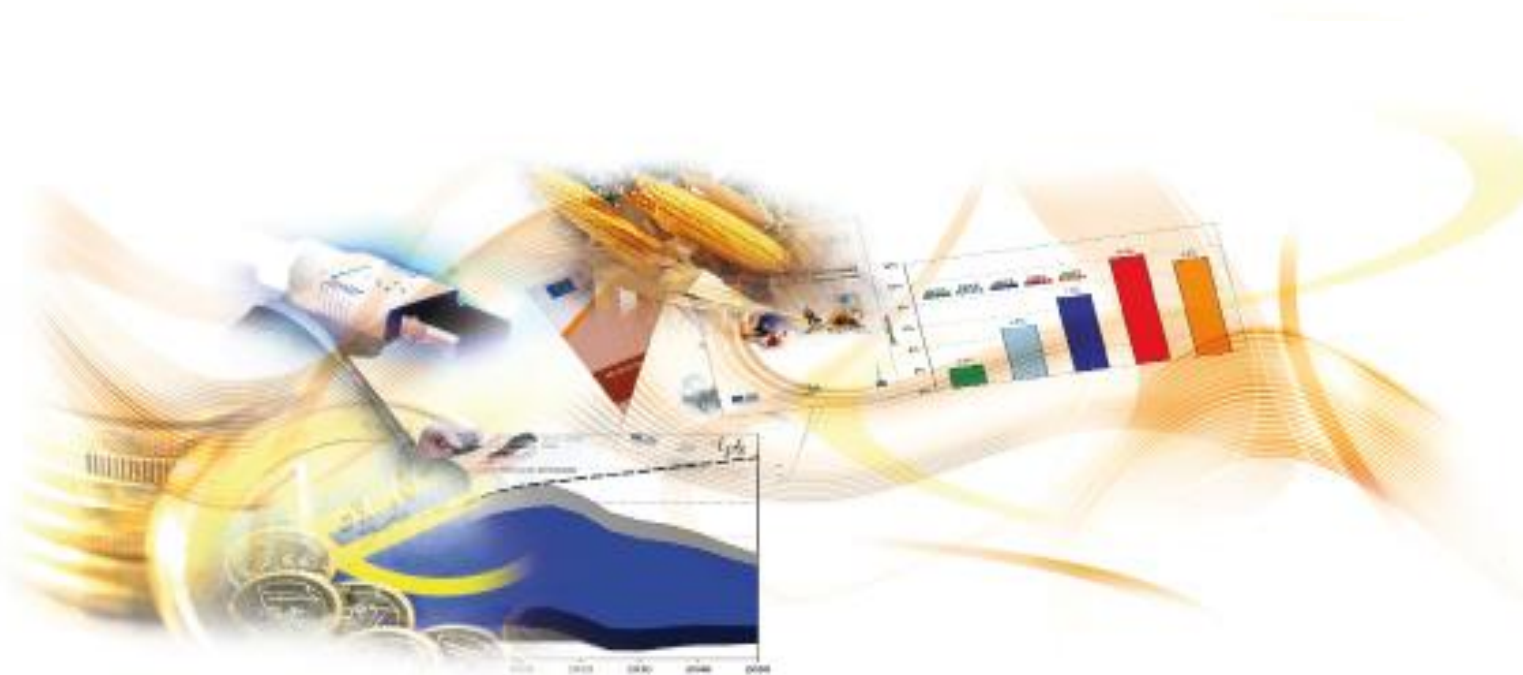European Commission

# JRC TECHNICAL REPORTS



# A CGE Model with ICT and R&D-driven Endogenous Growth:
# A General Description

Author: Martin Aarøe Christensen

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**Abstract**

This report describes the first release of the macroeconomic model developed under the project Prospective Insights on R&D in ICT (PREDICT 2), a research project co-financed by the Directorate General for Communications Networks, Content and Technology and the JRC-IPTS. One of the objectives of PREDICT 2 is the development of a macroeconomic model which allows the economic analysis of public support to ICT R&D in the European Union.

This report provides a motivation for the chosen modelling approach, describes the model structure and the calibration of the model to a reference growth path.

# Acknowledgements

# Table of Contents

# Executive Summary

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# 1. Introduction

This report describes the first release of the macroeconomic model developed under the project Prospective Insights on R&D in ICT (PREDICT 2), a research project co-financed by the Directorate General for Communications Networks, Content and Technology and the JRC-IPTS.[1] One of the objectives of PREDICT 2 is the development of a macroeconomic model which allows the economic analysis of public support to ICT R&D in the European Union.

This report explains the reasons for the modelling approach chosen, and describes the model structure and the calibration of the model to a reference growth path.

The model developed for the PREDICT 2 project is a dynamic Computable General Equilibrium Model (CGE). The CGE modelling approach attempts to reproduce the structure of the whole economy and to capture economic transactions among the diverse economic agents (productive sectors, households, and public sectors). A CGE analysis captures a wide set of economic impacts derived from the implementation of a specific policy reform. Hence, the CGE approach is especially useful when the expected effects of policy implementation are complex and materialize through different transmission channels.

The model has been designed to address some issues that are central to an applied economic analysis of alternative ICT R&D funding policies. First, the model accommodates a range of policy instruments that may be used to stimulate ICT R&D activity in the economy. Second, it addresses some special characteristics of R&D and the dissemination of knowledge that are important for an analysis of policies to promote R&D. Third, the model captures the central economic effects of R&D activity on the economy. How the model addresses these issues is outlined below.

