

**Modelling Spatial Economic Effects of
Transport Infrastructure Policies:
A Computable General Equilibrium Approach**



Inaugural-Dissertation zur Erlangung des akademischen Grades
eines Doktors der Wirtschafts- und Sozialwissenschaften
der Wirtschafts- und Sozialwissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

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Kiel, 2010

Gedruckt mit Genehmigung der
Wirtschafts- und Sozialwissenschaftlichen Fakultät
der Christian-Albrechts-Universität zu Kiel

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Tag der Abgabe der Arbeit:
5. November 2009

Tag der mündlichen Prüfung:
12. April, 2010

To my parents

Моим родителям

Summary

The purpose of this doctoral thesis is to suggest and operationalise several important extensions and improvements in the methodology used to evaluate regional economic effects of the large-scale transport infrastructure and pricing policies. The main contributions are divided into the static modelling part and the dynamic modelling part.

In the static modelling part, our focus is on the implications of the assumptions of partial capital mobility and wage rigidity for the evaluation of border-crossing infrastructure projects. In particular, we introduce a negative relationship between the regional real wage and the unemployment rate, usually called the "wage curve", into the model. We show that including these assumptions substantially increases the magnitude of the indirect effects predicted by the model. We also identify and describe the mechanisms governing these effects.

In the dynamic modelling part, we make a first attempt to introduce full forward-looking dynamics into the spatial CGE modelling framework by specifying the intertemporal optimization problems of the households and the firms. This framework also allows us to represent incomplete capital mobility in a more plausible way than in the static model by introducing the costs of investment. We perform numerical simulations in order to study the properties of the model, and to understand the added value of this approach as compared to static analysis.

Both models are employed to analyse the economic impacts of the Fehmarn Belt railway axis project, in particular the indirect effects thereof.

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Chapter 1. Introduction

1.1. Policy context

According to the regional economics literature, the existence of transport costs is one of the fundamental considerations underlying the complex patterns of location of economic activity (Hoover and Giarratani, 1999, Ch .1). The areas with better access to the locations of factors of production and to the markets for input materials and final products will, according to the spatial economic theory, be more productive, more competitive, and hence more successful than more isolated regions. This implies an important role of transport infrastructure for the regional economy and a strong impact of major improvements in the transport system on the regional development.

It is of no surprise thus that the spatial effects of the European transport policy, especially in relation with the “social and economic cohesion” objective (European Communities, 1992a, Articles 130a-130d)¹, constitute a research question of particular interest for the policymakers, as can, for instance, be inferred from the significant number of recent large-scale EU-funded research projects that focus on this issue.² The requests from the side of the European Commission to analyse the impacts of the specific policy measures are usually combined in these projects with the requests for researchers to come up with new or improved methodology to assess such impacts.

The focus of the European Commission on transport is relatively recent. The year 1992 was the completion date of the Internal Market – for the Common Transport Policy (CTP) it was very much the starting date. The White Paper of 1992 (European Communities, 1992b) formulated the objective of the EU transport policy: to help provide Europeans with efficient, effective transportation systems that would ensure sustainable mobility, protection, and innovation. The most important milestones of the CTP mentioned there are the following:

- opening-up of rail freight transport to competition,
- deregulation of trucking,
- deregulation of civil aviation,
- the use of road charges for the financing of infrastructure,

¹ Among other components, this includes the goal of reducing income inequality between regions.

² The author’s work in a series of such projects has been an important factor defining the scope of this dissertation. For a list of finished projects see <http://www.uni-kiel.de/ifr/index.php?id=51&doc=forschung>.

- promoting interconnection and interoperability between nationally fragmented systems as well as between different modes,
- applying progressively the principle of charging for marginal social costs not yet fully reflected in private transport costs,
- development of the *trans-European transport networks* (TEN-T).

The last item in this list encompasses the EU strategy in transport infrastructure development. The legal basis for this policy is provided in the Treaty on the European Union (European Communities, 1992a). Under the terms of Title XII of the Treaty (Articles 129b-129d), the European Union commits itself to promote the development of trans-European networks as a key element for the creation of the Internal Market and the reinforcement of economic and social cohesion. This development includes the interconnection and interoperability of national networks as well as access to such networks.

The TEN-T programme consists of hundreds of projects, defined as studies or works. The European Commission attributed particular importance to those of them that contribute to pan-European integration and economic development, and these were included into a priority list (hence so-called *priority projects*). Currently, there are 30 projects in this list (see High-Level Group, 2003), divided into many sections with different timetables of construction works. The majority of the projects have not yet been completed.

On March 30, 2009, the “TEN-T 2009 Call for Proposals” has been launched³, being a part of activities aimed at the determination of an updated list of priority projects. This call makes nearly 1€ billion of financing available for European infrastructure projects. The underlying selection process is expected to involve some sort of ex-ante analysis. Identifying the economic impacts of the proposed projects may thus be very relevant for the appropriate allocation of the financial resources in the EU. As already mentioned, the full-scale transport policy analysis would include all steps from developing appropriate models for impact assessment of improvements in the transport system to checking whether the targets of a given policy package (as given e.g. by the values of aggregate economic indicators) are being attained.

