivity.[70]

Agent-based models (ABM) provide an alternative based on assumptions about the way agents behave and interact, which are rooted in the actual empirical microeconomic evidence -see Simon (1977) and Kirman (2016). Evolution and the emergence of novelty are at the heart of these models -see David (2006), Dosi and Winter (2002), Dosi and Virgillito (2017). ABM or ACE focus explicitly on the heterogeneity of agents, their interactions and believes, the randomness and path-dependency of technological change, the non-linearity of economic phenomena and the resulting out-of-equilibrium dynamics, raising their potential to explain short-run fluctuations, long-run trends as well as sharp discontinuities and the possibility of crises. Yet they suffer, as most models, from the curse of dimensionality. The more agents in a model and the more complex their interrelationships, the more time it takes to run the model, to achieve convergence and to understand the driving forces and locations of tension in the model. While ABM models are able to replicate observed stylized facts of industrial dynamics and macroeconomic fluctuations in artificial economies, they have so far not been used to replicate the current stage of a particular economy and then predict its subsequent evolution.

Stabilization policies. There is a growing, recent literature bridging endogenous growth and **business cycle** approaches to macroeconomic analysis[71]. The FRAME (2019) project, based on Comin and Gertler (2006) and Anzoategui et al. (2019) is an example of this approach. As stated by Bianchi et al. (2019): "New insights from the FRAME project show that fiscal austerity has severe negative consequences for productivity and economic growth in the medium-run and can lead to slow recoveries." Benigno and Fornaro (2018), referred when discussing about path dependency in Section 2.1.2, is another relevant example. More recently, Vinci and Licandro (2020) suggest an endogenous growth DSGE model that replicates the behaviour of the US economy in both normal times and the Great Recession. In this framework, monetary policy not only favours economic recoveries, but due to knowledge spillovers, promotes productivity growth, giving rise to important welfare gains. In other words, by favouring a faster recovery, monetary policy not only has stabilization effects, but medium- and long-term effects on productivity and GDP per capita.

2.4.2. Competitiveness and globalization

Macro-models can also be used to evaluate R&I policies on their potential effects on *competitiveness*, i.e., the ability of a firm, sector or country to successfully compete

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[70] The economic theory of index numbers gives support to aggregation in the measurement of GDP and GDP growth in National Accounts. See Caves et al. (1982) and more recently Duran and Licandro (2015).

[71] See Fatás (2000), Comin and Gertler (2006), Aghion et al. (2009), (2010) and (2014), Sedlacek (2020), Anzoategui et al. (2019) and Benedetti-Fasil et al. (2020).

in global markets.[72] Structural competitiveness problems are typically associated with low productivity growth, while significant competitiveness divergences among deeply integrated economies may be perceived as potentially risky.[73] Competitiveness is, however, a multifaceted concept that can have several different meanings and measures, whether the focus is on firms, sectors or countries. At the macroeconomic level the focus is on **country-level competitiveness**, but in multi-sector macroeconomic models it is also possible to measure the impact of R&I policies on competitiveness at a **sectoral** level and provide insights into what may drive countries competitiveness at large. Unit Labour Costs and Real Effective Exchange Rates are the most established measures of competitiveness. Both measures are usually evaluated at economy-wide level, but in multi-sector macroeconomic models they can be assessed at more disaggregated levels.

Growth models with heterogeneity in firm-level productivity can account for the effects of R&I policies on **firm-level competitiveness** and for the rise of superstar firms. In general, more granular models and/or models with heterogenous firms are better suited for the evaluation of *vertical targeting* policies, aimed at promoting innovation and technological adoption in a selection of sectors and/or regions. In Baldwin and Robert-Nicoud (2008), the potential effect of innovation policies on firm-level productivity does not extend to national comparative advantage, as firms across countries compete horizontally as in Krugman (1980) and new technologies complement existing ones as in Romer (1990). Impullitti and Licandro (2018) incorporate an additional mechanism through which industrial policies (e.g. trade liberalization, R&D subsidies, bureaucratic barriers to entry) may affect firm-level and aggregate productivity, namely the competition channel. By affecting the profitability of new firms successfully entering export markets, trade policies have an impact on market concentration and product market competition, which feeds back to firm incentives to innovate, thereby contributing to national competitiveness.

Within the framework of endogenous growth theory, Grossman and Helpman (2015) discuss the classic channels linking **trade and growth**: International knowledge spillovers, market size and competition, relative prices, and technology diffusion. In macro-models of firm heterogeneity, the link between trade openness and productivity growth is also shaped by these classical channels, but they can be magnified by a rich set of selection effects. Impullitti and Licandro (2018) study productivity and welfare gains from trade in a macro-model of innovation-driven growth with firm heterogeneity and variable markups. They find that accounting for firms' innovation responses generates dynamic gains that double the traditional static gains from trade. Sampson (2016) studies welfare gains in a macro-model where productivity growth is driven by knowledge diffusion at the entry stage. Trade-induced selection accelerates knowledge diffusion and growth, thereby tripling the gains from trade relative to heterogeneous firms' economies with static productivity at the firm level. Along similar lines, Perla et al. (2019) set up a macro-model where growth is driven by knowledge diffusion between incumbent firms, and show that trade accelerates technology diffusion and growth.

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[72] See Fagerberg (1988). Among the stylised facts of modern growth, Jones and Romer (2010) report that globalization has increased the size of the market.

[73] See Gros (2012) on the Alert Mechanism of the EU Macroeconomic Imbalance Procedure.

Modelling R&I in a multi-country, open economy macro-model with heterogeneous firms would be needed to properly evaluate the effect of R&I policies on competitiveness in a globalized world. Akcigit et al. (2018) argue that policies promoting R&I (like R&D tax credits or R&D subsides) dominate protectionism. They quantitatively assess the introduction in the US in the eighties of R&D tax-credits and find that this policy instrument was an effective response to the increasing Japanese and European competition, leading to more innovation both in the short and in the long run, and substantial welfare gains.

2.4.3. Labour markets

The creation of new technologies is intrinsically related to the destruction of old ones and the associated skills. R&I policies have to consider the effects that technical progress has in the evolution of employment and wages across industries and occupations.

The by now abundant literatures on skill premia, job polarization, automation and skill obsolescence show the important the labour market effects of innovation and technical progress, which develops differently across sectors, affecting unevenly the dynamics of jobs and occupations.

There is an abundant empirical literature on the firm level relationship between productivity and employment, documenting the extent of labour reallocation associated to differences in productivity across firms.[74] Lentz and Mortensen (2008) study the labour market effects of such productivity differences in an extended version of the Schumpeterian model suggested by Klette and Kortum (2004) with firm heterogeneity and R&I. On a panel of Danish firms, they find that 53% of aggregate growth is due to selection as more productive firms grow faster, crowding out less productive firms. The labour market effects of R&I are somehow disrupted by the associated misallocation of labour across firms, as documented by Hsieh and Klenow (2009), among others.

The increase of the *skill premium*, defined as the relative wage of college vs non-college graduates, observed in the seventies and eighties in the US was attributed by Katz and Murphy (1992) to the fact that technical progress was biased in favour of skilled workers, i.e., the so-called ***skill bias technical change*** hypothesis.[75] In their view, the observed increase in both employment and wages of skilled workers, relative to unskilled workers, was governed by a rise in the demand for skills induced by skill bias technical change, which also induced an increase in the relative supply of skilled workers.[76] Acemoglu (1998) argues that during this period R&I

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[74] See Bartelsman and Doms (2000) for a survey. Some interesting measurement issues are in Foster et al. (2008).

[75] Acemoglu (2003) reports a little increase in the skill premium in Europe.

[76] Krusell et al. (2000) attribute this bias in technical progress to a combination of two facts: capital embodied technical progress and *capital-skill complementarity*. Autor et al. (2003) argue that the rise in automation observed during the last decades of the 20th century lead to the observed decline in routine jobs and the consequent increase in nonroutine jobs. In their view, computers substitute for workers performing routine tasks, but complement workers performing nonroutine tasks (a particular form of capital-skill complementarity).

efforts were mainly *directed* to increase the performance of skilled jobs, giving rise to the bias in technical progress reported by Katz and Murphy (1992). Acemoglu and Autor (2011) and Autor and Dorn (2013) subsequently observed that the simultaneous rise of the skill premium and the relative employment of skilled workers was part of a more complex phenomenon referred in the literature as *job polarization*, in which losses of wages and employment concentrated in the middle of the skill distribution.[77] They relate this phenomenon to a rise in automation and the destruction of what they call routine jobs, that concentrate in the middle of the skill distribution.[78]

Another strand of the literature analyses the labour market implications of the diverse evolution of technology across sectors, the so-called *structural transformation*. This literature aims at understanding the observed unbalanced patterns of sectorial evolution in modern economies between agriculture, manufacturing and services.[79] The unbalanced evolution of industries is mimicked by an unbalance evolution of occupations, as pointed out by Duernecker and Herrendorf (2019), consistent with the polarization of wages and employment observed in the data.

Innovation and the progress in technology in a world of heterogeneous workers, not only has an impact on employment but also on education and occupational choices. In Acemoglu and Autor (2011) and Autor and Dorn (2013), for example, workers have a choice between being skilled or unskilled which depends on the expected equilibrium wages.[80] As in Katz and Murphy (1992), the supply of skills follows the evolution of technology. Modelling the joint evolution of technology and occupations, and the associated evolution of skills is of fundamental importance to evaluate the labour market effect of R&I policies.

Macroeconomic models designed to understand R&I and evaluate the impact of R&I policies have to consider their effects on the labour market, ideally in a framework of heterogeneous firms and workers, and endogenous skills.

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77 Job polarization in Europe was studied by Goos et al (2009).

78 More recently, Acemoglu and Restrepo (2018) and Graetz and Michaels (2018), among others, studied the economic contributions of modern industrial robots, showing large gains in productivity. Basso and Jimeno (2020) stress the role of demographics in the interplay with robotization. In a Comin and Gertler (2006) endogenous growth framework, they find that low fertility and population ageing lead to reductions in the growth rate of GDP and the labour income share.

79 See Duarte and Restuccia (2010), Kongsamut et al. (2001), Ngai and Pissarides (2007), Acemoglu and Guerrieri (2008), Boppart (2014) and Comin et al. (2019). See also Herrendorf et al. (2014) for a survey on this literature.

80 A useful model of occupational choice was suggested by Roy (1951). Autor et al (2003) use the Roy model to understand how computers changed the demand and supply of skills.

2.4.4. Inequality

Social exclusion and *inequality* have emerged as major societal concerns, motivating the need for macro-models to include the relationship between technology advancement and inequality.[81]

There are different types of inequality that may be reduced or magnified by growth and technological progress. Inequality across countries requires a multi-country modelling structure with *heterogeneity* in innovative capabilities. Regional inequality can be studied in regional models where imbalances in the distribution of economic activities (i.e. *core-periphery* patterns)[82] emerge endogenously. Inequalities among individuals or across socio-economic groups require the explicit modelling of different categories of workers having different skills.

Acemoglu et al. (2006) develop a macro-model of innovation and adoption to better understand the relation between technical progress and crosscountry differences in development. Technological progress may favour some specific social groups and sectors. In models where growth is driven only by factor accumulation and where technological progress is neutral, inequalities among individuals or across socio-economic groups may emerge because different individuals and socio-economic groups have different propensities to accumulate factors and because factor accumulation, in turn, may affect the remuneration of the specific productive factors owned by individuals. In this context inequalities across workers employed in different sectors may emerge as a result of structural changes. Notably, structural changes may be generated by different channels: preference-driven channels generated by differences in the income elasticity of demand across goods (see e.g. Duarte and Restuccia 2010; Boppart 2014), or supply-driven channels generated by sectoral differences in factor proportions, sectoral differences in the degree of capital–labour substitutability or by sector-specific technical progress (see e.g. Ngai and Pissarides 2007, Acemoglu and Guerrieri 2008, Alvarez-Cuadrado et al. 2017). Multi-sector macroeconomic models can capture these aspects. However, the evidence on the unbalanced evolution of industries and occupations and on the polarization of wages (cf. supra) suggests the need of macroeconomic models able to capture aspects related to skill-based technical changes, skill obsolescence and the impact of robotization.

2.4.5. Health

Health is something that people value for themselves. In addition, there is also the productive side of health, since healthier people can work harder and longer. With an ageing population promoting a healthy ageing lifecycle approach is a societal and economic challenge shared by all European countries.

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81 Aghion et al. (1999) survey the literature on the relation between inequality and economic growth. On one side, they stress the role of capital market imperfections on shaping the trade-off between equity and efficiency. On the other side, they point out that technical change has been a crucial factor in explaining the recent upsurge in wage inequality. See Aghion et al (2019) on the relation between innovation and top income inequality.

82 See Forslid and Ottaviano (2003) and Baldwin (2001). See also Rodriguez-Pose (2018).

R&I can affect health through different channels.[83] A direct channel is through R&I in the medical and pharmaceutical sector.[84] An indirect channel is through R&I affecting environmental degradation and the related negative effects on human health.[85] Life expectancy is an important dimension of health that is also expected to interact with human capital and growth. Acemoglu and Johnson (2007) study the relation between life expectancy and growth concluding that "there is no evidence that the large increase in life expectancy raised income per capita." However, Cervelatti and Sunde (2011) challenge this view showing that life expectancy played an important role on the outset of the demographic transition.[86]

In macroeconomic models, since the seminal contribution of Grossmann (1972), health has been modelled as a durable good (health capital) that enters the utility function of individuals directly or indirectly through the effects that health has on the time that can be spent on activities. Health is subject to deterioration and may vary with the age of individuals in models of heterogeneous agents.

The assessment of health impacts of R&I poses several measurement issues requiring inputs from epidemiological studies on the health effects of different medical treatments, lifestyles, pollutants and several other factors.

2.4.6. Environment, non-renewable and waste disposal

Following the growing concern of society for a sustainable environment, the importance of environment has been gaining momentum in both policy-making and academic circles. This is particularly the case for the relationship between economic growth, environmental quality and natural resources. Macroeconomic models for R&I policies evaluation should embody **environmental externalities**, account for the **damage of pollutants** and deal with the issue of **resource scarcity**. The shift to new or improved low-emission and high-efficiency technologies in key sectors such as transport, power generation and energy may play a major role in tackling climate change. Technological progress can also help reduce pollutant emissions from industry, agriculture and other sources, limit the depletion of exhaustible resources, improve waste disposal and recycling, reduce the abatement costs and stimulate the developments of a broad portfolio of green technologies. In this process economic policies play a major role in fostering changes and in directing technical change. In this respect, general equilibrium models allow to capture direct and indirect effects of technological progress on the environment, and to highlight the possible trade-offs and the emergence of **rebound effects**.

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83 See Aghion et al. (2010) and Barro (2013). More recently, Bloom et al (2019).

84 Bloom et al. (2017) argue that research productivity has been declining sharply in the pharmaceutical sector. In particular, Di Masi et al. (2016) estimate that the real cost of R&D in the pharmaceutical industry has been raising at 8.5% annually in the last two decades.

85 See Science for Environment Policy (2018).

86 See also Kalemli-Ozcan et al. (2000) and Boucekkine et al. (2003).

The **directed technical change** literature stresses the importance of path dependency in R&D efforts and of policy actions in promoting the shift towards sustainable technologies. Because of path dependency, in a laissez-faire economy, firms failing to internalize environmental externalities may be induced to keep innovating in the "wrong direction". On directed technical change, see e.g. Aghion et al. (2016), Acemoglu et al. (2012), while for models with endogenous innovations in abatement technologies, see e.g. Bovenberg et al. (1995) and Goulder and Schneider (1999).