The model has been developed to analyse the economic effects of public support to R&D. It therefore needs to accommodate a range of policy instruments that could be used to stimulate private R&D expenditures. The model has been specified such that public support can stimulate private R&D through various changes in taxes, subsidies or procurement. This gives the flexibility to analyse the effects of a broad range of policy instruments.

The model is specified in such a way that it addresses the distinguishing features that characterise the R&D process. The output of the R&D process is considered as a special form of intangible capital – knowledge. Knowledge is defined as non-rival – its use by one person does not preclude its use by another person. Knowledge is not used up in the production process but continues to contribute to the common pool of knowledge. In addition, knowledge in the form of a new idea, design or blueprint may be non-excludable with one firm unable to prevent other firms from using it. When it is non-rival and non-excludable, knowledge takes the form of a public good, which discourages commercial R&D spending as it prevents firms from recovering their initial R&D expenditures. This market failure results in R&D expenditure levels below the social optimum.

However, knowledge may sometimes be characterised by some degree of excludability. In particular, it may in some cases be embedded in human capital, or firms may attempt at a cost to protect their idea or design through legal procedures such as patents or copyright. This gives rise to market power. Under these circumstances, monopoly rent makes it possible for a firm to finance R&D projects, which provides an incentive for innovation.

In the model presented here, R&D output contributes to the common pool of knowledge available to firms across sectors and countries. Hence, a firm's R&D-produced knowledge serves as a non-rival non-excludable public good benefitting all firms. However, the new knowledge in the model is also sold as blueprints that provide the purchasing firm with the exclusive right to its use. This excludable knowledge in the model entitles the purchasing firm to monopoly rent that covers the initial R&D expenditures.

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The CGE model is specified in such a way that R&D activity affects the economy through multiple channels. R&D production affects the allocation of labour, capital and goods in the economy. R&D producing firms compete for scarce resources with firms in other sectors. Hence, a change in R&D activity affects relative prices and the allocation of resource across the economy. For example, if the supply of skilled labour responds slowly to increasing demand from a growing R&D activity, this would affect skilled labour wages and production costs across the economy.

R&D in the model can foster growth in different ways. Firstly, R&D-produced knowledge expands the common pool of knowledge, which spills over into increased productivity of R&D producing firms as these benefit from the production of new knowledge and insights. Secondly, R&D leads to the development of new designs or blueprints, expanding the range of available production technologies. This is the case for ICT and for non-ICT production technologies. Thirdly, ICT technology in the model is a multipurpose technology, widely adopted across the economy in combination with skilled labour. Hence, an R&D-induced increase in new ICT technologies affects the production of goods and services across a broad range of sectors in the economy.

Summing up, the model presented here allows analysis of how public support to R&D funding policies affects economic growth, and the allocation of goods and production factors. The report is organised as follows. Section 2 presents the model. Section 3 describes the data and the calibration methodology.

5

# 2. The model

The model is a multi-country, multi-sector dynamic general equilibrium model. It is inspired by the Romer (1990) expanding capital variety model. Economic growth in the model is driven by R&D that increases the common pool of knowledge, improves labour productivity and expands the range of available production technologies.

The model contains four country blocs: Germany, France, the Rest of the EU (REU) and the Rest of the World (ROW). Each country is inhabited by a set of representative households which consumes final goods and supplies labour of a given skills level to the domestic production sectors. Each country contains a set of final goods sectors, homogenous capital producers, differentiated capital producers and R&D producers. The national government in each country collects taxes, pays out transfers and purchases government consumption. The EU Member States also pay contributions to the EU and receive EU transfers. The model is outlined below, and a more detailed presentation of the model can be found in Christensen (2015).

## 2.1 Production of final output

Final output production occurs in 5 sectors: (1) Agriculture, food and beverages, (2) Low-tech manufacturing, (3) High-tech manufacturing, (4) Services, and (5) Information and communication technologies (ICT). Each sector produces one type of output with a constant return to scale technology using intermediate goods, labour, and capital as input. Factors of production are perfectly mobile across sectors within a country but immobile internationally. Final output sector firms face perfectly competitive output markets. The output produced by a given final output sector is used as intermediate material input in all of the final output sectors and in the production of R&D. In addition, final outputs are consumed by domestic and foreign households and national governments. Final outputs are also used for investment by homogenous and differentiated capital producing firms.

The final output production technology is represented by a nested Constant Elasticity of Substitution (CES) – Leontief production function.

$$Y_F = f(L_{LS}, L_{MS}, L_{HS}, K_{LT}, K_{HT}, K_{ICT}, Y_D, Y_S, Y_T, \tilde{A}_{HT}, \tilde{A}_{ICT}, H_{LS}, H_{MS}, H_{HT}, H_{ICT})$$

The final output producer uses three types of labour skills (low $L_{LS}$, medium $L_{MS}$ and high $L_{HS}$), homogenous capital $K_{LT}$, two types of differentiated capital (ICT $K_{ICT}$ and other high-tech $K_{HT}$) and intermediate inputs that are sourced domestically $Y_D$ and internationally $Y_S$. Import of intermediate inputs gives rise to transportation costs in the form of international transport services $Y_T$. The production function also contains a number of factor specific exogenous productivity parameters ($\tilde{A}_{HT}$, $\tilde{A}_{ICT}$, $H_{LS}$, $H_{MS}$, $H_{HT}$, $H_{ICT}$). The entire nested input tree is shown in figure 1. Domestic and international intermediate inputs are considered to be imperfect substitutes and are differentiated according to an Armington function. Homogenous capital is combined with a mix of low and medium-skilled staff. High-skilled labour is used in combination with differentiated capital. Nesting differentiated capital and high-skilled labour makes it possible to introduce low elasticity of substitution between these production factors, reflecting that production using ICT technology or other high-tech technology requires some input from highly-skilled staff for operation and maintenance.

