- RHOMOLO -
A Dynamic Spatial General Equilibrium Model*

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Abstract

This paper presents a new dynamic general equilibrium modelling framework (RHOMOLO). The RHOMOLO model is being developed and will be applied by the European Commission for the evaluation of the EU's Regional Policies Compared to the existing economic models used for the evaluation of Cohesion Policy, RHOMOLO incorporates several important features, such as, endogenous location of firms and workers à la new economic geography and semi-endogenous growth. Empirically, RHOMOLO is being implemented for the EU-27 with regional and sectoral detail, different types of labour skills and household income classes, which allows detailed impact assessments to be made for alternative policy options. The application areas of RHOMOLO are wide and range from transport infrastructure improvements to investments into R&D and human capital.

Keywords: Economic modelling, dynamic spatial general equilibrium, semi-endogenous growth, economic geography, EU, Cohesion Policy.

JEL classification: F1, O1, R3, R4.

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1 Introduction

The objective of this paper is to provide an outline of the structure and capabilities of the Dynamic Spatial General Equilibrium Model (RHOMOLO) model which is being developed in European Commission for the purpose of impact assessment of Structural and Cohesion Fund expenditure.

RHOMOLO can be used not only for ex-ante European Cohesion Policy (ECP) impact assessment but also for ex-post impact assessment, other policy simulations and comparison between the policy scenarios. RHOMOLO incorporates the following important features: (i) linking regions within a New Economic Geography (NEG) framework; (ii) having inter-temporal dynamic features with endogenous growth engines; (iii) including detailed public sector interventions; and (iv) incorporating a multi-level governance system.

2 Model-based evaluation of Cohesion Policy at European Commission

Ever since the inception of Cohesion Policy there has been a need to model it's impact, but only a few models stand the test of time as having been used continuously to analyse impacts across the Member States on a consistent basis. Although there are many partial models looking at the impact of Cohesion Fund expenditure, there are few that take a broader view and attempt to incorporate feedback general equilibrium feedback effects. Two such models, which have been used by Commission Services, are the HERMIN and QUEST models.

The HERMIN model was developed in the 1980s (as a spin-off from the EC-led HERMES modelling system) to investigate the impact of Cohesion Fund spending on the Irish economy programmes and were subsequently extended during the following two decades to cover all the cohesion countries (initially Portugal, Greece and Spain within the EU15, then southern Italy, and more recently the New Member States). It has been (and continues to be) widely used for the purpose of Cohesion Policy evaluation by the European Commission, with separate models being developed for each Member State. The HERMIN model has a mix of neoclassical long-term (eg supply-side effects on human and physical capital) and Keynesian short-term features (e.g. multiplier effects generated through increased expenditure) and a limited sectoral disaggregation.

In addition to HERMIN, the QUEST model of DG ECFIN has been used to assess the impact of Cohesion policy expenditure (see *Varga* and *in't Veld* 2009).

In contrast to HERMIN, the QUEST model is forward-looking, with behavioural equations grounded in microeconomic theory and based on the inter-temporal optimisation of households and firms. In addition, households adjust their behaviour in the expectation of future tax payments arising from higher public expenditure, while real interest and exchange rates are determined endogenously, so that possible crowding-out effects can be taken into account. It is a country-based model with no sector disaggregation.

In 2006 the European Court of Auditors produced a special report which reviewed the ex-post evaluations of Objective 1 and 3 programmes 1994-1999. The HERMIN macroeconomic model was used to simulate the macroeconomic impact of Structural Fund interventions. The Court report noted that the macroeconomic model "suffered from significant limitations", and went on to say that if such models are to be used for evaluating economic impacts of Cohesion Funds then they should take proper account of the specific features of the economies being analysed, as well as making better use of the micro-data generated at project level. More specifically, the report noted particular difficulties with the HERMIN model's applicability to the ex post assessment:

- too-strong emphasis on the manufacturing sector, given the increasingly tradeable nature of services and the importance of tourism to some regional areas;
- econometric approach, i.e. model parameters based on period averages from 1980, unable to cope with the structural change that is endemic in regions that are undergoing rapid shifts during the period of analysis;
- exclusion of private sector co-financing and subsequent spillover effects, eg 'crowding-in';
- use of elasticities based on US regional literature to cope with the supply-side effects of the Structural Funds, i.e. human and physical capital stock augmentation.

However, not all these criticisms are directly to do with the model, and at the time it was seen as the best tool that was available for the purpose. However, the criticism of the Court of Auditors, together with developments in the theory of regional economics through the field of New Economic Geography which had been gaining momentum during the 1990s and was starting to generate empirical applications in the early part of the last decade, may have led to thoughts that the kind of changes needed to bring the HERMIN model up to date were too great to be made within the confines of the model's structure and that a new modelling approach was required.

The European Court of Auditors report provided a pressure to react and consider a new modelling approach. Neither the HERMIN nor the QUEST model allowed regional disaggregation of impacts, despite the fact that Cohesion Policy is place-based and many of the objectives are regional in nature.

In addition to the need for a model capable of delivering regional results, the findings of the Barca Report (Barca, 2009) have contributed to a need to look beyond the purely economic effects of policy impact, with a suggested reformulation of Cohesion Policy around six core priorities: innovation, climate change, migration, children, skills, and ageing . Indeed, for some time now a three-pronged approach has been followed, namely to look (where relevant) at economic, social and environmental dimensions. Neither the HERMIN nor the QUEST models are designed to investigate environmental and social impacts, and so the RHOMOLO model is aimed at filling this gap in the modelling space as well.

Both these models only focus on the economic impact of Cohesion Policy, however, ignoring the environmental aspect, for example on greenhouse gas emissions. The E3ME model has been used for some environmental analysis of Cohesion Funds along the lines of sustainable development, but here, as with the previous two models, the analysis is limited to the Member State level despite the obvious region-specific / spatial impact of much of the policy.