Since the seminal studies of Nordhaus (1974), Grossman and Krueger (1991) and Stokey (1998) on the relationship between growth and the environment, macroeconomic models have been addressing environmental constraints and the role of R&I along different, but complementary dimensions.

A first dimension is related to the emissions and/or the abatement of all **global and local pollutants** involving air, water, soil, light and noise. Greenhouse-gas emissions and climate change (global pollutants), among them, are of a first importance. In this domain central issues of concern are the development of clean technologies not involving fossil fuels and the improvement of the available abatement technologies. Policies against global pollutants and climate actions (both price and quantity regulations) can be introduced in all macroeconomic models based on general equilibrium. However, cap-and-trade schemes set at international level require the use of multi-country frameworks. Similarly, the study of the effects of unilateral environmental policies and of possible carbon leakages requires open economy models with multiple countries. For a throughout discussion on climate change from the perspective of macroeconomic modelling and quantitative evaluation, see Hassler et al. (2016). Concerning local pollutants, regional and sectoral models may represent the main tool of analysis.

At present CGE models and Integrated Assessment Models (IAMs) are the main policy-analysis tools used to estimate the economic costs and benefits of different actions against climate change. See e.g. the DICE and RICE models of Nordhaus (2007, 2008), the EPPA model (Paltsev et al. 2005), the CIM-EARTH model (Elliott 2010) and the REMIND model used in Rauner et al. (2020).[87] Multi-sector econometric models integrating macroeconomic activity with key climate variables are also used to evaluate short- and long-term impacts of climate actions. In recent years, dynamic stochastic general equilibrium models have been employed for the study of energy and environmental policies. For variants of dynamic general equilibrium models of the economy and climate, see Golosov et al. (2014) and Van der Ploeg and Rezai (2020). For an extension of the QUEST model in this direction, see Conte et al. (2010). Overall DSGE models can capture important factors for environmental policy analysis, such as physical and transition risks, short-run trade-offs and uncertainty.[88] In this respect, also environmental agent-based models with

[87] In an extended version of the DICE model of climate change with endogenous innovation in the energy sector, Popp (2004) shows how neglecting induced technological change overestimates the welfare costs of an optimal carbon tax policy by about 8 percent.

[88] For other examples of environmental DSGE models focusing on the short-run trade-offs of climate actions, see e.g. Fischer and Springborn (2011), Heutel (2012), Annicchiarico and Di Dio (2015), Annicchiarico et al. (2018) and Annicchiarico and Diluiso (2019).

climate risk can be used to construct mitigation scenarios under uncertainty and capture the dynamic adjustment towards a greener economy.[89]

A second dimension is that related to **resource scarcity** and the **management of non-renewable resources**. Multi-sector models can capture the economic mechanisms that may lead to save scarce resources and induce endogenous energysaving technical change. This aspect can be easily introduced in CGE models or in dynamic general equilibrium models with directed technical change or in econometric models -see e.g. Bergman (2005), Peretto (2009), Acemoglu et al. (2012), Peretto and Valente (2015).

A third dimension regards the role of innovation on the efficiency and the safety of **waste management**. Waste disposal aspects have been integrated in CGE and macro-econometric models, but in principle they may be explicitly introduced in any class of macroeconomic models.

Finally, innovation can favour the transition towards a **circular production system** and the implementation of cost-effective recycling programmes able to *close the loop*. Given their input-output structure, CGE models are natural candidates to represent this dimension related to environmental constraints, although all general equilibrium models can easily capture circular features. See McCarthy et al. (2018) for an overview on the potential modelling approaches to the transition towards a circular economy.

2.5. A concluding checklist of mean features, enablers, policy instruments and dimensions to evaluate R&I and R&I policies in macro-models

Based on the existing academic **macroeconomic literature on R&I and innovation policies**, this section described the critical features of the innovation process which macro-models need to include to appropriately account for its role on economic growth and welfare. It also identified the main policies to promote innovation, boosting growth and enhancing sustainability. In this section, these main features, enablers and main policy instruments are summarized in the following set of tables.

Starting from the notion that technological knowledge is the sum of methods and techniques employed in the production of goods and services, resulting from the cumulative aggregation of new technological ideas or innovations, resulting from a systematic effort of research and development (R&D) benefiting from multiple forms of knowledge spillovers, the main features characterizing this R&D and innovation process as well as its main enablers can be derived which applied-macro-models should cover when used for evaluating innovation and innovation policy.

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89 See e.g. Lamperti et al. (2018).

Table 2.1 - Main features of R&I

Technological Knowledge	Stock of knowledge (endogenously determined)	**Innovation Typology**	Basic and applied research
	Absorptive Capacity		Process and Product Innovation
	Non-Rivalry		Drastic and Incremental Innovations; GPTs
	Obsolescence		
Innovation & Creation of New Technologies	R&D	**Linking inputs and outputs: the knowledge production function**	R&D labour inputs
	Knowledge Spillovers		R&D equipment
	Rent Spillovers		“Standing on the shoulders of giants” effects
	Firm Heterogeneity		Congestion externalities
	Path Dependency		
Diffusion of New Technologies	Knowledge Spillovers		
	Absorptive Capacity		

Table 2.2 - Main R&I enablers

Size of the Market	
Competition	
Intellectual property rights	
Human capital	Stock (endogenously determined)
	Heterogeneity: different labour skills
Financing of R&D	Financial frictions (endogeneous)
	Risk Premia

Table 2.3 - Main R&I policy instruments

Section 2 also reviewed and assessed *R&I policy*, the distortions they are expected to correct and the relevant channels through which they are presumed to operate. Macro-models aimed to evaluate innovation policy should cover these main R&I policy instruments and other policies that directly or indirectly affect innovation, as well as the design of the appropriate *policy mix*.

R&D tax incentives	
Direct subsidies/grants	
Loans and public venture capital	
Public R&D	
Public-Private Partnerships	
Public Procurement	
Patents	
Other policy instruments	Regulation
	Corporate tax
	Environmental policies
	Competition Policy
	Education Policy
	Labour market policy
Policy Mix	Budget spent
	Interactions between national and supranational level policies
	Interactions between regional and national level policies
	Sector or technology specific policy interventions
Administrative Burden	

Although macroeconomic models are used mostly to assess the impact of R&I policy interventions on GDP at various horizons (short-, medium- and long-term), there are also other dimensions of societal welfare that can be assessed through macro-models.

Table 2.4 - Dimensions of macroeconomic impact of R&I

GDP (growth)	
Competitiveness	Firm; country; region
Labour markets	Employment & wages
Inequality	Across workers
	Across countries
	Across regions
Health	
Environment	

Section 3 will use this set of tables to assess the applied macro-models currently used by the European Commission for assessing their use for R&I policy evaluation. More particularly, these models are assessed on their inclusion of the basic features, enablers and policies as important for modelling R&I and assessing R&I policy interventions, and, if not, how they could be included.

It should be remarked that this summary only provides a *synthetic representation* of the *main features related to the modelling of knowledge creation and diffusion of technologies, the main policy instruments* and *the main dimensions of impact.* The list is not meant to be exhaustive and the presence or absence of individual features or instruments or dimensions of impacts should not be interpreted by itself as a sign of strength or weakness of the models.

3. THE MACROECONOMIC MODELS *CURRENTLY* USED FOR R&I POLICY, AND HOW THEY CAN BE IMPROVED

Section 3 checks whether and how the main R&I properties and policies discussed in Section 2 are accounted for in the macroeconomic models used by the European Commission and, if not, how they could be included. Three macroeconomic models are presently used by the Commission's DG for Research and Innovation (DG R&I): QUEST III, RHOMOLO and NEMESIS. [90]

- The QUEST III model is a dynamic macroeconomic model of the European Commission designed to be a laboratory for economic policy analysis for the EU countries. It is developed by DG for Economic and Financial Affairs (DG ECFIN) with support from the Joint Research Centre (JRC) in Ispra.
- RHOMOLO is a spatial computable general equilibrium model of the European Commission. The model is developed by the Regional Economic Modelling team at the JRC in Seville in cooperation with DG for Regional and Urban Policy (DG REGIO).
- NEMESIS (New Econometric Model for Evaluation by Sectoral Interdependency and Supply) is a European macro-sectoral econometric model initially developed by a consortium led by ERASME (a research team common to the University of Paris1 Sorbonne and the Ecole Centrale Paris), and including the CCIP (Chamber of Commerce of Paris), NTUA (University of Athens), the Federal Planning Bureau (Brussels) and the University of Maastricht. At present the model is managed by SEURECO (a spin- off from the ERASME team). It is not owned by the European Commission, but regularly procured by DG for Research and Innovation (DG R&I).

This section describes these three models, their main characteristics, their treatment of R&I and R&I policies, evaluates their strengths and limitations to do so and suggests how missing features could be included.

Macroeconomic models designed for policy evaluation are continuously updated, as new data become available, better estimates of the parameters are provided and improved theoretical foundations are introduced. In this respect this section presents a snapshot of the current version in use of the three models.

90 A comparison of QUEST III with R&D, RHOMOLO and NEMESIS that looks especially at the R&D and innovation features of such models is also available in Akcigit et al. (2020). The authors discuss also some applications of the models among which the impact assessment of Horizon Europe carried out by the European Commission in 2008.

3.1. The QUEST III model

3.1.1. Main features

QUEST III is a **New-Keynesian *dynamic stochastic general equilibrium model* (DSGE)**. DSGE models have a long tradition in macroeconomics as a useful instrument to study the long-, medium- and short-term performance of modern economies, as well as to evaluate the effects of macroeconomic policies in these dimensions. The use of dynamic general equilibrium models to study the long-term behaviour of modern economies and to evaluate the effects of macroeconomic policies can be traced back to the fifties and sixties, with the development of modern growth theory, inspired by the seminal work of Ramsey (1928) and initially developed by Solow (1956, 1957), among many others. Innovation in general equilibrium models was first introduced by Romer (1986, 1990), Aghion and Howitt (1992) and Grossman and Helpman (1991), and extended later by many others to produce a framework of critical importance for the study of innovation and innovation policy. The use of dynamic general equilibrium models to the analysis of business cycles fluctuations was pioneered by Kydland and Prescott (1982) influential work, giving rise to a powerful methodology used to relate models with the data, to then test the accuracy of model predictions with the behaviour of macroeconomic aggregates at different frequencies. Inspired by this methodology, a huge effort has been done during the past four decades by the so-called New Keynesians, Clarida et al (1999) and Woodford (2011), among others, to both render the DSGE model close to the behaviour of most aggregate observables and give a critical role to the working of monetary authorities. The New Keynesian approach has been adopted by monetary authorities and finance ministries of developed and developing countries to discuss the state of the economy and to evaluate the working of macroeconomic policy.

There exist **different versions** of the QUEST III model, each of which with a focus on specific sectors, countries and policy areas. The variant discussed here is the one that enriches the **QUEST III** model described and estimated in Ratto et al. (2009) by explicitly **incorporating an R&D sector and a semi-endogenous growth mechanism** *à la* Jones (1995), adapting the Romer (1990) model with expanding varieties. Roeger et al. (2008) and Varga and in't Veld (2011) provide details of the QUEST model.

In QUEST III, consistently with the **standard DSGE modelling approach**, equilibrium conditions for the main macroeconomic variables are derived from the optimising behaviour of agents, given technological, institutional and budgetary constraints. The model includes standard features useful for capturing data, including habit persistence, variable capacity utilisation, real frictions, such as imperfectly competitive markets, labour and investment adjustment costs, variable and nominal frictions on wages and prices. The model economy is populated by households, final and intermediate good producers, research labs, technology adopters, a fiscal authority and a central bank.

In the final good sector, **monopolistically competitive producers** produce horizontally differentiated goods using a composite of intermediate goods and three types of labour inputs of different skill levels. In the **intermediate good sector**, monopolistically competitive firms produce intermediate goods using capital, rented from households, and the designs of adopted technologies licensed from households. The process for creating new technologies takes place in **research**

institutes that use high-skilled labour inputs along with the existing stock of domestic and foreign ideas. Technology adopters employ skilled labour to convert non-adopted technologies into technologies that can be used for intermediate production. There are two types of **households**: the non-liquidity constrained, and the liquidity constrained. The non-liquidity constrained households have full access to financial and capital markets, buy the patents of adopted technologies and licence them to producers operating in the intermediate good sector. As in Galí et al. (2004), the liquidity constrained households do not have access to financial and capital markets, therefore they consume all their after-tax labour income in each period. The **fiscal authority** faces a budget constraint, collects social security contributions, taxes on labour income, on consumption and capital income, net of tax credits and tax allowances, pays transfers and unemployment benefits to households and subsidies that incentivize R&D, and spends on goods, services and public capital. The behaviour of the **central bank** is described by an interest rate rule of the Taylor type.

QUEST III is a multi-countrymodel calibrated for **EU countries** and the **rest of the world**. Individual country blocks are interdependent with one another through international trade, financial flows and knowledge spillovers. Euro area countries have in common the monetary authority.

3.1.2. Innovation and creation of new technological knowledge

In QUEST III innovation and the creation of new technologies take place in the **R&D sector,** which is operated by research institutes, according to a semi-endogenous growth mechanism in the spirit of Jones (1995). This implies that in the long run the growth rate of output per capita depends on population growth and on technological parameters.

The production of new ideas depends on the number of high skilled workers employed in the R&D sector, L_{RD}, and on the domestic and the international aggregate stocks of knowledge (labelled as Z and Z^* respectively), measured as the existing stock of patents. New ideas are accumulated and produced according to the following **knowledge production function**:

(1) $$Z_{t+1} = v_t L_{RD,t} + (1 - \delta_Z) Z_t,$$

(2) $$v_t = v Z_t^{*\omega} Z_t^{\phi} L_{RD,t}^{\rho_Z - 1},$$

where Z_t is the stock of knowledge available at the beginning of period t, $\nu > 0$ denotes total productivity of the R&D process, ω and ϕ capture the international and the domestic spillover effects of existing knowledge (i.e. the *standing on the shoulders of giants effect*), while $\rho_Z \in (0,1)$ measures the contribution of high-skilled labour inputs to the R&D activity. In each country block the aggregate stock of international knowledge is the weighted average of the trading partners stock of knowledge, where weights depend on bilateral trade flows. The decreasing returns of research activity is meant to represent congestion externalities (i.e. the *stepping on toes effect*) and is also related to the risk of duplication of new ideas. Ideas become obsolete at rate $\delta_Z \in (0,1)$. The two elasticities ω and ϕ are positive and such that their sum is less than one so as to account for potential diminishing returns to scale with respect to the existing stock of ideas.[91] The obsolescence rate captures the concept referring to the loss in value of existing technologies as a result of the emergence of new technologies. To benefit from international spillovers domestic firms must develop their own absorptive capacity which depends on the accumulation of their own knowledge.

The model presents a final good sector, an intermediate good sector, an R&D sector and a technological adoption sector, but it does not disaggregate business economies by industries and services. In each sector of QUEST III firms share the same technology and have the same size. In the two monopolistically competitive sectors firm are different in the sense that they produce different varieties of the same good according to the Dixit-Stiglitz setup. The number of intermediate-good firms that employ adopted technologies to produce marketable goods is endogenous. Firm entry is related to the expansion of adopted technologies, while exit is exogenous and depends on the obsolescence rate.

QUEST III distinguishes between **basic (innovation) and applied (adoption) research.** Innovation is **incremental** and there's **only product innovation.** The development of general-purpose technologies is not modelled. However, different types of innovations can be mapped by changing exogenously the productivity of the three sectors using existing estimates on the relevant elasticities.[92] Complementarities with ICT, the effects of automation and robotization can be introduced exogenously through shocks affecting the total factor efficiency of knowledge production.