6

**Figure 1: The nested structure of the final output production technology**
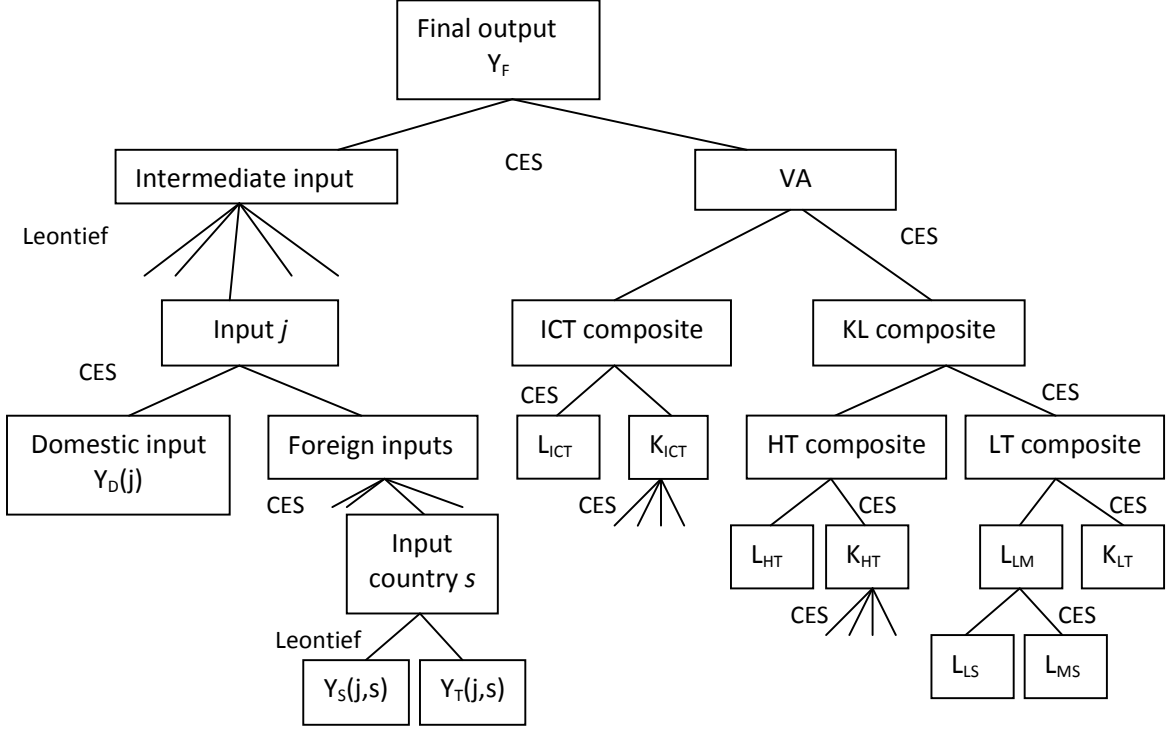


Input from differentiated capital is represented by a CES technology. The final output producing firm's demand for the ICT differentiated capital composite $K_{ICT}$ is given by:

$$K_{ICT} = \tilde{A}_{ICT}{}^{\nu_{ICT}} \left( \int_0^{A_{ICT}} K_{ICTV}(a)^{\frac{\sigma_{ICT}-1}{\sigma_{ICT}}} \, da \right)^{\frac{\sigma_{ICT}}{\sigma_{ICT}-1}}$$

where $K_{ICTV}(a)$ is the input of ICT capital of type $a$, $\tilde{A}_{ICT}$ is an exogenous productivity parameter, and $\sigma_{ICT}$ is the elasticity of substitution between ICT capital types. Introducing new production technologies increases $A_{ICT}$ and expands the ICT capital composite available for production.

## 2.2 Research and development

The model contains two types of R&D-producing firms: producers of ICT R&D and producers of non-ICT R&D. Though the model assumes, for simplicity's sake, that R&D production takes place separately from the production of final goods, this does not alter the outcome of the policy analysis. Each type of R&D firm produces new ideas or blueprints which are sold as patents and used in the production of new differentiated capital goods.

New ideas or blueprints are produced from intermediate inputs and primary factors. The production function of the R&D producer is represented by a nested CES-Leontief production function:

$$XD = f(L_{LS}, L_{MS}, L_{HS}, K_{LT}, Y_D, Y_S, Y_T, H_{LS}, H_{MS}, H_{HS})$$

Intermediate inputs are sourced domestically and abroad. Value added is produced from homogenous capital and the three types of labour skills. The variable $H_{HS}$ governs the productivity of high-skilled research staff and is endogenous in the model. The nesting tree is shown in figure 2.