3 RHOMOLO model description

The modelling structure of RHOMOLO is based in a class of models known as a spatial computable general equilibrium, SCGE for short. Typically, SCGE models are micro-founded comparative static equilibrium models using utility and production functions to describe household, firm and government decisions, and which incorporate the modelling of (dis)economies of scale, external economies of spatial clusters of activity, continuous substitution between primary production factors and material inputs in the case of firms, and between different consumption goods in the case of households. In order to do this, firms are usually assumed to operate under economies of scale in markets with monopolistic competition of the Dixit-Stiglitz type (*Dixit* and *Stiglitz* 1977) which allows for heterogeneous products implying variety, and therefore allows for cross hauling of close substitutes of products between regions.

The RHOMOLO model utilises the notion of the representative economic agent which aims to capture the behaviour of each population group or sector through that of a single aggregate agent. It is further assumed that the behaviour of each such aggregate agent is driven by optimisation criteria such as maximisation of utility or minimisation of costs. In this respect, the model is Neo-classical and assumes average cost pricing and no excess profits.

The world consists of R regions in the EU, $r \in \{1,..,o,..,r,..,d,..R\}$, one aggregate region capturing the rest of the EU, and one aggregate region capturing the rest of the world.[1] Each region is endowed with F types of production factors, $f \in \{LS_{er}, KS_r, LDS_r\}$. The model distinguishes between three types of workers according to their education level e: low, medium and high skill. Workers are mobile both between regions and sectors. The regional supply of labour, LS_{er}, with education e is determined by labour endowment in the previous period plus population growth net of migration. The total world-wide labour supply is fixed in each period. Capital is mobile between regions, but immobile between industries within a region. Capital supply, KS_r, in each period is determined by capital endowment in the previous period plus investment minus depreciation. The regional endowment with land, LDS_r, is fixed exogenously.

There are three types of economic agents: households, h, governments, g, and firms (industries), i. Households are further disaggregated according to five income classes. Households receive income from the employed factor ownership and government transfers. The income is spend on the consumption of goods and services, the rest is saved. There are two types of governments in each region: national and regional. Governments receive income mainly from taxes. Both regional and national governments consume goods and services, make transfers through subsidies, and save part of their income. Each region hosts also two types of firms (which are representative for the respective industries): 'traditional' type and 'modern' type. Both types of goods - traditional and modern - are traded among all regions. The traditional sector is perfectly competitive, it produces a homogenous good under constant returns to scale. Monopolistically competitive manufacturing industries, which represent increasing returns and mobile production activities in the economy, produce horizontally differentiated goods. In each modern sector we assume the Chamberlinean monopolistic competition with free entry and exit of firms. Hence, the output prices are equal to marginal costs plus mark-up, which depends on the elasticity of substitution between varieties of differentiated goods. The 'love of variety' preferences of consumers (*Dixit* and *Stiglitz* 1977) imply that there is demand for each variety of each differentiated good in every region. Both intra- and inter-regional

[1] Throughout the paper we use subscript o to denote the origin region and subscript d to denote the destination region for trade flows, migration, capital and income flows.

sales are subject to positive trade costs.

3.1 Households

In each period household h solves a static one-period optimisation problem by maximising the Stone-Geary utility function (1) subject to budget constraint (2):

$$\Omega_{hr} = \varrho_{hr} \Pi_i \left(C_{hir} - \mu H_{hir} \right)^{\alpha H_{hir}} \tag{1}$$

$$B_{hr} = Y_{hr} \left(1 - ty_r \right) + T_{ghr} + c_{hr} \sum_e \xi_{er} wu_{er} U_{er} - C_{hr} - SH_{hr} \tag{2}$$

where $C_i \left(> \mu H_i \geqslant 0 \right)$ is the demand for good i, μH_{hir} is the subsistence consumption level, and c_{hr} is the initial consumption share. Parameters sc_{ir} and tc_{ir} capture subsidies and taxes for product i, ξ_{er} is the replacement rate of unemployment for workers with education e in region r, and ϱ_{hr} is a scaling parameter. According to equation (2), the total budget, B_{hr}, of household h in region r consists of income, Y_{hr}, social transfers, T_{ghr}, from government g, and unemployment benefits, $wu_{er} U_{er}$, which is allocated between the consumption of goods of services, C_{hr}, income tax, ty_r, and savings, SH_{hr}.

Solving the consumer optimisation problem yields a Linear Expenditure demand System (LES):

$$\begin{aligned} P_{ir} \left(1 - sc_{ir} + tc_{ir} \right) C_{hir} \quad = \quad & \alpha H_{hir} \left(B_{hr} - \sum_i \mu H_{hir} P_{ir} \left(1 - sc_{ir} + tc_{ir} \right) \right) \\ & + P_{ir} \left(1 - sc_{ir} + tc_{ir} \right) \mu H_{hir} \end{aligned} \tag{3}$$

where P_{ir} is the consumer price for good i in region r.

The income of household h in region r stems from supplying labour, L_{ehir}, with education e to industry i at wage w_{eir}, and from the ownership of capital, K_{hir}, and land, LD_{hr}:

$$Y_{hr} = \sum_{ei} w_{eir} L_{ehir} + \sum_i RK_{ir} K_{hir} + PLD_r LD_{hr} \tag{4}$$

where RK_{ir} and PLD_r are the rental rates of capital and land, respectively.

Household h in region r saves a fixed share, SH_{hr}, of her budget:

$$SH_{hr} = mps_{hr} \left(Y_{hr} \left(1 - ty_r\right) + T_{hr} + c_{hr} \sum_e \xi_{er} wu_{er} U_{er} \right) \tag{5}$$

where mps_{hr} is the marginal propensity to save.