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91 This assumption prevents the model from delivering endogenous growth. The growth rate of innovation does not depend on the scale of production.

92 In a "green" variant of the model there is a distinction between clean and dirty technologies. See Conte et al. (2011).

3.1.3. Diffusion of new technologies

In the latest version of QUEST III, **the diffusion process of new ideas** is modelled **endogenously** following Comin and Gertler (2006) and Anzoategui et al. (2016).[93] Adopters convert non-adopted technologies (or ideas) into ones that can be used by the intermediate goods producers. The stock of adopted technologies, A,[94] evolves accordingly to the following law of motion:

(3) $$A_{t+1} = (1 - \delta_Z)[\lambda_t(Z_t - A_t) + A_t],$$

where $Z_t - A_t$ indicates the stock of unadopted technologies and λ_t measures the pace of adoption (i.e. the probability that a typical adopter succeeds in converting an idea into a usable technology) which, in turn, depends on the amount of high-skilled labour employed $L_{ad,t}$:

(4) $$\lambda_t = \bar{\lambda}(Z_t L_{ad,t})^{\rho_\lambda},$$

where $\bar{\lambda}$ measures the productivity of the adoption process and $\rho_\lambda \in (0,1)$. According to (4), then, there is a positive spillover effect from the total stock of existing ideas Z_t, so capturing the idea that economies that are on the frontier of innovation tend to be more effective in the conversion of new inventions in usable technologies. The inverse of λ measures the diffusion lag in the adoption process. As mentioned in Section 3.1.2, QUEST III can distinguish between scientific knowledge (related to basic research and captured by Z) and technological knowledge (related to applied research and captured by A).

Non-liquidity constrained households own the patents of adopted technologies and license them to intermediate-good procedures. The number of intermediate-good producers expands with that of the adopted technologies.

Complementarities with ICT can be introduced exogenously through changes in the productivity of the adoption process. The model does not differentiate between adoption and adaptation of technologies, and does not explicitly model the diffusion of new paradigms or of general-purpose technologies.

Technology transfers or exchanging patents and knowhow, and imitation phenomena are not modelled explicitly, however they can be mapped indirectly through the international and domestic knowledge spillovers. In each country the

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93 Comin and Gertler (2006) suggest a methodology to decompose aggregate macro series into short-, medium- and long-term frequencies, and extend the DSGE model to replicate all these dimensions of the data. This feature has been introduced in QUEST following a project financed by the Directorate General for Research and Innovation of the European Commission in the context of the Horizon 2020 Policy Support Facility. For details, see https://rio.jrc.ec.europa.eu/library/research-innovation-and-economic-growth-technology-diffusion. The FRAME program is also inspired in the Comin and Gertler (2006) approach.

94 The stock of adopted technologies determines the number of intermediate good varieties to be used in the final-good sector. See Roeger et al. (2008).

creation of new ideas depends on the trade-weighted knowledge stock of all trading partners, thus innovations propagate across countries through international trade.

3.1.4. Enablers for R&I creation, adoption and diffusion

In QUEST III, **the size of national and international markets** determines the market size for innovative goods but cannot permanently affect the rate of technological progress. An expansion of the final good sector, triggered by an expansion of domestic and/or foreign demand, gives rise to an increase in the demand for intermediate goods, so temporarily stimulating the entry of new firms and favouring adoption and R&D activity.[95] The size of the market for innovation also depends on the degree **of openness of an economy**. In QUEST III there are barriers to trade in the form of import adjustment costs and the structure of preferences is such that there is a limit to the diversification in international trade. Changes in these features have an impact on innovation and adoption. In addition, the intensity of the **international spillovers** of knowledge is related to the trade-weighted stock of knowledge of all trading partners.

Product market reforms that enhance **competition in goods markets** may have different effects on R&D activity. Markets are monopolistically competitive as in Dixit-Stiglitz, therefore markups do not depend on the number of firms but may be changed in the simulation scenarios to represent pro-competitive effects of shocks or policies. More competition in the final good sector tends to increase R&D intensity. By expanding the size of this sector, more competition generates an increase in the demand for intermediate goods that stimulates entry of new firms and increases R&D (positive market size effect). However, reform policies fostering competition in the intermediate good sector deters firm entry, thus slowing down technological progress and adoption.[96] Besides the existence of positive spillovers (representing the non-appropriable component of the R&D activity), knowledge creation and adoption are modelled as markets where labs, adopters and firms sell and buy technologies, similarly to any other commodity of the economy.

Intellectual property rights are introduced into the model via a patent system. Firms operating in the intermediate good sector acquire licences of existing patents when entering the market, that is why pro-competitive policies, by reducing markups in this sector, may have a detrimental impact on innovation and adoption, and so growth may temporarily slow down.

The model presents **different types of labour inputs (low, medium and high skilled)**. High skilled workers (scientists and engineers) are employed in the final good sector, in the R&D sector and in the adoption process. Therefore, allocating more high-skilled workers to R&D and adoption processes decreases the share of high-skilled available for final goods production. This explores the potential crowding out effects between production and R&D activities. The supply of labour is

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[95] The semi-endogenous framework used in QUEST III delivers only a scale effect *in levels*, implying that the stock of knowledge/ideas is increasing in the size of the market, while the rate of innovation and adoption can only be temporarily affected during the adjustment process towards the balanced growth path.

[96] See Roeger et al. (2008).

endogenous, therefore changes in the labour market conditions may induce skilled workers to work more and/or ask for a higher skill premium. However, in the version of QUEST currently in use, human capital formation is not endogenous. Nevertheless, it is possible to exogenously change the skill composition of the labour force and simulate the effects of policy interventions aimed at improving the quality of education, also accounting for the costs that these interventions may entail. For instance, in Varga and in't Veld (2011) the evolution over time of skill-specific human capital depends on the number of school years and on the participation in training activities. The skill upgrading is modelled as a slow change in the skill composition of the labour force, as education policies only affect the youngest cohorts before their passing through the labour market.

In QUEST III with R&D there is **no financial intermediation**, hence it is not possible to differentiate between internal and external financing of the R&D activity. However, there are **exogenous risk premia** on intangible and tangible assets that may reflect the existence of financial frictions (e.g. collateral constraints, asymmetric information) and of underdeveloped venture capital markets. By changing the risk premium on intangible assets, QUEST III can simulate the effects of policy interventions aimed at facilitating access to credit for firms transforming new ideas into marketable products and services. A streamlined version of QUEST with no R&D has been extended to include financial frictions in Kollmann et al. (2014).

3.1.5. R&I Policy

In QUEST R&I activities are carried out in the private sector. There is **no public R&D** and the public sector has no direct role in the diffusion of knowledge. However, the public sector has a rich set of tools and channels through which innovation and adoption can be promoted. The existence of knowledge spillovers justifies government interventions aimed at promoting R&I. Moreover, QUEST displays several sources of inefficiencies and market distortions (such as imperfect competition, overhead labour costs, adjustment costs etc…) typical of New Keynesian DSGE models, that provide a **rationale for public intervention**.

The government can grant **subsidies on the wage of skilled workers to the R&D and the adoption sectors**. Given the multi-country structure of the model, it is possible to distinguish between interventions at different levels (supranational and national). Specific **regional** policy measures can be simulated by accounting for the relative size of the regions involved. The productivity of firms is positively affected by the stock of public capital which is provided by the government through **public procurement**. Through this channel the model can simulate the effects of several public interventions, such as those related to transport, energy, telecommunication and ICT infrastructure. By increasing factor productivity public procurement stimulates the demand for intermediate goods and, therefore, technology adoption and R&D activities. In addition, government investments have a transitory positive demand-side effect during the period of implementation, further stimulating adoption and R&D. The government can expand the production possibilities of the economy through **reforms that increase productivity**. As an example, see the simulation exercise of Lorenzani and Varga (2014), who study the economic impact of digital structural reforms in the QUEST III model.

Governments can provide **tax credits on the income from intangible capital** (patents on adopted technology) in favour of non-liquidity constrained households.

Through this channel the cost paid by intermediate goods producing firms for using blueprints decreases, so raising the demand for new technologies and stimulating the entry of new firms. By this channel the speed of technology diffusion is enhanced, and knowledge creation is incentivised.

Public funding of R&I activities can be simulated by changing the exogenous risk premium on intangible assets. In this way it is possible to evaluate the effects of **public loans and public venture capital**. See for instance Roeger et al. (2008) and D'Auria et al. (2009).

In QUEST there are **several tax instruments,** such as taxes on consumption, labour and capital income. The model also includes social security contribution rates, differentiating the share borne by firms from that paid by workers. In addition, there are tax credits on tangible and intangible capital income, depreciation allowances and unemployment benefits. Through these policies the government can also affect innovation activities. **Interventions alleviating the administrative burden and simplifying regulation** can be simulated by reducing the overhead labour component in the final good sector. Overhead labour, in fact, includes the fraction of time that workers spend on administrative tasks and bureaucracy. Another policy instrument is represented by the fixed entry cost faced by new entrants in the intermediate-goods sector. Through this channel the model can simulate the potential effects of changes in **entry regulation** on R&I activities. [97]

Product market reforms that enhance competition in goods markets and that change the patent policy can be simulated as shocks that decrease the markup of prices over marginal costs. Public procurement related to **missions and sector-specific industrial policies** can be simulated indirectly by changing the aggregate policy variables of the model in proportion with size of the sectors involved. Several **environmental policy tools** are available in the "green" version of QUEST described in Conte et al. (2011). In the main version of the model it is, however, possible to simulate the macroeconomic effects of an increase of the excise taxes on fuel by properly changing the consumption tax rate.

The public financing problem is addressed in terms of **budget spent, cost of borrowing, and effects on public debt**. General equilibrium effects also allow to keep track of crowding-out and crowding-in phenomena, to directly evaluate the effects of policies on R&I activities and observe the complex interactions between short-run stabilization policies (monetary policy, automatic stabilizers, fiscal rules) and the long-run performances of the economy. Several simulation scenarios can be constructed under different hypotheses regarding **monetary** and **fiscal** policies.

Finally, the multi-country structure allows to differentiate between national and **supranational policies**, and to account for policy interdependence and trade barriers.

[97] See for instance the contribution of Benedetti-Fasil et. al (2020).

3.1.6. Dimensions of macroeconomic impact of R&I

By virtue of its general equilibrium structure with the QUEST III model it is possible to evaluate the potential effects of innovation on **GDP, employment and productivity**. Country-blocks are open to international trade and technological advancements improve their external **competitiveness**. The differentiation among different categories of workers by skill allows to study the impact of innovation on **inequalities**. Labour supply is endogenous, and households offer low-, medium- and high-skilled labour services. It is then possible to study income inequalities across different categories of workers and to measure skill premia as in Roeger et al. (2019). Creation of new ideas requires the employment of high-skilled workers, and more accumulated knowledge increases the productivity of high-skilled workers in the adoption sector. A large stock of adopted technologies, in turn, increases the productivity of the final good sector, but it does not alter the structural parameters of the labour aggregate (composed by low-skilled, medium-skilled and high-skilled labour inputs). Finally, in the model there is involuntary unemployment because of the market power of trade unions that charge a markup over the reservation wage of each category of workers.

The implications for the quality of the environment and environmental externalities are introduced in the "**green" version** of QUEST described in Conte et al. (2011). Non-economic effects, such as the implications of innovation on **health** are not observable.

3.1.7. Strengths and limitations

QUEST is a **dynamic general equilibrium model based on microfoundations**, where the behaviour of agents is the outcome of an intertemporal optimisation problem given technological, institutional and budgetary constraints. Since agents' decisions account for expectations about the future, anticipation effects of current and future policies are fully captured by the model. The model has a **well-defined welfare function**, which allows for performing welfare evaluation of policies in addition to the positive analysis of comprehensive reform packages.

The model embodies several imperfections and frictions in goods and labour markets that are useful to match data. QUEST III can provide **a direct link between concrete policy interventions and market outcomes, also in the area of R&I**. The explicit modelling of knowledge creation and of technology adoption can be used for policy analysis. The model, in fact, presents a rich set of mechanisms and parameters through which R&I policies can be simulated. The differentiation of workers by skill allows to study the effects of education policies and their impact on technological progress and growth. QUEST's general equilibrium structure allows to account for different transmission channels of innovation policies and to evaluate their impact on the main macroeconomic aggregates. For costly policies budgetary and financing issues are fully addressed. Due to its multi-country setup there are interlinkages across countries via trade, financial flows and knowledge spillovers, it is possible to differentiate between supranational and national innovation policies and there is policy interdependence. Finally, by integrating New Keynesian elements, QUEST III can be used to assess the short-run trade-offs of R&I policies and their interactions with fiscal and monetary policies.

Despite its sophisticated structure the current version of QUEST is not designed to factor in several important aspects related to R&I activities and policies.

The most important limitation of the present version of QUST III is the **absence of firm heterogeneity**. Firms operate under different market conditions, differ in their size and have access to different technologies. The gains from R&I policies cannot be evaluated properly without such distinctions. Similarly, firms may have limited access to credit, and this might be the case especially for small and new innovative firms. Accounting for **financial frictions** would further improve the ability of the model to evaluate the margins through which R&I policy may operate.[98]

A second limitation of QUEST is that the model does not allow to differentiate between public and private R&I and adoption activities. In the present version these activities are carried out **only by the private sector**. Therefore, it is not possible to distinguish the nature of public research conducted by public institutions from that conducted by private companies. In addition, complementarity and substitutability issues between public and private efforts in R&I activities cannot be addressed[99].

A third limitation is related to the fact that the **accumulation of human capital is not endogenous**. The introduction of endogenous skill accumulation may improve the ability of the model to simulate the effects of education policies on innovation activities and growth. Moreover, when R&D activities increase in QUEST there is a shortage of skilled workers in the final good sector, so restricting the expansionary effects of innovation policies.

A fourth limitation concerns the **absence of any environment-related dimensions** in the main version of the model. Given its multi-country and dynamic general equilibrium structure, QUEST III is well suited to incorporate aspects related to climate change and to assess the macroeconomic implications of climate actions (e.g. physical and transition risks).

Finally, there are some other limitations referring to the fact that in QUEST cyclical fluctuations emerge as a result of external shocks and waves of optimism and pessimism do not emerge endogenously. In QUEST there are **no** features related to **randomness** in the outcome of the R&I process, however the value of ideas and so the incentives to innovate depend on external shocks and on policy interventions. Imperfect and asymmetric information features may be introduced into QUEST by solving the model under different assumptions regarding the way in which agents formulate expectations or regarding the set of information their decisions are based on.

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[98] The modelling framework developed by Benedetti-Fasil et al. (2020) constitutes an effort in this direction.

[99] An extension of the model in this direction can be made along the lines of Akcigit et al. (2020).

3.2. The RHOMOLO model

3.2.1. Main features

RHOMOLO is a **spatial computable general equilibrium (SCGE) model**. A detailed description of RHOMOLO V3 is available in Lecca et al. (2018).

CGE models have a long tradition with roots in the input-output models *à la* Leontief, but where the interactions among sectors and factor inputs, and so output and demand depend on prices. Since Johansen (1960)'s Norway model, several computable general equilibrium models have been developed as a tool for policy analysis in various domains that range from fiscal policies, trade liberalization and development and regional market integration to climate change[100].

The structure of RHOMOLO is based on a large system of **simultaneous equations with multiple interacting agents**. Consistently with the tradition of the computable general equilibrium (CGE) class of models, RHOMOLO is based in a framework à la Arrow-Debreu where agents' interactions (along supply and demand) are mediated by markets and prices. However, as most CGE models, RHOMOLO has some features that do not strictly adhere to the theoretical general equilibrium paradigm. The model, in fact, allows for **imperfectly competitive product markets** and **labour market imperfections** resulting in unemployment.