**Figure 2: The nested structure of the R&D production technology**
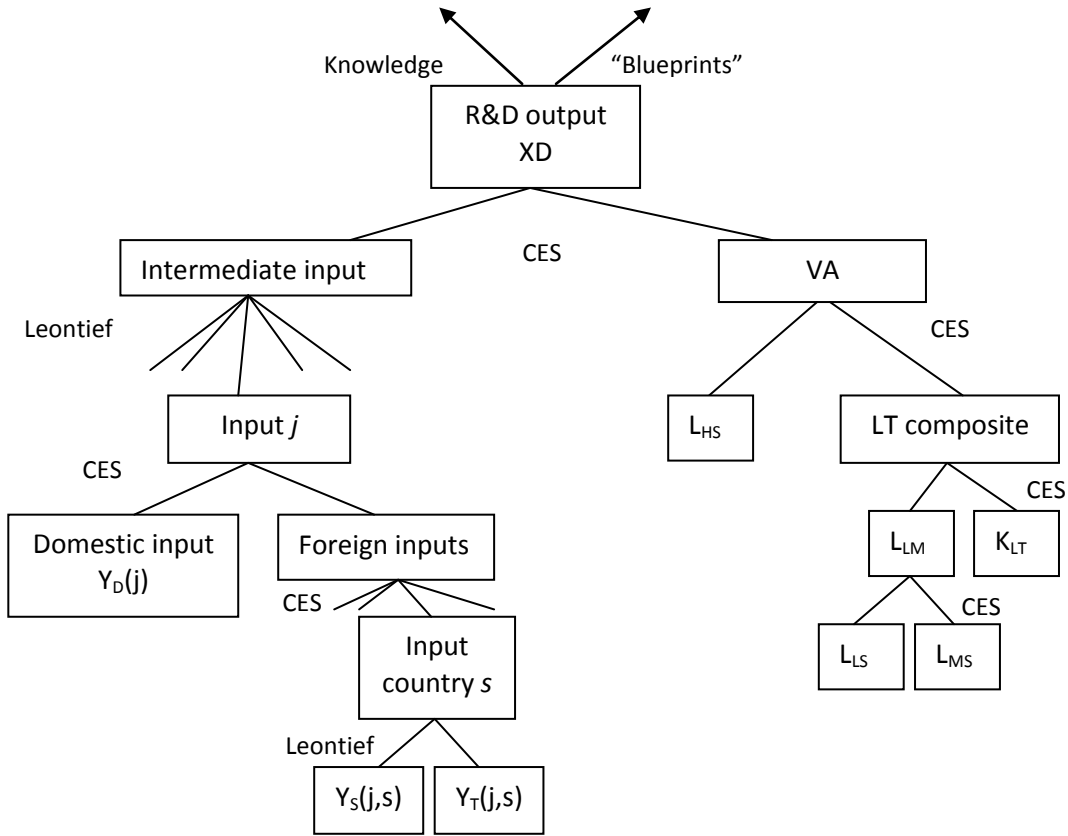


The output of each individual R&D producer expands the common pool of technological knowledge. The accumulation of technological knowledge leads to an increase in the productivity of the R&D active high-skilled labour force. Consequently, spillover becomes a source of further technological progress, increasing the efficiency of producing additional blueprints. The accumulated stock of technological knowledge $A_{RD}$ from R&D production of type $r$ is given by:

$$A_{RD,t+1}(r) = A_{RD,t}(r) + XD_t(r)$$

where XD is the production of new knowledge. We assume that the stock of new ideas from a given type of R&D potentially affects the productivity of all high-skilled research staff, domestically and abroad. We assume that the international spillover is related to bilateral trade flows.

It is assumed that all firms of a given R&D type have identical production technology and that they take prices as given in the factor and output markets. Each firm maximises the present value of after-tax cash flow by equating its output price with marginal costs.

## 2.3 Production of capital varieties

All regions host two differentiated capital producing sectors, ICT and other high-tech. Each of the two sectors consists of a number of firms, each producing a variety of differential capital. A producer of differentiated capital must first purchase a patented blueprint from a R&D producer. Firms in the ICT capital-producing sector purchase blueprints from the ICT R&D producers, while firms in the high-tech capital-producing sector purchase blueprints from the non-ICT R&D producers. Once the patent is bought, it excludes other firms from producing identical capital varieties. However, substitutes exist in the form of other capital varieties. Having obtained a patent

for a given capital variety, the capital producer invests in its capital variety and rents it to firms in the final output sectors. The ICT investment good is produced from intermediate inputs with a nested Leontief-CES production function with a nesting tree, as shown in figure 3.

**Figure 3: The nested structure of the differentiated investment goods composite**
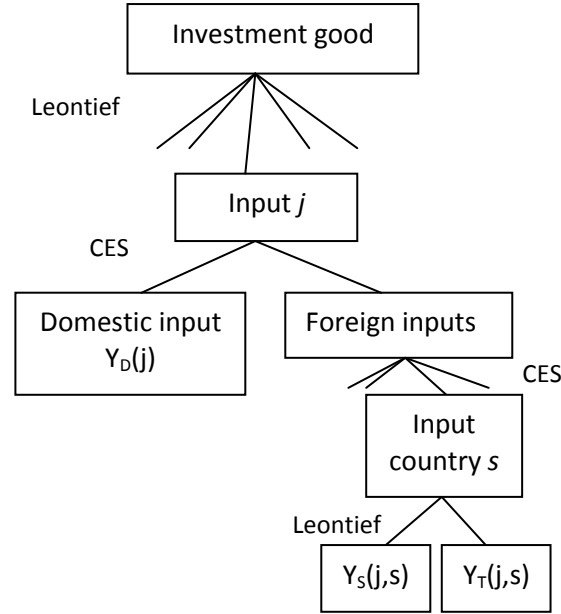


The ICT capital producer sets the capital utilization rate and makes investment decisions to maximise future expected profit, subject to the capital accumulation process and demand for its capital variety. The first order condition for investments is given by:

$$R_{ICTV,t+1}(a) = \frac{\sigma_{ICT}}{\sigma_{ICT}-1} \frac{\left((1+i_t)MC_{ICT,t}(a) - MC_{ICT,t+1}(a)\left(1-\delta_{ICT}-\phi_{ICT,t+1}(a)\right)+\psi_{ICT,t}(a)\right)}{u_{ICTV,t+1}(a)}$$

where $R_{ICTV}$ is the capital rental price, $MC_{ICT}$ is marginal cost of a unit of the investment good, $\delta_{ICT}$ is the depreciation rate of capital and $i$ is the risk free interest rate. $u_{ICTV}$ is the capital utilisation rate, and $\phi_{ICT}$ is the cost of deviating the rate of capital utilisation from its long run level. The variable $\psi_{ICT}$ captures the cost of adjusting the stock of capital and the investment levels. The firm invest such that the expected rental price is equal to a constant mark-up over the risk free return on its investment, adjusted for losses due to depreciation, adjustment costs and expected gains due to changes in the next period's price of its investment goods. It is assumed that all ICT capital producers share an identical production technology and, hence, all set identical capital rental prices and face the same demand for their ICT capital variety.