3.2 Firms

3.2.1 Input demand

The input demand and output supply of firms is modelled via nested CES-Leontief production functions. At the top level, depending on output level, XD_{ir}, firms determine the use of intermediate inputs, IO_{jir}, and the composite capital-labour-land-energy input, $LDKLE_{ir}$, according to the Leontief production technology:

$$IO_{jir} = io_{jir} XD_{ir} \tag{6}$$

$$LDKLE_{ir} = io_{ifr} XD_{ir} \tag{7}$$

where io_{jir} and io_{ifr} are input-output coefficients for intermediate inputs and value added, respectively. The associated price index for the composite intermediate input, PIO_{ir}, is a weighted average individual intermediate input prices, P_{ir}:

$$PIO_{ir} = \frac{\sum_j XD_{ir} P_{jr}}{IO_{jir}} \tag{8}$$

The associated price index for the composite capital-labour-land-energy input, $PLDKLE_{ir}$, is a weighted average of prices for land, PLD_r, and the composite capital-labour-energy input bundle, $PKLE_{ir}$:

$$PLDKLE_{ir} = \frac{PLD_r LD_{ir} + PKLE_{ir} KLE_{ir}}{LDKLE_{ir}} \tag{9}$$

In the following five subsequent stages the demand for capital, labour, land and energy inputs is determined through profit maximisation according to a nested CES production function:

$$XD_{ir} = TFP_{ir} \left(\sum_f a_{fir}^{\frac{1}{\sigma}} F_{fir}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{10}$$

where TFP_{ir} is the total factor productivity, σ is the elasticity of substitution, and a and γ are factor share parameters.[2] First, firms decide on dividing the composite primary factor demand, $LDKLE_{ir}$, between the composite capital-labour-energy input, KLE_{ir},[3] and land, LD_{ir}. As usual, the demand for primary factors KLE_{ir} and LD_{ir} is obtained by taking partial derivatives according to Shephard's lemma:

$$\begin{aligned} KLE_{ir} &= \left(LDKLE_{ir} \left(\frac{\gamma KLE_{ir}}{PKLE_{ir}} \right)^{\sigma} PLDKLE_{ir}^{\sigma} aLDKLE_{ir}^{\sigma-1} \right) \Upsilon_{aLDKLE_{ir}} \\ &\quad + \left(\frac{LDKLE_{ir} KLE_{ir}^{*}}{LDKLE_{ir}^{*}} \right) (1 - \Upsilon_{aLDKLE_{ir}}) \end{aligned} \tag{11}$$

with auxiliary binary variable, $\Upsilon_{aLDKLE_{ir}} \begin{cases} \Upsilon_{aLDKLE_{ir}} = 1 & \text{if} \quad aLDKLE_{ir} > 0 \\ \Upsilon_{aLDKLE_{ir}} = 0 & \text{if} \quad aLDKLE_{ir} = 0 \end{cases}$

$$LD_{ir} = LDKLE_{ir} \left(\frac{\gamma LD_{ir}}{PLD_{r}} \right)^{\sigma} PLDKLE_{ir}^{\sigma} aLDKLE_{ir}^{\sigma-1} \tag{12}$$

The associated price index for the composite capital-labour-energy input, $PKLE_{ir}$, is determined by prices for the composite capital-labour input, PKL_{ir}, and energy, PE_{ir}:

$$PKLE_{ir} KLE_{ir} = PKL_{ir} KL_{ir} + E_{ir} PE_{ir} \tag{13}$$

As above, firm decision to divide the composite capital-labour-energy input demand, KLE_{ir}, between the capital-labour demand, KL_{ir}, and energy demand, E_{ir}, can be derived by applying the Shephard's lemma:

$$\begin{aligned} KL_{ir} &= \left(KLE_{ir} \left(\frac{\gamma KL_{ir}}{PKL_{ir}} \right)^{\sigma} PKLE_{ir}^{\sigma} aKLE_{ir}^{\sigma-1} \right) \Upsilon_{\gamma KL_{ir}} \\ &\quad + \frac{KL_{ir}}{PKL_{ir}} (1 - \Upsilon_{\gamma KL_{ir}}) \end{aligned} \tag{14}$$

with auxiliary binary variable, $\Upsilon_{\gamma KL_{ir}} \begin{cases} \Upsilon_{\gamma KL_{ir}} = 1 & \text{if} \quad \gamma KL_{ir} < 1 \\ \Upsilon_{\gamma KL_{ir}} = 0 & \text{if} \quad \gamma KL_{ir} = 1 \end{cases}.$

[2] Note that in the model parameters are sector, region, and factor specific, respectively. Here, however, the subscripts of parameters are suppressed for the sake of transparency.

[3] Note that variables with * denote the base year value of the respective variable. For example, variable KLE_{ir}^{*} stands for KLE_{ir} in the base year.

$$E_{ir} = \left(KLE_{ir} \left(\frac{\gamma E_{ir}}{PE_{ir}} \right)^{\sigma} PKLE_{ir}^{\sigma} aKLE_{ir}^{\sigma-1} \right) \Upsilon_{\gamma E_{ir}} + \left(\frac{E_{ir}}{PE_{ir}} \right) \left(1 - \Upsilon_{\gamma E_{ir}}\right) \tag{15}$$

with auxiliary binary variable, $\Upsilon_{\gamma E_{ir}} \begin{cases} \Upsilon_{\gamma E_{ir}} = 1 & \text{if} \quad \gamma E_{ir} < 1 \\ \Upsilon_{\gamma E_{ir}} = 0 & \text{if} \quad \gamma E_{ir} = 1 \end{cases}$.

The associated price index for the composite capital-labour input, PKL_{ir}, is:

$$PKL_{ir} KL_{ir} = \left(\left(1 + tk_{ir}\right) RK_{ir} + \delta_{ir} PI_r \right) K_{ir} \frac{KV_{ir}}{KL_{ir}} + PLT_{ir} LT \frac{LTV_{ir}}{KL_{ir}} \tag{16}$$

where KV_{ir} captures variable capital costs, LTV_{ir} captures variable labour costs, and tk_{ir} is corporate tax rate for industry i in region r.