Individual behaviour is based on (static) optimisation, given technological, institutional and budgetary constraints. Expectations are assumed to be backward looking, although it is possible to switch towards a forward-looking approach.

Policy interventions, reforms and other changes in external factors are introduced as **shocks** to the model that is solved sequentially period after period with stock variables being upgraded at the beginning of each period according to a recursive-dynamic modelling strategy.

RHOMOLO has a **regional structure** covering 268 block-economies of which 267 correspond to the EU NUTS2 regions and 1 region corresponds to the rest of the world. In each region the business activity is **disaggregated** into 10 NACE rev. 2 economic sectors (also called **industries**). A subset of these sectors is characterised by a monopolistically-competitive market structure *à la* Dixit-Stiglitz in which identical firms produce horizontally differentiated varieties. In each of these sectors there is free entry, so the number of firms is endogenous and is pinned down by a zero-profit equilibrium condition (i.e. break-even condition).[101] The other sectors are instead characterized by perfect competition. All sectors are interlinked through **input-output relations**. In each sector firms use capital, labour and intermediate inputs from other sectors.

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[100] See e.g. Shoven and Whalley (1984) Robinson and Thierfelder (2002) and Bouët (2008) for surveys on CGE models and Eliott et al. (2010) for an example of CGE models integrating environmental features.

[101] The imperfectly competitive sectors of RHOMOLO are 'Mining and Utilities', 'Manufacturing', 'Construction' 'Retail and Transportation', 'Information and Communication', 'Financial, Insurance and Real Estate Activities' and 'Professional, Scientific and Technical Activities'.

In the baseline version of the model **markups** depend on the elasticity of substitution between varieties of the same good. However, alternative markup definitions of the oligopolistic type can be assumed (such as Bertrand and Cournot solutions). In such a way markups become endogenous and depend on the firm market share.

A region may sell goods and services to all the other regions at prices that depend on the local market shares. Each region is populated by a representative **household** consuming all varieties of final goods available in the economy. Households derive their income from labour (in the form of wages net of tax payments), government transfers and the ownership of physical capital (in the form of rents net of taxes) and of other financial assets. In each region a fraction of income is saved. To account for capital flows across regions, RHOMOLO separates investment from saving decisions. Current investments depend on the distance between the desired stock of capital and its current available stock consistently with an accelerator model *à la* Jorgenson and Stephenson (1969).

Labour services are differentiated by **skill levels in low, medium and high**. The government collects taxes from labour and capital income and from production activities. **Fiscal** revenues are used to finance transfers to the various agents in the economy and current spending on goods, services and capital.

RHOMOLO explicitly models **spatial linkages among regions**. Regions are connected through trade flows of goods and services, labour and capital mobility. Spatial frictions, such as transportation and migration costs, limit and make costly trade and factor mobility. Transport costs are specific to trading partners and to sectors. RHOMOLO includes backward and forward linkages between firms and workers/consumers. Regional goods are produced by combing labour and capital with bundles of domestic and imported intermediate goods. This technology gives rise to **vertical linkages between firms**. As a result of these features, the model can account for the existence of **agglomeration** and **dispersion** forces, and for the emergence of complex **core-periphery** patterns in the distribution of economic activity across regions.

3.2.2. Innovation and creation of new technological knowledge

In RHOMOLO V3 R&I activities occur in a separate sector, which is a broad sector "Professional, Scientific and Technical Activities, Administrative and Support Service Activities" (NACE REV 2 M-N sectors) characterized by imperfect competition. In this version of the model there is not any specific mechanism by which new knowledge is created (such as e.g. an endogenous growth mechanism). Yet, in the policy simulation scenarios **innovation activities can affect the economy through two main channels**: the productivity channel giving rise to a permanent structural effect and the demand channel, giving rise to a temporary effect.

Innovation has positive effects on total factor productivity (**productivity channel**). The idea behind this mechanism is that R&I investments give rise to knowledge accumulation that, in turn, positively affects productivity of the sectors and regions involved. Innovation is translated into the model as an increase in total factor productivity of the sectors involved using existing estimates on elasticities that, in turn, depend on the R&D intensity of the regions and on R&D value added. Elasticities are region- and sector-specific. **A higher R&D intensity of a region is**

associated with a higher elasticity of total factor productivity to R&D efforts. The rationale for this assumption that firms located in regions already characterized by high R&D spending are more prone to generate value from innovation activities. [102] This feature is meant to capture the existence of knowledge spillovers. The R&D spillover elasticities are taken from the estimates by Kancs and Siliverstovs (2016).

Through the productivity channel RHOMOLO can simulate indirectly **a vast range of policies** in support of R&D activities and the effects of **different types of R&I** (e.g. general-purpose technologies). The regional and sectoral disaggregation of the model allows to map the effects of innovation activities and policies on specific sectors and areas, and to evaluate the reallocation of factor inputs across sectors and regions that may follow. Increases in total factor productivity reduce production costs and make firms more competitive, so expanding production capacity and trade, and attracting more labour and capital. However, in the absence of an explicit modelling of a sector where new ideas are created RHOMOLO can hardly capture other aspects of the R&I process. Aspects related to path dependency are not modelled. No distinction can be made between product and process innovation, and between basic and applied research. TFP is a combination of both, and the same aggregate technology may emerge from a model of product or process innovation.

The demand channel refers to direct and temporary effects that innovation activities may have on aggregate demand. R&I spending is introduced as private investments, so that a higher expenditure gives rise to a higher demand for capital goods In particular, the rise of public spending in support of innovation induces an increase in private R&I investments, diverting resources from public investments and reducing the public demand for capital goods. As a result of this policy there will be a decline of public procurement and an increase in private R&I investments. The net effect on aggregate demand and on the level of economic activity deriving from this channel will depend on the input composition and on the import penetration of the sectors involved.

In the current version of RHOMOLO in each sector and region **firms share the same technology and have the same size**. In imperfectly competitive sectors firms produce different varieties of the same good according to the Dixit-Stiglitz logic of horizontal differentiation. However, the economic activity of each region-block is disaggregated into 10 NACE rev. 2 economic sectors a subset of which are treated as imperfectly competitive sectors. The calibration of the structural parameters reflects **region and sector heterogeneity**.

3.2.3. Diffusion of new technologies

In RHOMOLO V3 the **spatial diffusion** of innovation and the adoption lags inherent to the diffusion of new technologies and ideas is **simulated** indirectly by constructing specific simulation scenarios using the productivity channel and exploiting the regional and sectoral disaggregation of the model.

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[102] This characteristic of RHOMOLO is consistent with the logic of endogenous growth models without scale effects.

Technology transfers, possibilities or exchanging patents and knowhow, imitation phenomena and spatial knowledge spillovers (in neighbouring regions for instance) can be mapped through exogenous changes in the total factor productivity involving specific regions and sectors. The granularity of the model confers extreme flexibility in the design of these policy experiments. Regions are interlinked via trade, capital and labour flows, therefore R&I policies, fiscal policy interventions and structural reforms occurring in one region-block affect all the other regions via these channels (policy interdependence).

International technology spillovers and international diffusion are not explicitly modelled in the current version of RHOMOLO.

3.2.4. Enablers for R&I creation, adoption and diffusion

In RHOMOLO V3 R&I the effects of the incentives to the creation and adoption of new ideas can be simulated by constructing specific simulation scenarios based on existing estimates of the relevant elasticities relating to the intensity of competition, product market regulation, trade barriers and market size to R&I spending and to total factor productivity.

There are barriers to trade in the form of bilateral transportation costs of the iceberg type[103]. A subset of sectors is characterized by imperfect competition in which alternative markup definitions can be used (according to Bertrand and Cournot pricing assumptions or monopolistic competition). These features allow the construction of comprehensive reform scenarios in which the production capacity of regions and their size may be affected directly and indirectly through the dynamic effects that reforms may have on R&I.

In general, the granularity of the model allows for the simulation of specific pro-competitive policies and of changes in the entry conditions involving specific sectors and regions. In addition, the available pricing options permit the analysis of the effects of firm entry and of market size on markups. The strength of intellectual property rights may reflect on the size of the markups.

RHOMOLO considers three **different labour inputs, low, medium and high, corresponding to different skill or education level**. Labour supply is fixed and human capital formation is not endogenous;[104] however, the human capital of a region can change through migration of workers from other regions (e.g. Brandsma et al. 2014). In addition, the skill level of the labour force can be exogenously increased through education policies. The model can simulate interventions aimed at increasing the quality of education and account for the additional costs that these measures may entail for the public sector. The changes in the skill composition of the workforce is anchored to the number of school years as done in Varga and in't

103 See Persyn et al. (2019) for details on the estimation of the iceberg-cost matrix.

104 Only recently a new labour market setting has been introduced in which the labour supply can change as a result of individual participation decisions, both at the intensive and extensive margins. See Christensen and Persyn (2020).

Veld (2011) for the QUEST model. Human capital projects increase the productivity of labour differentiated by skill level and so the returns on investment. Through this channel it is therefore possible to increase the production capacity of specific regions.

The financing problem of the R&D activity is not directly addressed. However, RHOMOLO models explicitly a wide imperfectly competitive sector including **financial services**, along with insurance and real estate activities (NACE REV 2 K-L sectors). These services are used by firms of the other sectors as production inputs. RHOMOLO can thus simulate policies that facilitate the access to credit and/or promote venture capital. Given the input-output structure of the economy any policy that expands the financial sector and renders easier the access to financial services may have expansionary effects on all the other sectors of the economy. It is also possible to change the **user cost of capital** through an exogenous risk premium and mimic the macroeconomic effects of financial frictions, such as collateral constraints, asymmetric information and underdeveloped venture capital markets.

3.2.5. R&I policy

In RHOMOLO **policy shocks** in support of R&I expenditure (subsidies, tax incentives or direct pubic spending on R&I) are introduced as a reduction **in the user cost of capital** which in turn gives rise to an increase in R&I investments in the wide macro-sector in which innovation activities take place. The increase in investments generates the demand channel. The impact of R&I expenditure on total factor productivity is captured by a set of **regional spillover elasticities**. This is the productivity channel. By changing the user cost of capital, it is also possible to simulate public funding interventions such as loans and public venture capital. For a recent ex ante assessment of the Horizon Europe 2021-2027 programme, see Christensen (2018) and Christensen et al. (2019).

The sectoral and the spatial disaggregation allows for the simulation of comprehensive industrial policy packages targeting specific sectors and geographic areas. The geographic granularity of the model allows for the simulation of policy interventions at different levels (EU funding, national and regional. Christensen (2018) uses RHOMOLO to assess ex ante the potential economic impact of Horizon Europe for the programming period 2021-2027 under three different scenarios, (i) continuation, where the new programme is designed along the lines of the previous one, (ii) centralisation, in which a major share of funds is centralised at the EU level, (iii) decentralisation, in which the programme is decentralised at national level.

The government consumes goods and services produced by all sectors of the economy. This implies that RHOMOLO can simulate the effects of changes in the composition of public spending. Moreover, the productivity of firms depends positively on the stock of public capital that is accumulated by the government. Public capital is not modelled as a pure public good, but is characterized by a certain degree of congestion, therefore an increase in production reduces the benefits of the existing public capital stock.

Through the **public capital channel** RHOMOLO can simulate the effects of several public interventions, such as those related to transport, energy, telecommunication and ICT infrastructure.[105] Higher government procurement, in turn, implies transitory positive demand-side effects during the period of implementation, further stimulating the level of economic activity. In addition, with the transport policy tool it is possible to study transport infrastructure investments in specific regions, as in Persyn et al. (2019).

Several sectors are characterized by the existence of fixed costs and by imperfect competition. Through these channels RHOMOLO can simulate **product market reforms**, such as those falling in the domain of regulation, administrative burden, patents and competition. Policy initiatives encouraging the entry of innovative firms can be simulated by fixed entry cost reductions.

Thanks to its spatial structure RHOMOLO can account for the effects of policy initiatives facilitating the completion of the EU market promoting **capital and labour mobility**. Mobility improves the allocation of factor inputs across European countries and favours the matching between skill demand and skill supply.[106]

The general equilibrium structure allows to address the **public financing problem** of any costly policy interventions and to account for potential crowding-out and crowding-in phenomena. This is particularly important for comparing alternative innovation policy options and computing the fiscal multipliers of public spending. Costly policies interventions, such as subsidies incentivising R&I activities, require additional revenues that must be collected through higher taxes (or by spending cuts on other items). Higher taxes, in turn, may affect consumption, investment, employment and production, resizing the effects of the initial policy interventions.

In its present version RHOMOLO does not distinguish between clean and dirty technologies and does not embody **climate** action instruments or Pigouvian taxes or subsidies. However, the model presents a broad sector including electricity, gas, steam and air conditioning supply, water supply, sewerage, waste management and remediation activities (NACE REV 2 B, D, E sectors). Any direct or indirect policy interventions falling in the domain of environmental sustainability can be translated into the model through this sector. For a simulation analysis of policies promoting the shift toward clean energy in RHOMOLO, see Di Comite et al. (2018). [107]

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[105] For an example of simulation of modernization of the existent transport network, see Di Comite et al. (2019).

[106] See e.g. Ciaian and Kancs (2015) for a simulation of the European Qualifications Framework initiative aiming at improving the recognition of skills and qualifications across EU countries.

[107] The input-output and regional data of RHOMOLO-MRIO can be used as a separate laboratory for policy analysis based on a Leontief model. In this respect, for a study of the impact of coal phase-out plans, see Mandras et al. (2019).

3.2.6. Dimensions of macroeconomic impact of R&I

The effects of R&I policies are assessed through the effects that higher R&I expenditure have on demand and productivity. With RHOMOLO it is possible to assess the potential effects of R&I on **GDP** and employment for each region-block. Technological progress is modelled as an **increase in total factor productivity** using existing estimates on elasticities. Therefore, changes in the innovation effort affect productivity by construction. Increases in total factor productivity lower unit costs and make firms more competitive. The productivity improvement, in turn, expands trade and production capacity of a region, and increases the remuneration of factor inputs, so attracting more capital and labour from other regions.

Labour dynamics depend on a wage setting mechanism according to which the bargaining power of workers depends on market conditions. A higher level of **unemployment** reduces the market power of wage setters. The representation of the labour markets is such that involuntary unemployment may emerge. However, the modelling of the labour markets is flexible and allows switching from a wage setting mechanism to a Phillips curve or to a competitive equilibrium with no involuntary unemployment. With the differentiation of workers by skill RHOMOLO allows studying the impact of technological progress and of innovation policies on **inequalities**. The effects of **skill biased technical changes** can be mapped by changing exogenously the skill composition of the labour demand in response to technological progress consistently with data. For a recent study with RHOMOLO on the regional socio-economic impact of the European R&I programme, see Christensen (2018).

The current version of the model does not account for environmental externalities and climate change effects. However, as discussed in Section 3.2.5, RHOMOLO can be used to simulate the economic impact of **energy and environmental policies**. Thanks to its granularity and flexibility RHOMOLO can be integrated with other models and be used in different areas related to sustainability.[108] Non-economic dimensions such as **health** effects of R&I are not considered.

3.2.7. Strengths and weaknesses

RHOMOLO is a spatial CGE model designed for the **EU regions**. All behavioural equations reflect the (static) optimising behaviour of agents that formulate their decisions given the budgetary, the technological and the institutional constraints of the economy. The **general equilibrium structure** of the model allows to fully capture direct and indirect effects of alternative R&I policy options on the main macroeconomic variables of each region-block. The economic activity of each region is disaggregated into sectors. All **sectors are interlinked** through input-output relations. With these features it is possible to simulate R&I policies that target specific sectors and assess the spillover effects on the rest of the economy.