Asset market equilibrium requires that an investor is indifferent between investing in the ICT capital producer and holding a risk free bond. In equilibrium, the price of patents for new ICT capital varieties equals the expected discounted future return from producing the capital variety. New firms enter the ICT capital variety-producing sector as long as the firm's discounted net profit is equal to the entry costs. The price for new ICT patens $P_{XD}$ is thus given by:

$$P_{XD,t}(r) = \sum_{j=0}^{\infty} \left( \left(\frac{1}{1+i_t}\right)^j \left( R_{ICTV,t+j}(a)\widehat{K}_{ICTV,t+j}(a)u_{ICTV,t+j}(a) - MC_{ICT,t+j}(a)I_{ICTV,t+j}(a)\right)\right)$$

where $K_{ICTV}$ is the aggregate demand for the differentiated capital variety and $I_{ICTV}$ is investments in the capital variety. The production technology of the high-tech capital producer is assumed to be similar to that of the ICT producer. Hence, investment decisions of the differentiated high-tech capital producers can be found in a similar fashion.

## 2.4 Production of homogenous capital

The model contains one type of low-tech homogenous capital. Firms in the homogenous capital sector invest in homogenous capital goods and rent them to final output producing firms and R&D producing firms. The homogenous investment goods are produced from intermediate inputs with a nested Leontief-CES production function with a nesting tree identical to the one for the differentiated capital producers.

The homogenous capital producer chooses the capital utilisation rate and investment that maximizes the expected profit. The first order condition for investments is given by:

$$R_{LT,t+1}u_{LT,t+1} + MC_{LT,t+1}(1 - \delta_{LT} - \phi_{LT,t+1}) = (1 + i_t)MC_{LT,t} + \psi_{ICT,t}$$

where $R_{LT}$ is the rental price of capital, $MC_{LT}$ is the marginal cost of the investment goods, and $\delta_{LT}$ is the depreciation rate. $u_{LT}$ is the capital utilisation rate, and $\phi_{LT}$ is the cost of deviating the rate of capital utilisation from its long run level. The variable $\psi_{LT}$ captures the cost of adjusting the stock of capital and the investment levels. The expected return on investments depends on the risk free interest rate, the depreciation rate, adjustment costs and the expected price of the homogenous investment good in the next period.

## 2.5 Households

Each country bloc in the model is inhabited by 3 types of representative infinitely lived households. The households supply labour of their given skills type (low, medium or high) to domestic firms, earn income from their holdings of financial assets, and consume goods produced by the domestic and foreign final output producers. Labour supply in the model is endogenous, with the household at the margin choosing between an extra unit of goods consumption and an extra hour of leisure.

The representative households supplying low-skilled labour are assumed to be liquidity constrained with no access to credit markets and no holding of financial assets.

### 2.5.1 Non liquidity constrained households

The representative households supplying medium and high-skilled labour are assumed to have access to credit markets. These households are assumed to hold shares in domestic firms and trade in risk free government bonds and internationally-traded risk free bonds. The representative households derive utility from consumption and leisure. We allow for habit persistence in consumption and leisure to capture a gradual hump-shaped response of real consumption and labour to policy changes[2]. This utility function is given by:

$$U_s(h) = \sum_{t=s}^{\infty} \beta^{t-s} \frac{[(C_t(h) - h_C C_{t-1}(h))(H - (L_t(h) - h_L L_{t-1}(h)))^{\eta_{c(h)}}]^{1-\phi_{c(h)}}}{1 - \phi_{c(h)}}$$

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[2] Habit persistence are often used in medium scale macroeconomic models to capture the hump shaped response of consumption and labour observed in the data, in which the peak response occurs several periods after the policy implementation, see e.g. Christiano, Eichenbaum and Evans (2005), Smets and Wouters (2007) and Ratto et al. (2008).

where $\beta$ is the rate of time preference, $C$ is the aggregate bundle of commodities consumed, $L$ is the hours of total labour supply, and $H$ is the total hours available for leisure or work. The parameter $\eta$ measures the impact of leisure on the welfare of the representative household, while the parameter $\varphi$ is related to the inter-temporal rate of substitution. The parameters $h_C$ and $h_L$ governs the degree of habit persistence in consumption and leisure respectively. The aggregated composite of household consumption goods is given by a nested CES function with a nesting tree as shown in figure 4.