At the fourth level, the composite capital-labour input demand is split between the demand for capital, K_{ir} and the demand for the composite labour input, LT_{ir}. As above, the demand for primary factors K_{ir} and LT_{ir} is obtained by taking partial derivatives according to Shephard's lemma:

$$K_{ir} = \left(KL_{ir} \left(\frac{\gamma K_{ir}}{\left(1 + tk_{ir}\right) RK_{ir} + \delta_{ir} PI_r} \right)^{\sigma} PKL_{ir}^{\sigma} aKL_{ir}^{\sigma-1} \right) \Upsilon_{LT_{ir}} + \left(\frac{KL_{ir} PKL_{ir}^{*}}{\left(1 + tk_{ir}\right) RK_{ir}^{*} + \delta_{ir} PI_r^{*}} \right) \left(1 - \Upsilon_{LT_{ir}}\right) + N_{ir}^{*} KF_{ir} \tag{17}$$

with auxiliary binary variable, $\Upsilon_{LT_{ir}} \begin{cases} \Upsilon_{LT_{ir}} = 1 & \text{if} \quad LT_{ir} > 0 \\ \Upsilon_{LT_{ir}} = 0 & \text{if} \quad LT_{ir} = 0 \end{cases}$

$$LT_{ir} = \left(KL_{ir} \left(\frac{\gamma L_{ir}}{PLT_{ir}} \right)^{\sigma} PKL_{ir}^{\sigma} aKL_{ir}^{\sigma-1} \frac{LT_{ir}^{*}}{LTV_{ir}^{*}} \right) \Upsilon_{K_{ir}^{*}} + \left(\frac{KL_{ir} PKL_{ir}^{*}}{PLT_{ir}^{*}} \frac{LT_{ir}^{*}}{LTV_{ir}^{*}} \right) \left(1 - \Upsilon_{K_{ir}^{*}}\right) \tag{18}$$

with auxiliary binary variable, $\Upsilon_{K_{ir}^{*}} \begin{cases} \Upsilon_{K_{ir}^{*}} = 1 & \text{if} \quad K_{ir}^{*} > 0 \\ \Upsilon_{K_{ir}^{*}} = 0 & \text{if} \quad K_{ir}^{*} = 0 \end{cases}$

The associated price index for the composite labour input, PLT_{ir}, is:

$$PLT_{ir}LT_{ir} = \sum_{e} \left(L_{eir} - N_{ir}LF_{eir}\right) PL_{eir} \left(1 + \left(1 + tle_{ir}\right) tli_{ir}\right) \frac{LTV_{ir}^{*}}{LT_{ir}^{*}} \quad (19)$$

where N_{ir} is the number of firms active in modern sector i, KF_{ir} captures fixed capital costs, LTF_{ir} and LF_{eir} capture fixed labour costs, tli_{ir} is the employers tax rate on labour use, and tle_{ir} is the employees tax rate on labour use.

At the fifth level, the Shephard's lemma yields the demand for different types of labour, L_{eir}, by education group e:

$$\begin{aligned} L_{eir} &= LT_{ir}\frac{LTV_{ir}^{*}}{L_{eir}^{*}}\left(\frac{\gamma LT_{eir}}{PL_{eir}\left(1+\left(1+tle_{ir}\right)tli_{ir}\right)}\right)^{\sigma} PLT_{ir}^{\sigma} aLT_{ir}^{\sigma-1} \\ &\quad + \frac{N_{ir}^{*}LF_{eir}}{L_{eir}^{*}} \end{aligned} \quad (20)$$

3.2.2 Output supply

Good i produced in origin region o is sold in destination region d according to the CET production function:[4]

$$\begin{aligned} xdde_{iod} &= \left(\frac{\gamma_{3id}P_{id}}{PDDT_{id}}\right)^{\sigma} a_{Aid}^{\sigma-1}\left(\frac{\gamma_{4iod}PDDT_{id}}{PDC_{io}+PTM_{c}trmV_{iod}}\right)^{\sigma} a_{A1id}^{\sigma-1}\Upsilon_{r} \\ &\quad + \left(\frac{\gamma_{3id}P_{id}^{*}}{PDDT_{id}^{*}}\right)^{\sigma} a_{Aid}^{\sigma-1}\left(\frac{\gamma_{4iod}PDDT_{id}^{*}}{PDC_{io}+PTM_{c}trmV_{iod}}\right)^{\sigma} a_{A1id}^{\sigma-1}\left(1-\Upsilon_{r}\right) \end{aligned} \quad (21)$$

with auxiliary binary variable, $\Upsilon_r \begin{cases} \Upsilon_r = 1 & \text{if} \quad r \in d \\ \Upsilon_r = 0 & \text{if} \quad r \notin d \end{cases}$.

According to equation (21), trade, $xdde_{iod}$, is determined by domestic sales prices of commodity i in destination region d, P_{id}, producer price PDC_{io} in exporting region i, composite consumer price $PDDT_{id}$ for goods sold in importing region d, price for trade and transport services, PTM_c, in country c, transport costs, $trmV_{iod}$, and parameters of the model.