The economy is composed by 268 blocks representing 267 EU NUTS2 regions and the rest of the world. With this **geographic disaggregation** the model can capture

[108] In this respect, see the discussion in Lavalle et al. (2017) which explores the potential integration of RHOMOLO with the territorial modelling platform LUISA.

country and region-specific aspects of the economies and to simulate policy interventions and exogenous shocks involving targeted areas.

Regions are interlinked through trade, labour and capital mobility. Thanks to this spatial dimension RHOMOLO can model geographical spillovers, migration flows and the emergence of core-periphery patterns and of cross-region inequalities. Moreover, due to its detailed spatial dimension the model can effectively address questions related to different levels of policy interventions (EU, national and regional) and to the geographic concentration of innovation policies.

Another important strength of RHOMOLO is its flexibility. The model has **a rich set of channels and parameters** through which it is possible to **design complex scenarios** and **simulate innovation policy interventions.** However, RHOMOLO is a deterministic model able to provide only point estimates of the effects of exogenous shocks to the economy. Therefore, risk and uncertainty cannot be modelled explicitly. However, ***ad hoc* sensitivity analyses** are usually carried out **to account for uncertainty** related to the size of the parameters, and different policy scenarios are constructed to account for policy uncertainty.

Agents take their decisions by solving static optimisation problem. The wage setting process is based on a backward-looking mechanism, so that wage decisions depend on the lagged wage value. Labour migration decisions are modelled in a discrete-choice framework and are also based on backward-looking expectations. Waves of optimism or pessimism of agents cannot be simulated.

The current version of RHOMOLO does not model R&I activities as a separate sector of the economy, where innovations are created. **The effects of R&I policies are assessed through the effects that higher R&I expenditure have on productivity and demand**. Assessing the impacts of R&I in RHOMOLO consists of three main steps. The first step regards the quantification of the policy changes that are usually related to the amount of resources at disposal for each initiative. The second step consists of the econometric estimation of the elasticities that relate innovation policies to productivity of specific regions and sectors targeted by the interventions. Elasticities may also be taken from previous literature. In the third step the estimated policy impact on productivity is used as input in RHOMOLO to construct the simulation scenario and to evaluate the effects on regional macroeconomic variables such as GDP, employment, consumption, investments, inequalities, trade etc…

In some simulations, the direct effects of policies, such as those favouring venture capital or facilitating access to credit or consisting of public funding of private R&D, are modelled as reductions of the risk premia on capital. As QUEST III, the current version of RHOMOLO does not feature endogenous financial frictions. In other simulations, such as those concerning the quality of education, training and human capital, the direct effects of policy measures are introduced as exogenous changes in the skill composition of the labour force of the regions involved. Other interventions, such as those encouraging the entry of innovative firms, may be mapped through changes in the fixed cost. Also, in these cases the simulation of the policy requires a preventive empirical assessment of the link between the policy intervention and the model variables to be used in the simulation.

This simulation strategy confers extreme flexibility in the design of the policy scenarios and of reforms in the R&D system but requires data that are not always available at regional level. Therefore, **the lack of data availability** for specific indicators and variables **at regional level** may represent an impediment for the effective design of some simulation experiments and for the translation of policies into model variables.

The introduction of an endogenous growth mechanism and of an explicit modelling of technology diffusion and adoption in RHOMOLO would also require data necessary for the estimation of the deep structural parameters at regional level. These data are not always available at regional level.

Other limitations of RHOMOLO can be addressed in future developments to improve its ability to simulate R&I policies. For instance, the structure of RHOMOLO is **well suited to incorporate aspects related to the environment and resource efficiency**, such as those falling in the domain of clean v. dirty energy, resource efficiency, renewables, waste prevention and management, eco-tourism, eco-innovation etc… Extensions of the model in this direction and/or integrations with other models could open up to the possibility of simulating more effectively several policy measures promoting **green growth**, **energy efficiency** and the transition towards a *circular economy*.

Finally, **the skill composition of the labour force could in principle be made endogenous** to improve the ability of the model to simulate the effects of education policies and technological progress.

3.3. The NEMESIS model

3.3.1. Main features

NEMESIS is a large-scale, partly estimated, partly calibrated, econometric model of the neo-Keynesian tradition with demand predominant in the short run and supply pulled by technological change predominant in the long run. NEMESIS distinguishes 27 European countries, 30 sectors covering the whole economy, and 27 commodities. The rest of the world areas are represented in less detail. For a detailed explanation of the NEMESIS model, see Boitier et al. (2015), SEURECO (2018) and Le Mouël (2019).

There are four main categories of agents in the model: firms (financial and non-financial corporations), households, general government and the rest of the world.

The main **behavioural equations** (consumption by households, factor demand by firms, wage and price formation, imports and exports) are subject to **reaction delays**, reflecting the existence of adjustment costs and of adaptive expectations. Therefore, the economy takes some time to reach its long-run equilibrium where factors of production and consumption goods are at their desired level, while in the short run, exogenous shocks lead to cyclical price and quantity variations.

On the **supply side** in each sector firms use variable and quasi-fixed production inputs that are combined in a multilevel nested constant elasticity of substitution **(CES) production function**. The variable inputs are energy, materials, high skilled labour and low skilled labour, while the quasi-fixed inputs are physical capital and innovation services (i.e. state variables that in the current period depend on past investment decisions of the firm).[109] Innovation services enter the first level of the nested CES production function and affect directly the productivity of "ordinary" factor inputs (labour, physical capital, energy and material). The typical firm of each sector is a short-run cost minimizer with respect to the variable inputs (energy, intermediate inputs and the two types of labour) and an intertemporal value optimizer with respect to quasi-fixed inputs (capital stock and innovation services). The quasi-fixed inputs follow an error-correction model to reflect the existence of adjustment costs and to reproduce the gradual adjustment towards the long-run equilibrium.

Technical change is endogenized via investments in three categories of intangibles: R&D, ICT and other intangibles (OI) (including training and software). Both process and product innovations are jointly determined by the same investment effort. Services produced by the stock of knowledge intervene at the first level of the nested CES production function and reduce the cost of variable inputs (where the impact of innovations on production is Hicks-neutral). In addition, innovation services increase the quality of the goods produced. Innovations can then simultaneously lower the average cost of production and shift out the consumer's demand curve.

The **sectors** of the model are **interlinked** through two main channels: (i) the exchange of intermediate goods and services, that is also related to demand flows of energy, investment goods and materials; and (ii) spillovers that can occur through knowledge spillovers and through the diffusion of enabling technologies, such as ICT, that enlarge the technological opportunities of all sectors.

The price setting reflects a monopolistic competitive market structure with constant price markups specific to each sector.

Labour demand is determined by (static) firms' optimising behaviour, while wage dynamics evolve consistently with a wage bargaining process following an augmented wage Phillips curve.[110] As a result, real wages change in response to productivity shocks, and to changes in the unemployment rate evolution and in the wages outside the sector. The excess of labour demand over supply can create inflationary pressures through the augmented price Phillips curve channel. **The structure of the labour force**, in turn, depends the education level and the participation rate by qualification. Labour is mobile between sectors, but there are adjustment delays.

On the **demand side** aggregate consumption depends mainly on disposable income, wealth and on the demographic structure of the economy. Consumption is also a function of interest rates, price dynamics and unemployment rate. This last variable is taken as a proxy for uncertainty. Disposable income comes from wages, revenues from capital as well as transfers less taxes. Savings are given by the difference between real disposable income and consumption.

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[109] At each level of the nested CES production function there are compound inputs resulting from the use of variable and quasi-fixed inputs.

[110] The wage Phillips curve has coefficients that are country and labour-type specific, but not sector-specific.

Aggregate **consumption** is disaggregated into 27 sub-consumption components, which are grouped in durable and non-durable goods. The allocation of aggregate consumption in these components depends on price elasticities, degree of substitution, relative prices, total income and demographic changes, following an adaptation of the Almost Ideal Demand System proposed by Deaton and Muelbauer (1980).

Government spending is split into education, health, defence, infrastructures, investments and other items. The model features a rich set of taxes and subsidies such as taxes on production and imports, taxes on income and wealth, taxes on capital income, social security contributions, subsidies on production, investment grants, excises duties and other energy tax rates.

International trade occurs within Europe and with the rest of the world. Exports and imports depend on foreign relative to domestic prices and income. The stock of innovations is also included as a determinant of trade flows in order to capture the role of innovation on international competitiveness.[111]

3.3.2. Innovation and creation of new technological knowledge

In NEMESIS the modelling of R&I is to a certain extent **inspired by the endogenous growth theories**. Innovation takes place in each country/sector and stems from investments in **three types of innovation components: R&D, ICT and other intangibles (OI)**. This three-dimensional innovation process allows to account for a large variety of innovative activities and the related knowledge spillovers. While R&D activities mainly pertain to industrial sectors, the explicit modelling of intangible innovations allows to endogenize innovation in the services industry too.

When modelling R&I, NEMESIS uses as unit of analysis a country-sector pair. **Intangibles for each country/sector are built in four stages.** First, in a particular country/sector, for each of the three technological components (R&D, ICT and OI), a stock of intangible capital cumulates past investments conveniently depreciated at an exogenous rate. E.g., there is a stock of intangible R&D (ICT or OI) that cumulates past R&D (ICT or OI) investments in the country/sector. Second, the stock of technological knowledge for each of the three components, in each country/sector, builds on the stock of intangibles of the rest of countries/industries, benefiting from **knowledge spillovers** from the stock of intangibles of all other countries and industries. E.g., the stock of R&D knowledge in a particular country/sector depends on the stock of intangible R&D of this country/sector and benefits from spillovers from the stock of intangible R&D of all other countries and sectors. Specifically, stocks of intangibles from other sectors and other countries are aggregated by a weighting scheme that depends on patent citations.[112] These **sectoral interlinkages** reflect the existence of knowledge spillovers and of strategic complementarities between innovation services. Third, for each of the three components (R&D, ICT and OI), the corresponding stock of knowledge is used

[111] For further details, see Boitier et al. (2015) and documentation of the SIMPATIC project.

[112] The OECD concordance table is used to allocate citations across sectors and countries. See Johnson (2002).

to produce country/sector specific technological services. At this stage, knowledge externalities can be transformed into marketable innovations provided that there is a sufficient degree of **absorption capacity**. The absorption capacity is modelled as a linear function of the innovation investment intensity (relative to production). This feature allows to capture the idea of an increasing complexity of knowledge creation process and removes scale effects from the model. For each innovation component these knowledge functions are also country/sector specific. Finally, for each country/sector, R&D, ICT and OI services aggregate in country/sector specific technological services.

Technological services affect as a by-product the economic performance of firms through two channels. The first channel captures **process innovation**. Technological services enter the production function and **increase the productivity** of other production factors, resulting in a Hicks-neutral productivity improvement (TFP effect). The second channel reflects **product innovation**. In this case, innovation services **increase the quality of products** and shift out demand. In each sector the demand function for products reflects a taste for quality (quality effect).

While the model features **sector heterogeneity,** firms in each sector are homogenous. No distinction is made between incumbents and entrants or between large and small firms. Since in each sector firms invest in innovation there is **neither entry** of innovative firms, **nor exit** of obsolete products. As a result of obsolescence of technology, if the increase in research effort is not maintained in the long run the positive effects of innovations will fade away progressively.

Public investments in R&D are exogenously determined and their externalities are allocated to different sectors according to a grand-fathering distribution in proportion to the share of each sector in the overall business R&D expenditure. Public R&D enters the knowledge stock, but not the absorption capacity. Therefore, the impact that private and public R&D activities have on the production of innovations is asymmetric. In addition, public R&D takes a longer time than private R&D to enter the knowledge capital stock. This feature may allow to capture the fact that public investments in R&D may be more oriented to basic research.

3.3.3. Diffusion of new technologies

In NEMESIS, the **diffusion** process has a **serendipitous** nature, even though the propagation is mediated by the **absorption capacity**.

Diffusion of technologies is represented through interlinkages across all sectors and countries described in the previous section. For the three innovation components (R&D, ICT and OI), the knowledge variable is modelled as the sum of the intangible capital stocks in all countries and sectors, weighted by coefficients of diffusion reflecting the relative propensity of innovations to propagate and be adopted elsewhere.

The **diffusion coefficients** are calibrated using **patent citations between countries and sectors**. A system of matrices, based on the OECD concordance table (see Johnson, 2002), allocates patent citations by country and technology class.[113] In particular, the construction of R&D spillovers uses the concordance between patent classes and the sectors that produce the technology covered by patents (Industry of Manufacture) to weigh the patent citations. The other two technology indicators (ICT and OI) use the concordance between patent classes and the sectors that use technology (Sector of Use) to weigh patent citations. The spillovers related to R&D reflect pure knowledge externalities between sectors as Industry of Manufacture. The spillovers related to ICT and OI refer to network externalities and the diffusion of organizational innovations. Innovations propagate across countries through the same channels.

The model does not differentiate between adoption and adaptation of technologies, while it can account indirectly for the diffusion of new paradigms or of **general-purpose technologies**.

3.3.4. Enablers for R&I creation, adoption and diffusion

There is an optimal level of investments in R&D and in the other two intangibles, ICT and OI, which is given by the equality at the margin of the user cost and the marginal benefit from investments in innovation in terms of cost reduction and sales expansion. Innovation occurs in house. **Investments depend on the market conditions faced by firms, on their available technology and on the tax-subsidy mix they are subject to.** The optimal demand for innovation investments is a positive function of expected demand (or output) and a negative function of the ratio between the user cost and the production price. Therefore, all policy measures, reforms and shocks that modify the user costs or benefits change the innovation investment decisions of firms. **The endogeneity of the innovation investment decisions** implies that an expansion of domestic and/or foreign demand may incentivize investments in R&D, ICT and OI. Changes in the fixed costs faced by firms may free up resources to be used in innovation activities. The user cost can be lowered by giving firms R&D tax incentives.

The intensity of the three different innovation components increases with the level of innovation services they provide but tends to decrease if the growth rate of knowledge spillovers increases. As more R&D is done the R&D/output ratio increases, but as the productivity of R&D rises because of spillovers, the output rises as well, so that the R&D/output ratio can decrease.

Markets are **imperfectly competitive**, but markups are constant and do not depend on the number of firms. However, the effects of pro-competitive policies on innovation activities may be simulated by changing these markups.

Innovation takes place at firm level, as discussed in the previous section, patent citations across sectors and countries are the basis of the mechanism of knowledge spillovers and propagation.

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[113] These matrices were developed in the context of the DEMETER and SIMPATIC projects. See Meijers and Verspagen (2010) and Belderbos and Mohnen (2013).

There are two types of workers: **low-skilled and high-skilled**. Both skill categories are used as production inputs entering different levels of the nested CES framework describing production of each sector. **Human capital is exogenous** and reflects the skill composition of the labour force of the countries, based on the structure of the population and on investment in education. According to the International Standard Classification of Education (ISCED) levels, low-skilled workers regroup the categories from 0 to 4, while high skilled workers regroup the categories 5 and 6. In NEMESIS, human capital can be changed exogenously through the participation rates of the working age population by gender, age and skill.

The multidimensional nature of innovation, combining investment in R&D, in ICT and in OI, allows for an **endogenous** representation of the investments of private firms in **training**. Investment in training is explicitly modelled through the OI component.

In NEMESIS firms invest in innovation using internal resources. **The financial market is not modelled** and interest rates are exogenous. However, **risk premia** paid to capital owners may be changed exogenously, affecting the user cost of capital and agents' accounts. Different scenarios can then be constructed accounting for the possibility of financial frictions and limited access to capital markets. For instance, the model can account for variations in access to financial capital via cross-border venture capital funds, financing facilities from European or national institutions, or ease of financing via R&D tax credits or direct subsidies.