**Figure 4: The nested structure of the consumption composite**
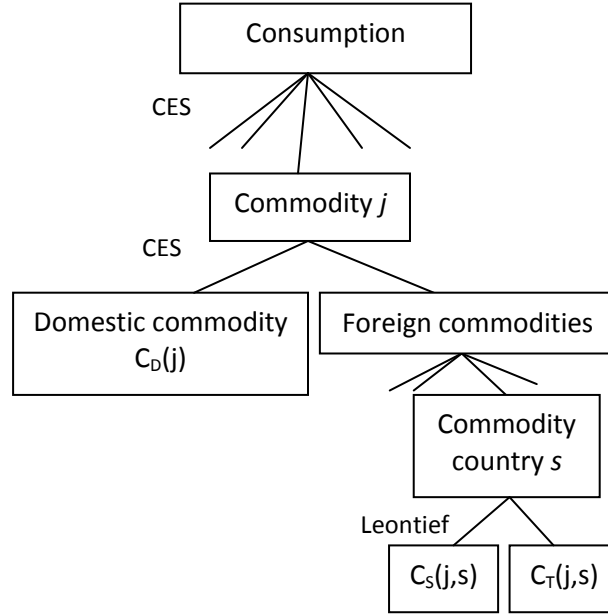


The representative household optimizes its utility subject to budget constraints:

$$\left(1 - \tau_{L,t}(h)\right)W_t(h)L_t(h) + \left(1 - \tau_{K,t}(h)\right)\left(\pi_{HT,t}(h) + \pi_{ICT,t}(h) + \pi_{LT,t}(h) + \pi_{FI,t}(h)\right)$$
$$+ D_t(h)\left(1 + i_{D,t}\right) + B_{G,t}(h)(1 + i_t) + T_{H,t}(h)$$
$$= P_{C,t}(h)C_t(h) + D_{t+1}(h) + B_{G,t+1}(h)$$

where $W$ is the wage for one hour of labour of skill $h$, $\tau_L$ is the income tax rate, $D$ is the net deposit at the financial intermediary, $B_G$ is the net holding of risk-free bonds issued by the national government in the region in which the household resides, The households receives dividends from the monopolist capital producers in the high-tech and the ICT sector, from the homogenous capital producers and from financial intermediaries. The household also receives a lump sum transfer, $T_H$, from the national government in the region in which it resides.

Inter-temporal optimization gives the first order conditions:

$$U_{C,t}(h) = \beta\left(1 + i_{D,t}\right)\frac{P_{C,t}(h)}{P_{C,t+1}(h)}U_{C,t+1}(h)$$

$$U_{C,t}(h) = \beta(1 + i_t)\frac{P_{C,t}(h)}{P_{C,t+1}(h)}U_{C,t+1}(h)$$

$$\left(1 - \tau_{L,t}(h)\right)\frac{W_t(h)}{P_{C,t}(h)}U_{C,t}(h) = U_{L,t}(h)$$

The household balances the marginal utility of current consumption with marginal utility of future consumption. Furthermore, the household supply labour such that the marginal utility of consumption from an additional hour of labour equals the marginal utility from an additional hour of leisure.

### 2.5.2 Liquidity constrained households

In each country bloc, a representative household supplies low-skilled labour to firms producing final goods and R&D. The representative household's utility and the aggregate composite of household consumption is defined in a similar fashion to that of the non-liquidity constrained households. We assume that the household is liquidity constrained with no holding of financial assets. Hence, the household consumes all its income each period. Labour supply can be found in a similar fashion to that of the non-liquidity constrained households.

## 2.6 National governments

The national government in each country collects taxes, pays out subsidies and household transfers and purchases commodities for government consumption which are provided free of charge to the representative households residing in the country. The national governments in the countries which are members of the EU also pay contributions to the EU and receive transfers from the EU. Government consumption is a CES composite of domestic and foreign final goods defined in a similar fashion to that of the private households. The government budget constraint is given by

$$TR_t - B_{G,t}(1 + i_t) = P_{G,t}G_t + T_{H,t} + T_{EU} - B_{G,t+1}$$

where $B_G$ is national government issued bonds which is held by domestic households, $T_H$ is net transfers to domestic households, $T_{EU}$ is net transfers to the EU and $TR$ is net tax revenue. Net tax revenue consists of revenue from taxation of the production factors, gross output taxation, consumption taxation, taxes on investment demand, intermediate input taxation, and revenue from import tariffs, less export subsidies. Income taxes are levied on each of the 3 skills types of labour and on dividend income from holding of shares

Government consumption is assumed to be a fixed proportion of GDP. To rule out explosive levels of government debt, we assume that the national governments adjust the net transfers to domestic households in response to changes in the public debt to GDP ratio.

## 2.7 Financial intermediary

Each country bloc in the model has a financial sector with perfectly competitive financial intermediaries. The financial intermediary receives net deposit from the non-liquidity constrained households and places these in international traded bonds. We assume that the financial intermediary operates at no cost (an assumption that may be relaxed later to allow for financial services funded by an interest rate margin). In a given period the financial intermediary receives net deposit and converts these into internationally traded bonds. Each period the financial intermediary, thus, faces the funding restriction

$$\sum_{h=1}^{nh} D_{t+1}(f,h) = B_{EU,t+1}(f) + S_t B_{ROW,t+1}(f)$$

where $D$ is the net deposit in financial intermediary $f$ by household of type $h$, $B_{EU}$ and $B_{ROW}$ are net holdings of EU and ROW currency basket denominated bonds respectively, while $S$ is the spot market exchange rate. Note that a positive net deposit by domestic households means that the domestic financial intermediaries holds internationally-traded bonds issued by financial intermediaries in other countries, while a negative net deposit by domestic households means that the domestic financial intermediaries issues internationally-traded bonds held by financial

intermediaries in other countries. The financial intermediary takes the deposit rate as given and chooses its bond holdings such that it balances next periods return on household net deposits with the expected return on international bond holding. The first order conditions for EU and ROW currency denominated bond holdings is given by

$$(1 + i_{D,t}) = (1 + i_{EU,t})$$

$$(1 + i_{D,t}) = (1 + i_{ROW,t})\frac{S^e_{t+1}}{S_t}$$

Combining these first order conditions for internationally-traded bonds shows that the uncovered interest parity holds:

$$(1 + i_{EU,t}) = (1 + i_{ROW,t})\frac{S^e_{t+1}}{S_t}$$

## 2.8  The EU

The EU receives net contributions from its Member States and revenue from import tariffs. Import tariffs are levied on imported commodities goods and inputs that are sourced from non EU-member countries (ROW). Furthermore, the EU pays subsidies to firms in the Member States. The net contribution to the EU from Member State *c* is given by:

$$T_{EU,t}(c) = TR_{MS,t}(c) + a_{EU,t}(c)GNI_t(c) - T_{MS,t}(c)$$

where *TR_MS* is the revenue from tariffs on extra EU imports, the coefficient *a_EU* determine the country's GNI contribution, and *T_MS* is a lump sum transfer from the EU to the Member State.[3]

The EU is assumed to balance its budget in every period by proportional adjustments of the GNI contributions from Member States. Note that while we assume that the EU budget is balanced in each period, we do not assume that each Member State's net contribution to the EU is balanced. Some Member States may receive net benefits while others pay net contributions (where this last is the case, the EU redistributes public funds across the Member States).

## 2.9  International transport services

A perfectly competitive international transport sector produces transportation services of international traded goods. The transport service is sold to importers of goods across all sectors and countries. The international transport service is produced from intermediate inputs sourced from the service sector in all countries. The intermediate inputs from different countries are assumed to be imperfect substitutes. The production of international transport services follows a CES production function.

## 2.10  Foreign trade

All final outputs can be traded internationally. Final outputs are sourced internationally by firms, households and national governments. Imported final outputs are considered to be imperfect substitutes for domestically produced final outputs.

We allow for international capital mobility. Domestic financial intermediaries lend or borrow through internationally-traded risk free bonds. The region´s current account *CA* is given by:

$$CA_t = TB_t - T_{EU,t} + i_{EU,t}B_t + i_{ROW,t}S_tB_t$$

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[3]   The lump sum transfer covers payments from the Common Agricultural Policy (CAP), structural funds etc.

where *TB* is the region's trade balance, $T_{EU}$ is the net transfer to the EU and $B_{EU}$ *and* $B_{ROW}$ are the region's aggregated holdings of internationally-traded bonds. The country's accumulated holding of international traded bonds is given by:

$$B_{EU,t+1} + S_t B_{ROW,t+1} = CA_t + B_{EU,t} + S_t B_{ROW,t}$$

## *2.11 Market clearing*

All markets clear in each time period. This requires that (1) demand for each production factor in each country equals its supply, (2) demand for the output from each final output sector in each country equals its supply, (3) The output by R&D producers in each country equals the number of new capital varieties invested, (4) total net holding of internationally traded bonds across all countries equals zero, and (5) total household savings across all countries equals total investment.

# 3. Data and calibration

The model is calibrated to replicate a given initial base year and to generate a specified reference growth path.

## 3.1 Data and parameters

The model is calibrated to a dataset based on the GTAP 8 database. This database covers 129 countries and contains data on value added, material inputs, factor inputs, private consumption, public consumption, investments and international trade for the base year 2007. The GTAP database is modified to a model consistent dataset using weights calculated from the Predict database, national account data and other supplementary datasets.

The 57 sectors in the GTAP 8 database are aggregated to form the model's 5 final output production sectors. The ICT sector is defined here according to definition guidelines from the OECD.[4]

The ICT sector, in some cases, represents fractions of the existing GTAP 8 sectors. These GTAP 8 sectors are split into ICT and the non-ICT parts by use of weights calculated from national account data. The aggregation of the GTAP manufacturing sectors into high-tech manufacturing and low-tech manufacturing sectors is done in accordance with guidelines from Eurostat that groups manufacturing sectors by their technological intensity. The remaining final output sectors services and agriculture, food and beverage follows the standard GTAP 8 classification.

R&D expenditures are calculated for the 5 final output sectors using data from the PREDICT database. The PREDICT database contains data on private sector and public sector R&D expenditures. The R&D expenditure by each sector is subtracted from the final commodity output and allocated to R&D output. R&D expenditures in the ICT sector are allocated to ICT R&D output, the remaining R&D expenditures are allocated to non-ICT R&D output.

Investments in physical capital are divided into the model's three capital types – homogeneous capital, ICT capital and other high-tech capital – using the national accounting classification of gross fixed capital formation by asset types.

The GTAP 8 database splits payments to labour into payments to skilled and unskilled labour. The GTAP-defined payments to skilled labour are taken as payments to high-skilled labour in the model. Payments to unskilled labour are split into payments to low and medium-skilled households using weights taken from the Socio-economic Accounts of the World Input-Output Database (Timmer (2012)). The value of private consumption is split between the three household types using weights based on the skills group's relative income in the base year.

Tax rates on labour and capital income are taken from the OECD tax database. For the tax rate on labour income for low skilled households, we use the average tax wedge for a single person at 67% of average earning with no children. The tax rates for medium and high-skilled households are set as the average tax wedge for a single person at 100% of average earning with no children. The tax rate on dividend income is set to equal the net personal income tax rate on dividend income. The aggregate net lump sum transfer from the national government to households is set in such a way that the government primary budget surplus is consistent with the dataset.