The associated CES price index, $PDDT_{io}$, for domestic good i produced in region o is:

[4] Note that variables in small letters denote share of the respective variable in capital letters. For example, $xdde_{irs}$ denotes the share of $XDDE_{irs}$.

$$
\begin{aligned}
aA_{1io}PDDT_{io}^{1-\sigma} &= \sum_{d\in c_o}\gamma_{4ido}^{\sigma}\left(PDC_{id}+PTM_c trmV_{ido}\right)^{1-\sigma} \\
&\quad +\sum_{d\notin c_o}\gamma_{4ido}^{\sigma}\left(PDC_{id}^{*}ER_c PTM_c^{*}ER_c trmV_{ido}\right)^{1-\sigma} \qquad (22)
\end{aligned}
$$

where exchange rate, ER_c, is used, if origin and destination regions are not in the same country. Part of goods consumed in region r stem from own production, the rest is imported from the rest of the EU and the rest of the world. The import demand from the rest of the EU, $MREU_{ir}$, is derived from the CES production function (10):

$$
mreu_{ir} = \left(\frac{\gamma_{A1ir}}{PWMREU_i^{*}ER_c}\right)^{\sigma} P_{ir}^{\sigma}a_{Air}^{\sigma-1} \qquad (23)
$$

where $PWMREU_i$ is price for imports from the rest of the EU. Analogously, the import demand from the rest of world, $MROW_{ir}$, is derived from the CES production function (10):

$$
mrow_{ir} = \left(\frac{\gamma_{A2ir}}{PWMROW_i^{*}ER_c}\right)^{\sigma} P_{ir}^{\sigma}a_{Air}^{\sigma-1} \qquad (24)
$$

where $PWMROW_i$ is price for imports from the rest of the world, and γ_{Air}^{σ} are CES share parameters in the Armington function for imports. The associated price, P_{ir}, is a composite index of weighted prices for locally produced goods and imports from the rest of the EU and the rest of the world:

$$
\begin{aligned}
aA_{ir}P_{ir}^{1-\sigma} &= \gamma_{A3ir}^{\sigma}PDDT_{ir}^{1-\sigma}+\gamma_{A1ir}^{\sigma}\left(PWMREU_i^{*}ER_c\right)^{1-\sigma} \\
&\quad +\gamma_{A2ir}^{\sigma}\left(PWMROW_i^{*}ER_c\right)^{1-\sigma} \qquad (25)
\end{aligned}
$$

Analogously, from the CET production function one can derive the supply of exports to the rest of the EU, $EREU_{ir}$:

$$
EREU_{ir} = XD_{ir}\left(\frac{\gamma_{T1ir}}{PDC_{ir}}\right)^{\sigma} PD_{ir}^{\sigma}a_{Tir}^{\sigma-1} \qquad (26)
$$

and the supply of exports to the rest of the world, $EROW_{ir}$:

$$
EROW_{ir} = XD_{ir}\left(\frac{\gamma_{T2ir}}{PDC_{ir}}\right)^{\sigma} PD_{ir}^{\sigma}a_{Tir}^{\sigma-1} \qquad (27)
$$

where γ_{Tir} are CET share parameters for exports, and a_{Tir} is scaling parameter in the CET export function.

3.3 Equilibrium conditions

The supply of good i in region r equals the sum of household demand, C_{hir}, government demand, CG_{ir} and CGR_{ir}, investment demand, I_{ir}, changes in the stocks, SV_{ir}, production of transport and trade margin, TMX_{ir}, and intermediate demand $io_{jir}XD_{ir}$ for good i in region r:

$$\begin{aligned} X_{ir} \quad = \quad & \left(\begin{array}{c} \sum_h C_{hir} + CG_{ir} + CGR_{ir} + I_{ir} \\ + SV_{ir} + TMX_{ir} + \sum_j io_{jir} XD_{ir} \end{array} \right) (1 - \Upsilon_i) \\ & + \sum_j E_{jr} \Upsilon_i \end{aligned} \tag{28}$$

with auxiliary binary variable, $\Upsilon_i \begin{cases} \Upsilon_i = 1 & \text{if} \quad i \in energy \\ \Upsilon_i = 0 & \text{if} \quad i \notin energy \end{cases}$.

Changes in the stocks, SV_{ir}, is fixed part, svs_{ir}, of output, X_{ir}:

$$SV_{ir} = svs_{ir} X_{ir}$$

The long-run equilibrium also requires that the number of firms in each region is no longer changing in response to short-run profits, which implies zero profits.

$$\begin{aligned} 0 \quad = \quad & \left(\frac{N_{ir}\sigma_{ir} \left(\sum_e LF_{eir} + fcK_{ir} \right) CPI_r}{XD_{ir} TFP_{ir}} - PD_{ir} \right) (1 - \Upsilon_i) \\ & + (N_{ir} - 1) \Upsilon_i \end{aligned} \tag{29}$$

with auxiliary binary variable, $\Upsilon_i \begin{cases} \Upsilon_i = 1 & \text{if} \quad i \in traditional \\ \Upsilon_i = 0 & \text{if} \quad i \notin traditional \end{cases}$. The zero profit condition (29) determines the number of firms, which will operate in each monopolistically competitive sector. In the perfectly competitive (traditional) industries the fixed cost is zero and the number of firms is equal to one.

The profits of firms operating in monopolistically competitive sectors:

$$\Pi_{ir} = N_{ir} \left(\sum_e LF_{eir} + KF_{ir} \right) CPI_r \tag{30}$$

The domestic producer prices of commodities, PD_{ir}:

$$
\begin{aligned}
0 &= K_{ir}\left(\left(1+tk_{ir}\right)RK_{ir}+\delta_{ir}PI_r\right) \\
&\quad +KYN^*_{ir}DEF_c+\sum_e PL_{eir}L_{eir}\left(1+\left(1+tle_{ir}\right)tli_{ir}\right) \\
&\quad +\sum_j io_{jir}XD_{ir}P_{jr}+E_{ir}PE_r+PLD_rLD_{ir} \\
&\quad -PD_{ir}\left(1-txd_{ir}+sp_{ir}\right)XD_{ir}TFP_{ir} \qquad (31)
\end{aligned}
$$

where KYN_{ir} is negative operative surplus in 'traditional' sectors, txd_{ir} is tax rate on production, and sp_{ir} is subsidy rate on production.