3.3.5. R&I policy

The presence of knowledge spillovers at the basis of the analytical framework used in NEMESIS to endogenize growth justifies the need for public interventions in R&I. The social returns of innovation activities are higher than the private returns. Hence, in the absence of an *ad hoc* policy mix, private sector's R&I activities are below the optimal social level.

NEMESIS can be used to **simulate** the macroeconomic and sectoral **impacts of R&I policy instruments** such as public R&D, EU or National public funding, tax incentives and subsidies. This positive approach in the evaluation of the innovation policies is based on three key channels of the model. The first channel regards the effects of the policies on R&I investment decisions and of the related additionality effects. The second channel refers to the effects that different policies may have on the size and the direction of knowledge spillovers. The third channel is related to the diffusion of knowledge across sectors.

In the context of the I3U project (Investigating the Impact of the Innovation Union), the following main policy areas were incorporated in NEMESIS: (i) human capital; (2) finance; (3) action to market. The first area incorporates measures that increase the productivity of public research by influencing the strength and direction of knowledge spillovers. This area includes all policy interventions aimed at improving the quality of human capital and the allocation of skills and qualifications. The second area on finance incorporates government measures aimed at easing the financing of R&D, be it direct grants, financial incentives to attract private capital, special measures for SMEs, access to venture capital, matching private and public funds to finance R&D or access to structural funds. Action to market regroups commitments that foster market conditions for innovation such as the European Design Leadership Board and European Creative Industries.[114]

Other policy related aspects can be simulated in NEMESIS such as environmental and energy policies, with the Environment Module (NEEM) that delivers indicators on energy demand and supply, distinguishing between different types of energy sources and technologies. NEEM allows to consider the effects of environmental policies, such as carbon tax, emission permits, Pigouvian subsidies etc…

In NEMESIS there are several **tax and subsidy instruments**, such as VAT, tax on labour and capital income, excises duties and consumption taxes, subsidies on production, social security contributions. Through these policy tools the model can be used to construct complex policy scenarios, also accounting for public financing issues of R&I policies and for the possible emergence of crowding-out and crowding-in phenomena.

The multi-country structure of NEMESIS allows to **differentiate between national and supranational policies**, while its multi-sectoral structure enables the study of the impact of **sector-specific policy** measures, as well as the effects on the production structure of broad interventions.

Finally, the NEMESIS Agriculture and Land-Use module (NALU) can be used to simulate several structural interventions in all the main land-use intensive sectors.

3.3.6. Dimensions of macroeconomic impact of R&I

NEMESIS can evaluate the impact of innovation activities and of the related policies for key economic indicators. There are three layers of indicators. The first layer refers to the **main macroeconomic indicators**, such as GDP, consumption, investments, imports, exports, unemployment rates etc… The second layer refers to the **sectoral variables**, such as value added and employment per NACE sector. The third layer refers to the accounts of the **different categories of agents** (households, financial and non-financial corporations, general government and the rest of the world).

The demographic structure of NEMESIS and its detailed workforce allows to keep track of **social indicators**, such as unemployment, participation rates by age, gender and qualifications, inequality index for wages and earnings across countries and regions.

Firms employ low and high skilled workers. On the demand side households are not heterogenous, however it is possible to study the impact of R&I policies on the **distribution of income** by looking at wage dynamics by skill. In each sector wage is determined according to the model developed by Chagny et al. (2002), accounting for the distinction between high and low skilled labour inputs and the related market and institutional factors.

Innovations deliver Hicks neutral productivity improvements, but by changing the quality of goods and given the non-homotheticity of preferences, they may give rise

[114] See Le Mouël et al. (2017).

to change in the relative demand of goods and services. The effects of skill-biased technical change can be studied by considering the impact of major innovation efforts occurring in skill-intensive sectors.

The NEMESIS Energy Environment Module (NEEM) accounts for the negative **environmental externalities** of economic activities providing detailed results on different pollutant emissions (CF6, CO2, HFC, NOX, PFC and SO2).

3.3.7. Strengths and weaknesses

NEMESIS is a **macro-econometric model** belonging to the **neo-Keynesian tradition**. The equations describing agents' decisions are empirically specified, **partly estimated and partly calibrated**. This feature ensures that the model can **mimic the observed dynamics** for the main macroeconomic indicators. The model can capture the cyclical variations of prices and quantities in response to policy shocks and describe the adjustment dynamics towards the medium and long-run equilibrium.

The presence of **three types of innovation activities (R&D, ICT and OI)** allows to simulate different policies and to account for the effects of knowledge and network externalities. R&I leads to both **cost reductions** (via Hicks neutral productivity improvements) and **demand expansions** (via quality upgrades). Moreover, NEMESIS distinguishes between **private and public R&D investments** with different effects on knowledge formation and on economic performance.

Countries and sectors are interlinked via exchange of goods and knowledge externalities. With this feature NEMESIS can study the direct and indirect effects R&I policies at national or supranational level and/or targeting specific sectors.

The NEMESIS model, although inspired by endogenous growth models, is **less theoretically grounded, but empirically richer**, as it allows for sector heterogeneity, various sources of technological change and spillovers across sectors and countries.

The additional module NEEM can be used to study the impact of R&I policies on the environment (emissions and land use) and to construct complex scenarios of policies for smart and sustainable growth.

The detailed modelling of population and working force allows for the study of the impact of R&I policies on unemployment, participation rates and inequalities across different categories of workers (by skill, age and gender) and across countries.

Despite all the above strengths NEMESIS has some **limitations**, most of them typical of models based on an econometric approach.

The model does not feature **firm heterogeneity**. Each firm undertakes R&I activities and there is neither **entry** of innovative firms, nor **exit** of less efficient firms.

The overall effects of innovation activities are amplified by cross sector and country **spillovers**. In each country/sector block both process and product innovations are jointly determined by the same investment effort, while the functional specification of the three components of innovation services is based on cross-sector and international spillover effects, and the diffusion process of innovation has a serendipitous nature, even though propagation is related to the country/sector absorption capacity. These features run **the risk of overestimating the positive impact of R&I policies**.

NEMESIS does not capture the intrinsic **risks** associated and randomness in the outcome of the R&I process and does not feature endogenous **financial** frictions and risk premia are exogenous.

The representation and the role of **human capital** are limited in NEMESIS. The skill composition of the labour force is not endogenously determined.

The simulation strategy adopted is **extremely flexible,** but it may require **data** that are not always **available**, or their quality may not be as good. In addition, the use of external empirical studies may be necessary to introduce the shocks into the model. These aspects may represent an obstacle for the design of simulation scenarios and for the translations of policy shocks into model variables.

The model **lacks microfoundations**, therefore the mechanism of transmission from policy shocks to endogenous variables is based on reduced form equations. It is not possible to disentangle direct from indirect effects of policy actions. In addition, several assumptions have to be made about the empirical specifications of agents' behavioural equations, their dynamic structure and the way in which expectations are formulated.

In NEMESIS, consistently with the other econometric models, agents formulate **adaptive expectations**. This way of formulating expectation introduces further lagged variables into the behavioural equations, so that it is not possible to disentangle the partial adjustment effects from the expectation effects. From this perspective, the transition from theory to data is not straightforward.

Finally, another important limitation is that agents' behaviour is described by equations that do not adjust to policy changes; therefore, NEMESIS is subject to the **"Lucas critique"** and cannot account for the fact that agents change their decisions when faced with a change in the policy regime. The lack of forward-looking decision making can then be a source of bias in the simulation results.

3.4. Evaluating the modelling of R&I and R&I policies in QUEST III, RHOMOLO and NEMESIS

This final section will assess the three models, QUEST, RHOMOLO and NEMESIS on the basic R&I features and R&I policies identified in Section 2 as important for macro-modelling R&I and assessing R&I policy interventions, using the series of tables presented in below.

Tables 3.1-3.4 show how QUEST III, RHOMOLO and NEMESIS score on the critical properties and characteristics described in Section 2. The tables are not meant to be an exhaustive and precise representation of the three models. They only provide a synthetic representation of the main features related to the detailed modelling of knowledge creation, diffusion, enablers of innovation, impact dimensions and of the relevant policy tools. Some features can be present either in an external module or in other variants of the core model, while other features are captured indirectly (or exogenously) by the models, meaning that the impact evaluation requires an ex ante empirical assessment of the link between specific policy interventions and the model variables to be used in the simulation. Therefore, an indirect or exogenous representation of a specific feature is not a mark of weakness. Similarly, the presence or absence of a feature is not by itself a sign of strength or weakness.

Table 3.1 - Main features of R&I in QUEST III, RHOMOLO and NEMESIS

		QUEST III	RHOMO LO	NEME SIS
Technological Knowledge				
	Stock of knowledge	V	VX	V
	Absorptive capacity	V	VX	V
	Non-rivalry	V	VX	V
	Obsolescence	V	X	V
Innovation and the creation of new technologies				
	R&D	V	VX	V
	Knowledge spillovers	V	VX	V
	Rent spillovers	X	X	X
	Firm heterogeneity	X	X	X
	Path dependency	X	X	X
Innovation typology				
	Basic and applied research	V	X	V
	Process and product innovation	X	X	V
	Drastic versus incremental innovations	X	X	X
Diffusion of new technologies				
	Endogenous diffusion of technologies	V	X	V
	Knowledge spillovers	V	VX	V
	Absorptive capacity	V	VX	V
Linking inputs and output: the knowledge production function				
	R&D labour inputs	V	VX	V
	R&D equipment	X	VX	V
	Standing on the shoulders of giants effects	V	X	V
	Congestion externalities	V	X	V

Note: this table only provides a synthetic *representation of the main features of the models related to the detailed modelling of knowledge creation and diffusion of technologies.* V (X) indicates that the feature is (not) present in the model. VX indicates that the feature is currently modelled indirectly (or exogenously) or that has been modelled in other variants (or external modules) of the main model. The presence or absence of a feature is not by itself a sign of strength or weakness.

Table 3.2 - Enablers for R&I creation, adoption and diffusion in QUEST III, RHOMOLO and NEMESIS

		QUEST III	RHOMOLO	NEMESIS
Size of the market		V	V	V
Competition		V	V	V
Intellectual property rights		V	VX	X
Human capital				
	Stock endogenously determined	X	X	X
	Different labour skills	V	V	V
Financing of R&D				
	Endogenous financial frictions	X	X	X
	Exogenous risk premia	V	V	V

Note: this table only provides a synthetic *representation of the main features of the models related to the enablers for R&I creation, adoption and diffusion.* V (X) indicates that the feature is (not) present in the model. VX indicates that the feature is currently modelled indirectly (or exogenously) or that has been modelled in other variants (or external modules) of the main model. The presence or absence of a feature is not by itself a sign of strength or weakness.

Table 3.3 - R&I policy in QUEST III, RHOMOLO and NEMESIS

		QUEST III	RHOMOLO	NEMESIS
R&D tax incentives		V	VX	V
Direct subsidies		V	VX	V
Loans and public venture capital		VX	VX	VX
Public R&D and public-private partnerships		VX	VX	V
Public procurement		V	V	V
Patents		V	VX	VX
Regulations		V	V	VX
Corporate taxes		V	V	V
Environmental policies		VX	VX	VX
Policy mix				
	Budget spent	V	V	V
	Antitrust policies	V	V	V
	Education policies	VX	VX	VX
	General taxes or subsidies/support	V	V	V
	Interactions between national and supranational level policies	V	V	V
	Interactions between regional and national level policies	X	V	X
	Sector specific policy interventions	VX	V	V
Administrative burdens		V	V	V

Note: this table only provides a synthetic *representation of the main features of the models related to R&I policy.* V (X) indicates that the feature is (not) present in the model. VX indicates that the feature is currently modelled indirectly (or exogenously) or that has been modelled in other variants (or external modules) of the main model. The presence or absence of a feature is not by itself a sign of strength or weakness.

Table 3.4 - Dimensions of macroeconomic impact of R&I in QUEST III, RHOMOLO and NEMESIS

		QUEST III	RHOMOLO	NEMESIS
GDP		V	V	V
Labour markets		V	V	V
Competitiveness and globalization		V	V	V
Inequality				
	Across workers	V	V	V
	Across countries	V	V	V
	Across regions	X	V	X
Health		X	X	X
Environment, non-renewable and waste disposal		VX	VX	VX

Note: this table only provides a synthetic *representation of the main features of the models related to the dimensions of the macroeconomic impact of R&I.* V (X) indicates that the feature is (not) present in the model. VX indicates that the feature is currently modelled indirectly (or exogenously) or that has been modelled in other variants (or external modules) of the main model. The presence or absence of a feature is not by itself a sign of strength or weakness.

4. CONCLUSIONS AND RECOMMENDATIONS

This section closes with some conclusions and recommendations on how to move forward in the medium-long term agenda on the development and use of macroeconomic models for R&I policy analysis.

Before we set out the recommendations which follow from our analysis in Sections 4.1-4.4, it is important to first recall some ***general principles*** **on why and how to use quantitative macroeconomic models for innovation policy analysis**.

- Quantitative macro models are an important tool to have in the toolkit for innovation policy analysis because they offer the benefit of taking the interdependence between markets, sectors, regions and countries into account and thus help to identify the critical enablers of R&I and any possible weak points (like frictions in labour, financial and product markets) that could prevent the effectiveness of innovation policy.

- As innovation is an important driver for medium and long-term macroeconomic performance, macroeconomic models should include a proper modelling of R&I and R&I policies.

- Institutions using macro-models on a regular basis typically have a portfolio of different models useful for different purposes. A single encompassing model will be frustratingly simple for some purposes and unnecessarily complicated for others. Analysis of the macroeconomic implications of innovation and of innovation policies will typically be done inside or in interaction with macroeconomic models which are commonly used for the main purposes of the macroeconomist.

- In order to be a good laboratory for the quantitative evaluation of R&I policy, macroeconomic models of R&I need to be disciplined by the **available macro and micro data** on those dimensions in which policies are expected to operate. Limited availability of macro and micro data may seriously jeopardize the full modelling of R&I and R&I policies.

- Continuous interactions among modellers, users, outside experts and policymakers is essential to ensure relevant models. Any model needs to be transparent and sufficiently understandable for decision makers to work with it. Users' adoption requires a strong effort to facilitate comprehensibility of the model functioning and of its results, which requires good and frequent communication between the groups.

- Models need not necessarily be utterly complicated. As models are already complex, it should be avoided to make them intractable black boxes by trying to enlarge them with too many new features. Models cannot have everything nor should they.

- Yet any simplification should be analysed on its impact on the dynamics of the model, and sensitivity tests need to be conducted to predict at least upper and lower bounds for the variables of interest depending on the assumptions made.

4.1. Recommendations on how to include R&I and R&I policies in macro-models

Macroeconomic models designed to evaluate innovation policies have to include a fair, even if highly simplified, description of the **key features** that describe the working of innovation and the main policies at hand to promote innovation and maximize its impact on the macro economy. By omitting the relevant channels through which innovation policies are expected to affect the macro economy, no model can be of good advice for innovation policy. This report reviewed in Section 2 the key features that describe the workings of innovation and the main policies at hand to promote innovation.

- The key **R&I features** are: 1) Well-defined technologies transforming *R&D* inputs into *innovation* outputs, dynamically cumulating into an aggregate stock of *technological knowledge* (sectorial, regional, national); 2) R&D technologies benefiting from positive *knowledge spillovers* (geographical and sectorial), and (oligopolistic) market structures allowing for negative *rent spillovers* (in the form of business stealing or obsolescence); 3) heterogeneous and firm-specific production and R&D technologies, explicitly modelling the creation of new products, and shaping the endogenous random process of firm-specific productivity (in terms of product quality and efficiency of the production process); 4) *firm heterogeneity* and *market dynamics* (entry, exit and firm life-cycles) *endogenously* emerge; 5) when needed, the distinction between *basic and applied research*, *product and process innovation*, *incremental and drastic innovations* should be made; 6) an explicit modelling of the *diffusion process* (aiming to catch-up the frontier technology or in the form of vintage technologies).