Households supplying low-skilled labour are assumed to be liquidity constrained with no holding of financial assets. The net income from national government lump sum transfers for this household type therefore equals the after-tax labour income, less the value of consumption. The remaining

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[4] The ICT sector include the following NACE 1.1 sectors:
Manufacturing; Manufacture of office, accounting and computing machinery (30) , Manufacture of radio, television and communication equipment and apparatus (32), Manufacture of medical, precision and optical instruments, watches and clocks (33). Services; Post and telecommunications (64), Computer and related activities (72).

net income from national government lump sum transfers is allocated to households, supplying respectively medium-skilled and high-skilled labour according to their after-tax income from labour and capital.

We assume that the model in the base year is in steady state with a balanced current account. Hence, bilateral trade flows, bond holdings and lump sum transfers in the model are adjusted accordingly.

A number of model parameters are specified exogenously. The elasticities of substitution in the model are set to reflect estimates in the literature (see e.g. Van der Werf (2008), Okagawa and Ban (2008), and Koesler and Schymura (2012)). A detailed description of the setting of the substitution elasticies in production nests and consumer preferences in the model can be found in Christensen (2015). We do not have a strong empirical foundation for choosing the substitution elasticties between the various capital-labour composites in the production function. We assume that the elasticity of substitution between differentiated capital and high-skilled labour is relatively low at 0.15 to reflect the assumption that highly specialised technology requires some inputs from a highly-skilled workforce. In comparison the elasticity of substitution between the low-medium labour composite and homogenous capital in the model varies from 0.29 to 0.45 reflecting estimates in Koesler and Schymura (2012). The parameters governing habit persistence in consumption and labour are also set exogenously. The capital utilization rate for differentiated capital and homogenous capital are assumed to be 0.8. Cost of adjusting capital utilization for all capital types is set as follows. The parameter governing the quadratic cost term is specified exogenously for all capital types, while the reaming parameter is given by the first order condition for capital utilization in the model. The parameters governing cost of adjustment to capital and investment is set exogenously for all capital types. The parameter governing the cost of adjusting R&D output is similarly determined exogenously.

The remaining parameters in the model are calibrated such that the model replicates the dataset for the reference year and the specified reference growth path.

## 3.2   The reference growth path

The model is calibrated to generate a reference growth path. We assume a reference growth path where production, GDP, consumption and investments across all countries growth at the model's reference growth rate. The reference growth rate is set to 1.64 pct. p.a. This corresponds to the annual average real growth rate for the 28 EU Member States for the period 1995-2013. It is possible to specify an alternative reference growth path in which specified reference growth rates varies over time and across countries. The annual inflation rate is set to 1.81 pct. p.a. which corresponds to the annual inflation in the implicit GDP deflator for the 28 EU Member States for the period 1995-2013. In its main scenario Eurostat projects the annual growth in the population aged 15-64 in the 28 EU member states from 2015 to 2050 to -0.31 pct. p.a. We set the annual growth in the labour force accordingly.

The annual nominal interest rate for a risk free bond is set to equal 4 pct. The households' discount rate is set such that the model generates its long run growth rate.

In the model economic growth is driven partly endogenously through R&D and partly by exogenously specified growth components. The R&D-driven endogenous growth in a country is generated from domestic knowledge accumulation and from cross-border spillover of foreign knowledge. The growth from domestic knowledge accumulation is govern by R&D productivity elasticities with respect to the domestic R&D knowledge stock. These are set at levels comparable to estimates of TFP elasticities with respect to domestic R&D stocks reported in Coe et al. (2008). The growth due to cross border spillover of knowledge is governed by the R&D productivity elasticities with respect to the foreign R&D knowledge stocks. These elasticity parameters are also set to levels comparable with estimates of TFP elasticities with respect to foreign R&D stocks

reported in Coe et al. (2008). Given parameters for cross-border spillover, the initial stocks of knowledge are calibrated such that the growth generated from R&D in each country equal the country's reference growth rates. The exogenous growth components is then set such that the model generates its reference growth path. This is done to ensure that the model converge to a balanced growth path in which all endogenous variables in all countries growth at the same long term growth rate and the transversality conditions for bond holding are satisfied.

# 4. Concluding remarks

This report describes the first pilot version of the CGE model developed under the PREDICT 2 research project. The model is specified in such a way that it captures the multiple channels through which R&D activity in the ICT sector affect the economy. The model is therefore well suited to the analysis of public support to R&D targeted at the ICT sector. R&D-promoting policies affect the allocation of labour, capital and goods in the economy. A change in R&D activity affects relative prices and the allocation of resources across the economy. ICT R&D in the model serves as an engine for growth through multiple channels. Firstly, R&D-produced knowledge expands the common pool of knowledge, which spills over into increased productivity in the R&D sectors as these benefit the production of new knowledge and insights. Secondly, R&D leads to the development of new designs or blueprints, which expand the range of available production technologies. This is the case for ICT and for non-ICT production technologies. Thirdly, ICT technology in the model is a multipurpose technology, which is widely adopted across the economy in combination with skilled labour. Hence, an R&D-induced increase in new ICT technologies affects the production of goods and services across a broad range of sectors in the economy.

In addition, the model presented here allows analysis of how public support to R&D affects welfare. The CGE approach adopted for the model is well-suited to quantitative evaluation of welfare effects of alternative policy scenarios. Using the households' assumed utility functions to evaluate welfare makes it possible to examine how much better or worse off the households are due to the implementation of a given policy. The changes in welfare can be quantified by an Equivalent Variation (EV) measure, which expresses the change in income that households would have needed to afford the new level of utility at pre-policy prices. The scope for analysing welfare effects of alternative policy scenarios will be explored in future work.

As a follow up to the work described in the present document, the merits of the model will be explored in future work through a series of policy scenarios covering different amounts of spending, policy instruments and sources of funding. The sensitivity of results to the setting of central model parameters will also be analysed.

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