The consumer price for good i in region r depends on domestic producer prices of commodities, PD_{ir}, the number of varieties, N_{ir}, and the elasticity of substitution between varieties, σ:

$$PDC_{ir} = PD_{ir}N_{ir}^{\frac{1}{1-\sigma}} \qquad (32)$$

The gross output of sector i in region o equals the local sales and exports to the rest of the EU and the rest of the world:

$$
\begin{aligned}
XD_{io}PD_{io}TFP_{io} &= \sum_{d\in r} xdde_{iod}X_{id}PDC_{io}+\sum_{d\notin r} xdde_{iod}X^*_{id}PDC_{id} \\
&\quad +EREU_{io}PDC_{io}+EROW_{io}PDC_{io} \qquad (33)
\end{aligned}
$$

The supply of good i for production of transport and trade margin, TMX_{io}, in region o equals the transport sector's demand for good i in region o:

$$TMX_{io} = atm_{io}\sum_{i,o} trmV_{iod}xdde_{iod}X_{id} \qquad (34)$$

where atm_{io} is the share of commodity i used for production of transport and trade margin in region o. The associated price for the composite transport and trade margin, PTM_c, is a weighted average of regional and sectoral trade margins in country c:

$$PTM_c = \sum_{io} atm_{io}P_{io} \qquad (35)$$

3.4 Factor markets

Labour supply, LS_{er}, with education e in region r is determined by the stock of human capital, LSH_{er}, and labour migration $LMIG_{er}$:

$$LS_{er} = (LSH^*_{er} + LMIG_{er}) \frac{LSH_{er}}{LSH^*_{er}} \tag{36}$$

In equilibrium the supply of workers , LS_{er}, with education e in region r equals to the total labour demand from all industries, L_{eir}, and unemployment, U_{er}:

$$LS_{er} = \sum_i L_{eir} + U_{er} \tag{37}$$

The unemployment, U_{er}, is a fixed proportion, u_{er}, of the total labour supply, LS_{er}:

$$U_{er} = LS_{er} + u_{er} \tag{38}$$

The wage, PL_{eir}, of worker with education e employed in sector i depends on labour supply, LS_{er}, labour demand, L_{eir}, unemployment, U_{er}, in region r, and parameters of the model:

$$\log\left(\frac{\sum_i PL_{eir}L_{eir}}{CPI_r \sum_i L_{eir}}\right) = \chi_1 \log\left(\frac{U_{er}}{LS_{er}}\right) + \chi_2 \tag{39}$$

where χ_1 and χ_2 are constants.

The net migration rate, $LMIG_{eo}$, is determined through the relative wage rate, PL_{ei}, and labour demand, L_{ei}, in origin region o and destination region d:

$$\begin{aligned} \chi_3 \frac{LMIG_{eo}}{LS_{eo}} &= \chi_4 + \chi_5 \frac{\left(\sum_i PL_{eio}L_{eio}\right) \sum_{id\in r} L_{eio}}{\left(\sum_{id\in r} PL_{eid}L_{eid}\right) \sum_i L_{eid}} \\ &\quad + \chi_6 \left(\frac{\left(\sum_i PL_{eio}L_{eio}\right) \sum_{id\in r} L_{eio}}{\left(\sum_{id\in r} PL_{eid}L_{eid}\right) \sum_i L_{eid}}\right)^2 \\ &\quad - \frac{\sum_{d\in r} LMIG_{eo} \frac{LMIG^*_{ed}}{LMIG^*_{eo}}}{R} \end{aligned} \tag{40}$$

where χ_3-χ_6 are constants, and R is the number of regions.

The total demand for land, LD_{ir}, is equal to fixed land supply, LDS^*_r, in region r:

$$\sum_{i} LD_{ir} = LDS_r^* \tag{41}$$

3.5 Savings and investment

The total savings, S_c, in country c is sum of savings made by households, SH_{hr}, firms (capital depreciation), $\sum_{ir} \delta_{ir} K_{ir} PI_r$, the national and regional governments, SG_c and $\sum_r SG_r$, respectively:

$$S_c = \sum_{hr} SH_{hr} + \sum_{ir} \delta_{ir} K_{ir} PI_r + SG_c + \sum_{r} SG_r \tag{42}$$

Savings from the rest of the EU, $SREU_c$, are equal to imports plus salaries of workers employed abroad minus exports and transfers from the rest of the EU:

$$\begin{aligned} SREU_c \quad = \quad & \sum_{ir} PWMREU_i^* ER_c mreu_{ir} X_{ir} + \sum_{er} LROW_{er} PLROW_e ER_c \\ & - \sum_{ir} EREU_{ir} PDC_{ir} - TRREU_c ER_c \end{aligned} \tag{43}$$

The total savings accumulated in each period are invested into sector-specific physical capital accumulation. The total investment equals savings net of changes in the stocks:

$$IT_c = S_c + SREU_c + SROW_c ER_c - \sum_{ir} SV_{ir} P_{ir} \tag{44}$$

The composition of capital goods in the composite investment demand is determined by utility maximisation of an 'investment bank', which is a virtual economic agent in charge of buying physical capital investment goods for all sectors and regions.[5] The demand for investment good i in region r is share αI_{ir} of the total private investment, IT_c, in country c:

$$\iota_{ir} I_{ir} P_{ir} = aI_{ir} IT_c \tag{45}$$

where the composite tax variable $\iota_{ir} = 1 - sc_{ir} + tc_{ir} + vatc_{ir} + exst_{ir}$. The price for the composite investment good can be derived as a unit expenditure function of

[5] Hence, the interregional capital flows do not flow directly between sectors, but through a national investment pool. Instead, the savings are distributed between the regions and sectors according to industry/region-specific demand equation for investment.

the Cobb-Douglas investment production function:

$$PI_r = \Pi_{i,r \in reg} \left(\iota_{ir} \frac{P_{ir}}{aI_{ir}} \right)^{\alpha I_{ir}} \tag{46}$$