- The following **enablers** are key to design the mechanisms of the R&I process: a well-defined market size effect, an inverse U-shaped relation between competition and innovation, markup dispersion, an education system providing the needed human capital, and an explicit modelling of R&I financing.

- Macro-models should be aimed to evaluate the **main R&I policy instruments** used in practice: 1) R&D tax incentives, in particular R&D tax-credits; 2) direct subsidies, in particular research grants; 3) public research loans and public venture capital; 4) public R&D and public-private partnership; 5) public procurement; 6) a well-defined patent system. Other policy instruments include corporate taxes and regulations addressed to protect the environment and the health of citizens.

- In the evaluation of innovation policies, macro-models should reflect the existence of trade-offs, of general equilibrium effects and of budget constraints, and account for the fact that agents may react to changes in policy by modifying their behaviour consistently.

- Macroeconomic models should provide a good quantitative evaluation of the **macroeconomic impact** of R&I in dimensions like: 1) *GDP* and its main components (level and growth); 2) *labour market* outcomes, including the effect on the creation and destruction of jobs and skills (job polarization, skill obsolescence, structural transformation); 3) *competitiveness and globalization*, including the channels through which innovation strengthens competitiveness and builds comparative advantages; 4) *social exclusion and inequality*, in a framework of heterogeneous households with different education and skills; 5) heterogeneous states of *health*, population aging and life-expectancy; 6) the relation between economic growth, the *environment* and *sustainability*.

In order to implement these key innovation (policy) ingredients in macroeconomic models, it will not be possible to include all of them. **No single macro-model** can simultaneously account for all these features of the R&I process, and still consistently produce the accurate quantitative figures needed for the macro-evaluation of all current R&I policies. Choices will have to be made about which features and policies are more relevant for the economy. Depending on the objectives and the innovation policies being evaluated as well as the channels and the dimensions of impact considered, some features may be more crucial than others. In making these choices, a few principles should be kept in mind:

- A good macroeconomic model designed to evaluate innovation policies should ideally include **heterogeneous firms and heterogeneous production and R&I technologies**. This requires, in particular, an important disaggregation at the level of firms, including innovation incentives and performance, as well as the associated dynamics, including the entry of new innovative firms, their development and eventual exit.

- When the different features of the R&I process, their diffusion channels (the enablers), the different policy instruments and the different dimensions of macroeconomic impact are studied in **different models (or sub-models)**, or at different levels of disaggregation, their results should nevertheless remain comparable with a common core.

- For the **geographic** dimension in the case of the European Union, a macro model designed to evaluate innovation policies ideally has to mimic a multi-country, multi-region Europe trading with the rest of the world, the degree of disaggregation depending on the policy under evaluation.

- Innovation, by creating and destroying jobs and the value of the associated skills, impacts **social inequality**, deeply affecting the distribution of income and wealth. To evaluate this dimension of R&I, macroeconomic models must be designed to properly account for **heterogeneity** across workers and households and the associated **dynamics**. Modelling skill and education heterogeneity is of fundamental importance to evaluate the labour market and the distributional implications of innovation policies.

- **Environmental** issues, such as those falling in the domain of climate change, have become pressing in the recent decade. Environmental policies direct technical change towards the development of environmental-friendly technologies. However, the advancement of green and clean energy technologies and the development of abatement technologies require large investments in R&I. These two dimensions should be addressed together in models integrating environmental aspects with endogenous technical change mechanisms.

4.2. Lessons learned from macroeconomic models currently used in DG R&I

Applying the checklist developed in this report of the key ingredients required to deliver a sound macroeconomic evaluation of innovation policy to the three macroeconomic models presently used by the Commission's Directorate-General for Research and Innovation - QUEST III, RHOMOLO and NEMESIS - the following lessons stand out:

- All three models present a rich set of mechanisms and parameters through which R&I policies can be simulated.
- Yet, none of the models covers all of the key characteristics of innovation and innovation policy. This implies that none of them can be considered as dominantly better for the modelling of innovation and innovation policies. Each has its own strengths and weaknesses. Which model to choose will depend on what the major objectives and preferences of the users are.
- All models require further developments to better cover key features of innovation and innovation policy. Some key features can be included with minor changes to the models, others will require bigger adjustments.
- The following key features are poorly included in all three models: the heterogeneity and dynamics of the population of innovative firms, the modelling of financial frictions, the modelling of risk and uncertainty, the formation of human capital for the creation and the adoption of innovations, and the environment-related aspects.
- All of the models struggle with a lack of sufficiently recent and disaggregated data to calibrate/estimate critical parameters. All models can be improved with better data.

4.3. Some suggestions for the way forward

- There will never be one perfect or right model. All models are wrong, but some are more useful than others.
- More progress could be made in sharing and mutual learning among the currently used models.
- Addressing the commonly **missing features** in the current models will require bigger adjustments. When contemplating big adjustments to the models, a more modular approach should be considered, with a stable "core" model that is capable and flexible to link to (new) submodules, which address in more detail key features of innovation or different dimensions of macroeconomic performance, and which can be activated when needed.
- To achieve the objectives mentioned above in the development of R&I macro-models for the evaluation of R&I policies the following **families of models** should be seriously considered: endogenous growth models with firm dynamics, models of vintage technologies, models of directed technical change, models of human capital formation and occupational choice, and models of search in the labour market, among others.

- Beyond further developing currently used models, **new models** should be on the radar as well, such as, models of networks, models of structural transformation, models of bounded rationality, evolutionary game theory, and agent-based computational models. New models offer new perspectives for modelling currently missing features.

- Macroeconomic models can only be a good laboratory for the evaluation of economic policy, if they are as close as possible to the available data on those dimensions in which the policy is supposed to operate. This is a basic requirement for any macroeconomic model to provide accurate quantitative figures that help evaluating the contribution of innovation policies. High on the to-do list should be to improve **the data availability** for modelling of the key R&I features and key R&I policy interventions, in particular data on innovation policies in Europe.

- Modern macroeconomic models based on microeconomic foundations should be designed consistently with **microeconomic data** and the institutional framework in which economies operate. This is generally done by an exercise of calibration and/or estimation of behavioural parameters of the model that are reasonable (i.e. consistent with empirical evidence from microstudies on different dimensions of the model) but that also allow the replication of the observed data.

- Improve **transparency** of any model being used to enable a more informed use by policy makers of the results. Ideally, **a full description of the model, code and dataset** should not only be transparent to the users, but also be **open access,** to enable a more interactive mode of continuous development of the models.

4.4. Some suggestions for moving the EC-R&I agenda moving forward

Within this overall agenda for moving the macro-modelling of innovation policies forward, DG R&I can play a pivotal role through the following actions:

- Providing grants for excellent research at the knowledge frontier of macroeconomic models contributing to the developments of the modelling of R&I and R&I policy as well research into new models.
- Procuring research into further developments of currently used models by the EC to improve the modelling of their R&I policy evaluation, with a close involvement of policy modellers and users;
- Full transparency should be a condition (a full description of the model, code and dataset should be open access);
- Improving the provision of common data inputs to macro-models, most notably data on innovation policies;
- Providing a platform for macro-models where research results and best practices can be exchanged, databases can be shared and where open access to models and codes can instigate further (co-)development of existing macro-models or inspire the research on new models;
- Regularly bringing together producers and users of macro-models, improving the transparency of models to users and improving the user friendliness of models for model-users.

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APPENDIX

Box 1: R&I POLICIES IN THE EU and its MEMBER STATES

The EU landscape of research and innovation (R&I) policies is characterised by the interplay of different levels of governance, with most policy initiatives being undertaken at the national and the European level.[115] This box describes the overall R&I policy framework in Europe, focusing on the main tools and objectives at the EU level, for then analysing the main policy instruments from a modelling perspective consistently with Section 2 of this report. It also provides some insights on national policy actions that complement the EU instruments or are specific to member states (e.g. tax incentives).

R&I policy has historically aimed at fixing market failures, as to incentivise private R&D investments towards the social optimum, as well as at addressing systemic failures that prevent the diffusion and take-up of scientific and technological knowledge. More recently, a new frame has emerged calling for a transformative R&I policy providing the direction to tackle contemporary economic, social and environmental challenges and to achieve the Sustainable Development Goals (see Schot and Steinmueller, 2018; Biggeri and Ferrannini, 2020).

The **EU R&I policy** has embraced the transformative framework, most notably to deliver on the Green Deal, as to set the direction of investments, reforms and regulation (European Commission, 2020). This direction complements and provides a new frame for existing tools, e.g. tax incentives, grants, direct public investments, partnerships, etc. Within the framework of the sustainability transition, R&I policies at the EU level aim to promote **excellence in research** and **convergence across regions**.

Horizon Europe. The current main policy action is **Horizon 2020**, the Framework Programme, which will be followed by its successor, **Horizon Europe**, the Framework Programme 9. These are the main EU instrument for stepping up investment in R&I capacity and they cover the period 2014-2020 and 2021-2027 respectively. *Competitive, mission-oriented grants* are the main policy instrument used in this programme aimed to promote excellence in research, knowledge diffusion and collaboration between universities and private firms.

[115] Regional policy is also a crucial dimension of the R&I framework in Europe, since huge differences do persist across regions and within countries in terms of economic development, R&I investments and performance. Furthermore, regional governments and stakeholders are key actors when it comes to R&I policy interventions. Therefore, consistently with the acknowledgement of the importance of place-based policies that account for and embrace the specificities of regional ecosystems, EU regions are required to develop their Smart Specialisation Strategies. These are conceived within the Cohesion policy of the European Commission and constitute a place-based approach to policy, identifying strategic areas for intervention based on an assessment of strengths and potential of regional economies and their R&I ecosystems. For further information see https://s3platform.jrc.ec.europa.eu/what-is-smart-specialisation- .

In particular, Horizon Europe will be the largest ever Framework Programme, including novelties compare to its predecessor, Horizon 2020. These include EU-wide **missions**, i.e. time-bound and specific goals on issues (e.g. cancer) where Europe needs to deliver, the **European Innovation Council (EIC)**, as a major tool to support Europe transition into the next wave of innovations across digital/AI and deep tech, and **partnerships** responding to strategic priorities of Member states and stakeholders, including industry and civil society. Overall, at the time of writing, Horizon Europe is expected to have a budget of **94.1 billion EUR** for the period 2021-2027, of which:

- **Open Science Pillar (25.8 billion EUR):** Supports research through fellowship, exchanges and others activities financed by European Research Council grants (16.6 billion EUR), Marie Curie Fellowships (6.8 billion EUR), and invests in world-class research infrastructures (2.4 billion EUR). (Emphasis on Open Access knowledge, reproducibility and reusability, i.e. mostly **basic** research).
- **Global Challenge Pillar and Industrial competitiveness (52.7 billion EUR):** directly supports research related to societal challenges reinforcing technological and industrial capabilities[116].
- **Open Innovation Pillar (13.5 billion EUR):** Supports market-creating innovation, breakthrough ideas, and scaling-up innovative enterprises through the European Innovation Council (10.5 billion EUR) and the European Institute of Innovation and Technology to foster the integration of business, research, high education and entrepreneurship (3 billion EUR), i.e. mostly **applied** research. These are "bottom-up" activities that will be often **co-founded by national programmes.**

<u>Invest EU Fund</u>. Furthermore, the European Commission aims to guarantee affordable finance and mobilise private funds for R&I investments through different instruments. These include the dedicated window under the **InvestEU Fund**[117], for which the European Commission has proposed a mobilization of about 16.6 billion EUR through market-based instruments (as financial instruments and budgetary guarantees) that are expected to leverage 200 billion EUR in the private sector.

<u>Structural Funds</u>. Direct subsidies that go mainly, but not only, to lagging Member States or regions under the European Cohesion policy. The period 2021-2027 foresees **1279.4 billion EUR**, of which **187.4** for research and innovation, together with European Strategic Investments, Single Market and Space. Furthermore, **Smart specialization strategies** under the **EU Structural Funds** are a key initiative supporting R&I investments, contributing with more than **40 billion EUR** to the development of R&I strategies across regions and Member States in the period 2014-2020.

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[116] Most notably, 7.7 billion EUR are foreseen for Health, 2.8 for Inclusive and Secure Society, 15 for Digital and Industry, 15 for Climate, Energy and Mobility and 10 for Food and Natural Resources. Finally, 2.2 billion EUR go to non-nuclear direct actions of the Joint Research Centre (JRC) of the European Commission.

[117] See https://ec.europa.eu/commission/priorities/jobs-growth-and-investment/investment-plan-europe-juncker-plan/whats-next-investeu-programme-2021-2027_en.

Major R&I Policy instruments

Following the outline of Section 2.3, a non-exhaustive summary of the major policy instruments in the EU and its member states is presented below. To be noted that the policy landscape is quite complex and diverse. Table X reports some examples of such policies across Member States and in Figure X the distribution of indirect (tax incentives) and direct (grants and subsidies) R&I support.

Although overall R&D expenditure in the EU has been increasing annually by 1.3% since 2010, it remains lower than the 3% target and the gap with main international competitors persists. Business R&D investment is particularly subdued and relatively low in international comparison, being equal to 1.45% of GDP in 2017 against 2.04% in the US, 2.52% in Japan, 1.65% in China and 3.62% in South Korea (European Commission, 2020).

Tax incentives

Tax incentives is a *national policy instrument*, widely used in the EU to reduce the cost of R&D activities and to leverage private resources. The amount of foregone revenue varies across member states, ranging from 0.30% of GDP in countries strongly relying on tax incentives, e.g. France and Belgium, to shares below 0.01%, e.g. Sweden and Poland. The average level of foregone tax revenues in the EU had a threefold increase in the EU since 2007, being equal to 0.11% in 2017. While some countries do not make use of R&D tax incentives, the number of Member States providing them increased from 12 in 2000 to 21 in 2018 (Appelt et al., 2019). (see Figure X).

Grants and subsidies

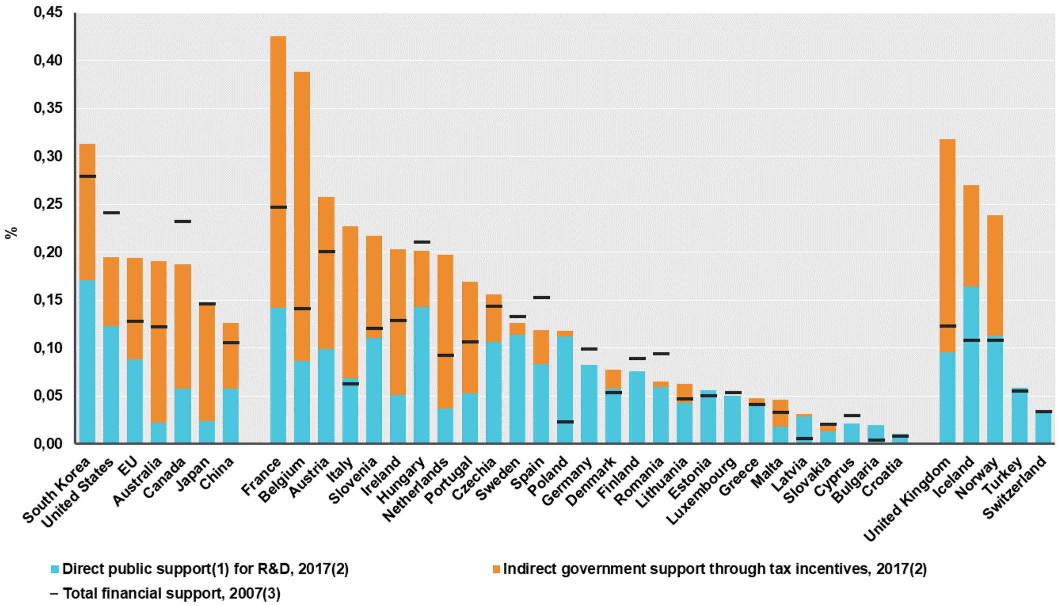
As it can be observed in Figure A.1, direct support in the form of grants and subsidies account for around **45% of total public support** to business R&D investments in the EU in 2017. As for the use tax incentives, there is large heterogeneity across Member States but they are used in every and single country, being the most prominent (in a few cases the only one) support scheme in countries such as Spain, Poland, Sweden and Germany. To be noted that direct support tools allow for a more narrowed targeting of researchprojects, providing more directionality to public funding compared to tax incentives that tend to be mostly horizontal tools. [118]

Direct supportinstruments are also provided directly at the European level. The most notable case is Horizon 2020 and its successor Horizon Europe, providing grants on a competitive basis to applicants from EU Member States and Associated Countries. Horizon 2020 also includes tools aimed at financing innovative projects and breakthrough innovations. Overall, over 8 billion EUR are expected to directly finance R&I activities performed by SMEs, with 4.13 billion EUR already financed at the end of 2017. While the EIC will be one of the main tools of the next Framework

[118] This does not mean that tax incentives cannot be somehow targeted. For instance, the tax incentives provisions in the most recent Industry 4.0 policy package in Italy are “targeted” to innovative activities and investments, while keeping their horizontal dimension.

Programme starting in 2021, an EIC pilot has been activated as part of Horizon 2020 with a budget of 3 billion EUR.

Figure A.1 – Direct and indirect public support to business R&D (in % of GDP)



Source. European Commission (2020), based on OECD data (online data code: rd_e_gerdfund)

Direct public R&D and public-private partnerships

As discussed elsewhere in this report, there may be several reasons why the public sector may decide to directly perform R&D investments, rather than leaving it to or financing business efforts[119]. This is done through public research centres, universities and public administrations. In the EU, direct public R&D accounts for around **33%** of total R&D expenditure in 2018, of which **2/3** are performed in the higher education sector. Public efforts have remained substantially unchanged in the last two decades in the EU, public R&D intensity remaining close to 0.7% of GDP in 2018.[120] Substantial heterogeneity can be observed across Member States.

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119 The quality of public science, the characteristics and scope of public research and the creation of a public pool of knowledge are usually cited as specific traits justifying direct public R&D (Archibugi and Filippetti, 2018).

120 There is no "official accounting" for public R&D directly performed by the European Union as an institution. It is worth noting that, as mentioned above, Horizon Europe foresees a budget of 2.2 billion EUR for the Joint Research Centre of the European Commission for the period 2021-2027

At the EU level, European Partnerships provide a framework for programme level collaboration in the EU. It allows to translate common EU priorities into concrete roadmaps and coordinated implementation of activities. European Partnerships are specific collaborative research instruments involving a broad range of public and/or private actors, such as research funders and organisations, universities, industry, bodies with a public service remit at local, regional, national or international level or civil society.

Public procurement

Public procurement aims at directly creating demand for innovation. While 14% of EU GDP is spent every year on public procurement (European Commission, 2020), several Member States have in place different public procurement programmes for research and innovation, as for instance Belgium, France, Austria and Italy (see Table X). According to a report by the OECD (2017), around 80% of OECD countries have developed a strategy to support innovative outcomes through the use of public procurement.[121]

Loans and venture capital

Loans and venture capital funds address the issue of inadequate access to finance for innovative projects. Countries can set up agencies or schemes that may reduce the cost of loans or by providing public guarantees for the access to credit, as for instance in Italy (Cassa Depositi e Prestiti). There are also instances of public venture capital, e.g. Banque Publique d'Investissement in France and Invitalia in Italy. Public venture capital has proven to be crucial in Europe in the last decade. Indeed, while private sources have been volatile during macroeconomic shocks as the last economic crisis in 2008, public venture capital has been resilient overtime and has increased its share on total fund from 13% in 2007 to 22% in 2018. Some examples are reported in Table A.1.

The European Union provides programmes to ease the access to venture capital for innovative SMEs and midcaps. They include:

- **VentureEU** aims at reducing Europe's equity gap relatively to peer economies, reducing the fragmentation of the European Venture Capital markets and aims to attract additional private investors. Under VentureEU, the EU will provide funds for 410 million EUR for the period 2021-2027 (200 from Horizon 2020) aiming to raise up to 2.1 billion EUR of public and private investments.
- The **Single EU Equity Financial Instrument**, supporting businesses' growth and R&I activities at different stages.

- The European Fund for Strategic Investments **(EFSI) Equity Instrument**. In particular, the **InnovFin Equity** instrument mobiles 4-5 billion EUR to be invested in companies operating in innovative sectors covered Horizon 2020.

[121] Survey data based on 35 respondents among OECD countries.

Regulation

Framework conditions are considered as enablers of investments, most notably in risky innovative activities. Regulation in the labour, product and goods market is country specific[122]. At the European level, two main policy tools related to regulation and innovation should be mentioned:

- The EU Single Market Programme (SMP), which aim is to create a territory without any internal borders or other regulatory obstacles to the free movement of goods and services. While not specific to research and innovation, the SMP contributes to the diffusion of knowledge and technology and their take-up. Furthermore, free mobility of researchers as a key priority of the European Research Area contributes to research circulation between EU countries.

- The Innovation Principle, regulatory tool conceived to help policy makers achieving EU policy objectives by ensuring that legislation is designed in a way that creates the best possible conditions for innovation to flourish. In particular, the innovation principle implies that future initiative undertaken by the European Commission, e.g. policy or regulations, will consider the effect on innovation. The purpose is to set up an innovation-friendly regulatory framework.

[122] Data on the strictness of regulation in each domain is produced by several organisations, e.g. the OECD, the World Bank and the World Economic Forum among others.

Table A.1 – A sample of policy instruments in EU Member States

Policies	Policy instruments	Country examples	Budget p.a.
Direct and indirect financing	Grants and matching grants for innovation and/or R&D projects	- AT: Impact Innovation Programme - MT: R&D Feasibility Studies - NL: SME Innovation Support to Top Sectors - FI: Business Finland Programme for young innovative companies - ES: Grants for innovative clusters - IE: Enterprise Ireland R&D&I Fund	1-5M€ <1M€ 20-50M€ 20-50M€ 5-20M€ 20-50M€
	Vouchers for innovation and collaboration	- EE: Innovation vouchers - LT: Innovation vouchers - PT: Innovation Vouchers	<1M€ 1-5M€ 5-20M€
	Loans & guarantees for innovation	- SI: Slovenia enterprise fund - bank loans guarantees / interest rate subsidy. - PT: Incentive scheme for the qualification of SMEs	50-100M€ 20-50M€
	Tax incentives for R&D (e.g. tax credits)	- LV: Corporate income tax incentive for R&D investments - PT: Fiscal incentives for the employment of doctorate holders - NL: Innovation Box	
	Equity finance for innovative enterprises	- MT: Business Startup Funding Programme - FR: Digital Ambition Fund - FI: European Angels Fund Finland - LU: Luxembourg Future Fund - SI: Seed capital for startup innovative enterprises	 100-500M€ 20-50M€ 5-20M€ 1-5M€
Demand pull instruments	Public procurement for R&D	- CY: Financial support to business R&D and innovation: procurement grants for R&D and innovation - BE(Flanders): Programme for innovative public procurement - FR: Online platform for public procurement of innovation - AT: Action plan on public procurement promoting innovation	20-50M€ 5-20M€
	Pre-commercial procurement	- LT: Pre-commercial public procurement - IT: Pre-commercial Procurement	20-50M€
	Supplier development programmes	- PT: INTERFACE Programme- Suppliers' Clubs	
	Corporate open innovation	- AT: Open Innovation- A strategy for Austria - EL: Special call on aquaculture, industrial materials and open innovation culture	1-5M€ 5-20M€
Technology adoption and generation instruments	Business advisory services	- FI: Activating Finnish Living Labs - CY: Innovation habitats - ES: International Network (Red Exterior) programme	<1M€
	Technology extension services	- IE: Knowledge Transfer Ireland - EE: Technology Competence Centers - EE: Product Development Masterclass	>500M€ 1-5M€ <1M€
	Technology	- DE: Innovative Hochschule	50-100M€

	centres		
Early-stage support for innovative ventures	Incubators Accelerators	- LU: Technoport - BE (Flanders): IMEC.ISTART- Business acceleration programme - PT: Collaborative laboratories	
Cooperation	Supporting clusters and networks for innovation	- DE: Innovation Forums SME - DE: WIR! Change through innovation within the region - PT: INTERFACE Program - PT: Competitiveness Clusters - IE: Innovation 4 Growth	1-5M€
Framework conditions	Inducement (incentive setting); recognition awards; appropriate IPR; standard setting; quality infrastructure; investing in education / skills; 'green cards' for highly skilled immigrants	- CY: National policy statement on enhancing the entrepreneurial ecosystem - PT: Startup Visa - DE: Technology Transfer with Norms and Standards - PT: SME Leader and SME Excellence - LV: Guidelines for the Development of Education: STEM Skills - LV: Structural Funds Programme for the development of STEM infrastructure in Colleges - NL: 2020 National Technology Pact - IE: National Skills Strategy 2025 - SI: Co-financing of Research Equipment	

Source: European Commission (2019). Selection based on the information available at the EC-OECD STIP Compass portal.

Box 2: GUIDE TO MACRO-MODELLING INNOVATION AND INNOVATION POLICY

Innovation attributes, the policy instruments addressed to correct distortions, and the key features a macro-model needs to include.

NON-RIVALRY

Issue: Like ideas, technological knowledge can be used by many agents at the same time. Innovators cannot fully appropriate the social return of their investments.

Policy modelling: Non-rivalry justifies the use of *patents* to protect innovation (property-right-protection). But, patents generate *monopoly rents*.

Macro-modelling implications: Patent protection and imperfect competition.

KNOWLEDGE SPILLOVERS

Issue: Innovation benefits from multiple forms of (unintended) knowledge transfers.

Policy modelling: *Tax-credits* and *subsidies* increase the private return to R&D, closing the gap with the social return.

Macro-modelling implications: Different forms of knowledge spillovers. Networks.

MARKET SPILLOVERS

Issue: *Market spillovers* emerge from *creative-destruction* and designate the transfer of monopoly rents between firms resulting from the introduction of innovations. *Obsolescence*; loss of value of current business due to the emergence of new technologies. *Business stealing* is a particular case.

Policy modelling: Social policies designed to compensate the negative redistributive effects of creative-destruction. Competition policy.

Macro-modelling implications: Creative-destruction. Schumpeterian growth. Vintage technologies. Heterogenous firms and selection. Market competition.

FIRM HETEROGENEITY

Issue: *Firm heterogeneity* emerges from the stochastic nature of the innovation process. *Misallocation*; Markup dispersion and financial constraints, among others, make R&D to be inefficiently allocated among heterogeneous firms, negatively affecting efficiency.

Policy modelling: Non-neutral tax-credits, research subsidies and research loans should help correcting misallocation by supporting promising startups, innovative firms and excellence in research.

Macro-modelling implications: Firm heterogeneity, entry and exit, startups, firm's age profiles. Non-neutral innovation policies.

ABSORPTIVE CAPACITY

Issue: *Limits to create absorptive capacity*; the ability of a firm to absorb knowledge spillovers generated by other firms; which depends on past R&D.

Policy modelling: Policies addressed to promote absorptive capacity.

Macro-modelling implications: Spillovers, R&D and absorptive capacity in a framework of heterogeneous firms.

BASIC and APPLIED RESEARCH

Issue: *Basic research* is addressed to the advancement of scientific knowledge. *Applied research* uses scientific knowledge to solve technological problems. Basic research is at highest level of knowledge spillovers.

Policy modelling: Subsidies addressed to support basic research and the collaboration between scientists and firms. Public research centres and universities, public-private partnership.

Macro-modelling implications: Basic and applied research. Innovation and adoption. Technological diffusion.

COMPETITION and MARKUP DISPERSION

Issue: *Misallocation*; Innovation generates natural and patent induced market power, heterogeneous across firms; *markup dispersion* distort the allocation of resources (relative prices are different from relative marginal productivities).

Policy modelling: Non-neutral tax-credit, research grants and research loans designed to reduce misallocation, complemented with the regulation of competition.

Macro-modelling implications: Heterogenous firms; heterogeneous markups; market competition.

UNCERTAINTY and FINANCIAL FRICTIONS

Issue: R&I faces large *idiosyncratic uncertainty* and *asymmetric information*, making financial restrictions to be particularly high due to adverse selection and moral hazard, particularly affecting startups and innovative SME.

Policy modelling: No-neutral public loans and public venture capital oriented to finance highly innovative research projects. Financial regulation in general.

Macro-modelling implications: Financial restrictions in a framework of heterogeneous firms including startups; entry and exit.

MARKET SIZE

Issue: Firms are more willing to do R&D when there is a large market to recover the fruits of their R&D investment.

Policy modelling: Public procurement.

Macro-modelling implications: Firm heterogeneity, innovation-by-incumbents, granularity.

ENVIRONMENTAL SUSTAINABILITY

Issue: Market forces may direct technical change towards an unsustainable path; failure to internalize the social cost of environmental degradation.

Policy modelling: Innovation policy should be oriented towards the protection of the environment and the progress of society.

Macro-modelling implications: Negative externalities, like pollution, should be included.

HUMAN CAPITAL, SKILLS AND INEQUALITIES

Issue: A large body of researchers with high *human capital* is needed to support the R&I sector. *Skill obsolescence*: Innovation and the diffusion of new technologies destroy skill, affect the wage distribution, employment and the occupational structure.

Policy modelling: A mix of innovation, education and social policies. In particular, a highly performant education system.

Macro-modelling implications: Heterogeneous households; heterogeneous workers; skill-biased technical change. Vintage technologies, occupational choice, overlapping generations. Redistributive policies.

COMPETITIVINESS AND GLOBALIZATION

Issue: *knowledge spillovers* diffuse through trade, which may be constrained by trade barriers and barriers to *competitiveness* (the ability of a firm, sector or country to successfully compete in global markets).

Policy modelling: Trade policy combined with pro-innovation policies aimed at promoting competitiveness and developing comparative advantages in technological industries.

Macro-modelling implications: Multi-country, open economy; heterogeneous firms with endogenous market competition and concentration; endogenous comparative advantages.

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The aim of the report is double. First, it aims to identify those characteristics and properties of research and innovation (R&I) that should ideally be included in macro-models, i.e., those that would help to understand the behaviour of innovation and to produce sound evaluations of R&I policies The critical properties and policies of the R&I process may affect the incentives on doing research and development (R&D) and the probability of innovating, how much is or ought to be spent on R&I and the effects of R&I investments on various measures of economic performance and other dimensions of relevance for policy makers, like environmental and socio-economic sustainability. For each of these properties and policies, the report aims at explaining why it would be worth to include them in the modelling, what effects their inclusion is expected to have on the performance of the model and the scope for R&I policy evaluation. The report will also discuss what is required in order to include these properties and policies in the modelling, both in terms of model design and empirical implementation. Second, it aims at identifying the main R&I policies used in practice, those that macro-models need to include in order to produce well-founded assessments. The report closes with some conclusions and recommendations on how to move forward the medium-long term agenda on the development and use of macroeconomic models to inform and advise research and innovation policy making

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