3.6 Government

The country c's government demand, CG_{ir}, for good i sold in region r $(\in c)$:

$$\begin{aligned} CG_{ir} \iota_{ir} \frac{P_{ir}}{aG_{ir}} &= TAXR_c + \sum_{\substack{r \in reg \\ i \in pub}} trf_r \left(K_{ir} RK_{ir} + KYN^*_{ir} DEF_c \right) \\ &+ \sum_{r \in reg} TRFRG_r DEF_c - \sum_{r \in reg} TRFNG_r DEF_c - SUBS_c \\ &- \sum_{h,r \in reg} \left(TRF_{hr} DEF_c + c_{hr} \sum_e \xi_{er} wu_{er} U_{er} \right) \\ &- SG_c DEF_c + TRREU_c ER_c \end{aligned} \tag{47}$$

The regional government r's demand, CGR_{ir}, for good i sold in region r:

$$\begin{aligned} CGR_{ir} \iota_{ir} \frac{P_{ir}}{aGR_{ir}} &= TAXRR_r + (1 - trf_r) \sum_{i \in pub} \left(K_{ir} RK_{ir} + KYN^*_{ir} DEF_c \right) \\ &- TRFRG_r DEF_c + TRFNG_r DEF_c - SUBS_r \\ &- \sum_h TRFR_{hr} DEF_c - SGR_r DEF_c + TRREU_r ER_c \end{aligned} \tag{48}$$

The tax revenue, $TAXRR_c$, of country c's government:

$$\begin{aligned} TAXR_c &= \sum_i \left(tc_{gir} + vatc_{gir} + exst_{gir} \right) P_{ir} \left(\sum_h C_{hir} + I_{ir} + CG_{ir} + CGR_{ir} \right) \\ &+ \sum_i \left(\sum_e PL_{eir} L_{eir} \right) \left(tle_{gir} + tli_{gir} \left(1 + tle_{ir} \right) \right) + tk_{gir} K_{ir} RK_{ir} \\ &+ txd_{gir} XD_{ir} TFP_{ir} PD_{ir} + ty_{gr} \sum_h Y_{hr} \end{aligned} \tag{49}$$

with $r \in c$. The tax revenue, $TAXRR_r$, of region r's government:

$$
\begin{aligned}
TAXRR_r &= \sum_i (tc_{gir} + vatc_{gir} + exst_{gir}) P_{ir} \left(\sum_h C_{hir} + I_{ir} + CG_{ir} + CGR_{ir} \right) \\
&+ \sum_i \left(\sum_e PL_{eir} L_{eir} \right) (tle_{gir} + tli_{gir} (1 + tle_{ir})) + tk_{gir} K_{ir} RK_{ir} \\
&+ txd_{gir} XD_{ir} TFP_{ir} PD_{ir} + ty_{gr} \sum_h Y_{hr} \qquad (50)
\end{aligned}
$$

The subsidies, $SUBS_c$, from country c's government:

$$
\begin{aligned}
SUBS_c &= \sum_i sc_{gir} P_{ir} \left(\sum_h C_{hir} + I_{ir} + CG_{ir} + CGR_{ir} \right) \\
&+ \sum_i sp_{gir} XD_{ir} TFP_{ir} PD_{ir} \qquad (51)
\end{aligned}
$$

with $r \in c$. The subsidies, $SUBSR_r$, from region r's government:

$$
\begin{aligned}
SUBSR_r &= \sum_i sc_{gir} P_{ir} \left(\sum_h C_{hir} + I_{ir} + CG_{ir} + CGR_{ir} \right) \\
&+ \sum_i sp_{gir} XD_{ir} TFP_{ir} PD_{ir} \qquad (52)
\end{aligned}
$$

3.7 Welfare indicators

Laspeyres price index for consumer goods:

$$
CPI_r = \frac{\sum_{hi} C^*_{hir} P_{ir} \iota_{ir}}{\sum_{hi} C^*_{hir} P^*_{ir} \iota^*_{ir}} \qquad (53)
$$

The real gross regional product, $GDPR_r$, for region r is defined as the gross output minus intermediate inputs plus commodity taxes:

$$
\begin{aligned}
GDPR_r &= \sum_i XD_{ir} TFP_{ir} PD^*_{ir} - \sum_{ij} io_{jir} XD_{ir} P^*_{jr} - \sum_i E_{ir} P^*_{jr} \\
&+ \sum_i (\iota_{ir} - 1) P^*_{ir} \left(\sum_h C_{hir} + I_{ir} + CG_{ir} + CGR_{ir} \right) \qquad (54)
\end{aligned}
$$

The nominal gross regional product, $GDPRC_r$, for region r is defined as the gross output minus intermediate inputs plus commodity taxes:

$$GDPRC_r = \sum_i XD_{ir}TFP_{ir}PD_{ir} - \sum_{ij} io_{jir}XD_{ir}P_{jr} - \sum_i E_{ir}P_{jr} + \sum_i (\iota_{ir} - 1) P_{ir} \left(\sum_h C_{hir} + I_{ir} + CG_{ir} + CGR_{ir} \right) \quad (55)$$

The real gross domestic product, GDP_c, for country c is a sum of the real gross regional products, $GDPR_r$:

$$GDP_c = \sum_{r \in c} GDPR_r \quad (56)$$

Analogously, the nominal gross domestic product, $GDPC_c$, for country c is a sum of the nominal gross regional products, $GDPRC_r$:

$$GDPC_c = \sum_{r \in c} GDPR_r \quad (57)$$

The GDP deflator, DEF_c, for country c is the ratio of the nominal gross domestic product, $GDPC_c$, and the real gross domestic product, GDP_c:

$$DEF_c = \frac{GDPC_c}{GDP_c} \quad (58)$$

The compensating variation price index, PCV_{hr}:

$$PCV_{hr} = \Pi_i \left(\left(\frac{\iota_{ir} P_{ir}}{\iota_{ir} P^*_{ir}} \right)^{aH_{hir}} \right) \quad (59)$$

The compensating variation budget, BCV_{hr}, is defined as difference between the disposable consumer budget, B_{hr}, and expenditures on the minimum required quantity, $\sum_i \mu H_{hir} P_{ir} \iota_{ir}$:

$$BCV_{hr} = B_{hr} - \sum_i \mu H_{hir} P_{ir} \iota_{ir} \quad (60)$$

The compensating variation for household h living in region r:

$$CV_{hr} = BCV_{hr} - PCV_{hr} BCV^*_{hr} \quad (61)$$

The compensating variation, CVC_c, for country c is sum of CV_{hr} over all households and regions in country c:

$$CVC_c = \sum_{h,r \in c} CV_{hr} \tag{62}$$

The export price index, EPI_c, for country c is calculated as the Laspeyre index:

$$EPI_c = \frac{\sum_{i,r \in c} (EREU^*_{ir} PDC_{ir} + EROW^*_{ir} PDC_{ir})}{\sum_{i,r \in c} (EREU^*_{ir} PDC^*_{ir} + EROW^*_{ir} PDC^*_{ir})} \tag{63}$$

Analogously, the import price index, MPI_c, for country c is calculated as the Laspeyre index:

$$MPI_c = \frac{\sum_{i,r \in c} (MREU^*_{ir} PWMREU^*_{ir} ER_c + MROW^*_{ir} PWMROW^*_{ir} ER_c)}{\sum_{i,r \in c} (MREU^*_{ir} PWMREU^*_{ir} + MROW^*_{ir} PWMROW^*_{ir})} \tag{64}$$

The real total exports, ET_c, to non-EU countries:

$$ET_c = \frac{\sum_{i,r \in c} EREU^*_{ir} PDC_{ir} + EROW^*_{ir} PDC_{ir}}{EPI_c}$$

3.8 Dynamics

The total factor productivity, TFP_{ir} in sector i in region r:

$$\triangle TFP_{ir} = \beta_{1i} + \beta_{2i} \ln H_r + \beta_{3i} RD_r + \beta_{4i} \ln H_r \left(\frac{TFP_{ir}}{TFP_{is}} \right) \tag{65}$$

Cumulative growth over t periods:

$$grs = (1 + gr^*)^t \tag{66}$$

The capital available in period $t+1$ is equal to capital in period t plus investment minus depreciation:

$$K_{irt+1} = (1 - \delta_{ir}) K_{irt} + INV_{irt} \tag{67}$$

The price for capital, PK_{ir}, is the ratio of region-level return, RK_{ir}, relative to the nominal interest rate, RGD_c in country c:

$$PK_{ir} = \frac{PK_{ir}}{RGD_c} \tag{68}$$

The nominal interest rate, RGD_c, equals the weighted average return to capital, K_{ir}:

$$RGD_c = \frac{\sum_{ir} RK_{ir}K_{ir}}{\sum_{ir} K_{ir}} \tag{69}$$

The rate of return, ROR_{irt-1}, in period $t-1$:

$$ROR_{irt-1} = PK_{irt} - 1 + gr^{*}PK_{irt} + \delta_{irt} \tag{70}$$

The demand for investment good i in region r:

$$INV_{ir} = \frac{Igrav_{ir}IT_cK_{ir}TFP_{ir}e^{ROR_{irt-1}}}{\sum_{j,s\in regc_r} K_{js}TFP_{js}e^{ROR_{jst-1}}} \tag{71}$$

The human capital stock, LSH_{er}, in period $t+1$:

$$\begin{aligned} LSH_{ert+1} \quad = \quad & \left(\sum_{h,i\in edu} eh_{ceht}C_{hirt} + \frac{LSH_{ert}}{\sum_e LSH_{ert}}\sum_{i\in edu}(CG_{irt}+CG_{irt})\right)^{\delta H_{ert}} \\ & AH_{ert}LSH_{ert}^{1-\delta H_{ert}} \end{aligned} \tag{72}$$

4 Conclusions

The RHOMOLO model represents an advance on previous impact assessment tools for Cohesion (and potentially other) policy, firstly because it provides detail at sub-national level, and secondly because it allows for a more integrated form of analysis, incorporating economic, social and environmental indicators to give a more balanced measure of impact. The model is still in prototype form, however, covering a limited number of Member States and still not fully-functional in terms of all its modelling capabilities. Over the next few years the development will continue with the aim to broaden the geographical coverage to all EU27 regions and to deepen the methodological underpinnings to properly reflect state-of-the-art knowledge in spatial analysis. The quantification of NEG theory on such a scale is also a relatively new development, and modelling experiments of this type are quite ground-breaking. This means that the results from the model should be examined in detail and compared with more bottom-up case studies and against the real world in general in order to establish an "external consistency" to match the internal consistency that is already achieved through the model's theoretical underpinnings.

Looking forward from a policy perspective, the 5th Cohesion Report acknowledges the challenges ahead for Europe and the need for Cohesion Policy to integrate with the Europe 2020 strategy as well as other elements such as the Innovation Union. The report also notes that "Higher-quality, better-functioning monitoring and evaluation systems are crucial for moving towards a more strategic and results-oriented approach to Cohesion Policy." It is hoped that the RHOMOLO modelling system will have a place in these systems of evaluation. It is also true that thematic concentration on a smaller number of priority actions is also something that can be experimented with in a modelling context.

Finally, coming back to the Barca report, it has already been noted that the suggested re-focussing around six possible candidates for core priorities requires a modelling approach that goes beyond the traditional economic one. In addition, the emphasis on place-based policy would seem to require a place-based (bottom-up) approach to modelling, at the very least where sub-national variation and effects can be identified. Moreover, the approach to impact assessment has to be open to further changes in direction according to how the future of policy is determined for the coming period and beyond.

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