The purpose of this thesis is to suggest and operationalise several important extensions and improvements in the methodology used to evaluate regional economic effects of the large-scale transport infrastructure and pricing policies.

³ http://tentea.ec.europa.eu/en/news__events/newsroom/ten-t_2009_calls_for_proposals.htm

1.2. Modelling context

One common feature of the mentioned EU-funded research projects is that the actual policy measures, such as building the trans-European networks, revitalizing railways, implementing effective road pricing etc, are first translated into the values of economically treatable indicators of interregional transport costs. An economic model is then needed that can explicitly incorporate this information and calculate the policy impact. More specifically, what one often wants to evaluate in these cases is the “total economic impact”, which simply means the aggregate change in social welfare (Laird et al., 2005). We will further clarify this term in the following.

The most traditional method of identifying the economic effects of transport projects bases upon a standard microeconomic argument suggested by Dodgson (1973) and formalized by Jara-Diaz (1986). According to that, the demand for transport is a derived demand, it arises from the desire to undertake other activities. Thus, the users of transport infrastructure will consider making a particular trip only if their willingness to pay for a connected activity is bigger or equal to its total price, including the transport costs. Jara-Diaz then shows that under the conditions of perfect competition in all sectors, such that the prices equal the marginal social costs, the total impact on the economy of a transport infrastructure improvement would be exactly measured by the change in the consumer surplus of transport users. This approach underpins the conventional *cost-benefit analysis* in transport (Bristow and Nellthorp, 2000; Grant-Muller et al., 2001).

In reality, prices may differ from marginal social costs, most evident reasons being the economies of scale, monopoly power, taxes, externalities, and other market imperfections. The interplay between the sectors of economy under these conditions produces welfare surpluses and losses that are additional to those measured in the transport market alone. As a result, the ultimate effect of any infrastructure project implementation cannot be analytically determined a priori, in terms of both magnitude and sign (Mackie and Preston, 1998; Vickerman, 2008).

There is no clear consensus among different authors on how to classify these additional welfare effects. All together, they are most often referred to as *indirect effects* or *economy-wide effects* (SACTRA, 1999) in contrast to the *direct effects* that are given by the behavioural responses of the transport users only (measured e.g. by the consumer surplus), whereby the rest of the economy is treated as unchanged. The sum of direct and indirect effects gives the total effect of a transport project.

A particularly challenging task in the impact evaluation process is to assign the benefits from newly installed capacities to the regions. Economic intuition would suggest the presence of *spillover effects* distributed over large areas in the cases, where a bottleneck in the transport network has been removed. Positive effects on the economy may then be observed not only in the neighbouring regions, but also in the areas quite distant from the place where the corresponding investment was done (e.g. Venables and Gasiorek, 1996; Cantos et al., 2005). Moreover, if the bottleneck removal makes one transport route preferable to another, the effect on the regions lying along the inferior route can well be negative.

The traditional cost-benefit analysis in transport, as described in the official manuals issued by the national governments or the international organizations (see e.g. BMV, 1993; OEEL, 2000; DETR, 2000; UNECE, 2003) focuses on the direct effects in the transport sector (or in its small segments). This approach thus fails both in accounting for the economy-wide effects, as well as in tracing out the regional spillover effects. Most often, all benefits are simply assigned to the place of investment itself. Several alternative methods are used in practice to assign the benefits from using a new or improved transport link to the regions.

Production function approaches apply econometric techniques to model economic activity in a region as a function of production factors. The classical production factors are capital, labour, and land. In revised production function approach infrastructure is added as a public input used by firms within a region. The most famous application of this approach is probably the work done by Aschauer (1989a, b). The assumption behind this expanded production function is that regions with higher levels of infrastructure provision will have higher output levels. Aschauer and other authors produced a variety of estimates of the effect of public infrastructure on production activity, and eventually a consensus emerged that the output elasticity is positive and probably in the order of 0.1 (Lynde and Richmond, 1993). In order to quantify the regional spillover effects some authors added the stock of infrastructure in the adjacent regions into the production function. For example, Cantos et al. (2005) extend the region's own infrastructure stock by the trade-weighted sum of infrastructure stocks in the neighbouring regions. In general, however, this method is not very suitable for the evaluation of the effects associated with any particular infrastructure project, the main reason being the inability to distinguish between different mechanisms generating these effects (Gutiérrez et al., 2009).

Accessibility approaches are based on a similar method, but the simple infrastructure stock measure is substituted here by a more complex accessibility indicator. "Accessibility"

means the facility with which activities may be reached from a given location by using a certain transport system (Morris et al., 1978). One of the most popular indicators in the accessibility studies is the economic (or market) potential (Harris, 1954). This is a gravity-based measure of the volume of economic activity to which a given location has access, which depends positively on the levels of activity in the potential destinations and negatively – on the distance (or travel time) to them. The underlying assumption is that the locations with better access to markets are more likely to become economically successful. Accessibility studies would predict the distributional effects of transport policy by means of econometric estimation, where factors of production including labour, capital, knowledge, etc play an important role, resembling the production function method. The most important factor is, however, the change of accessibility. Compared to the production function method, much more information on interregional linkages can be taken into account when accessibility indicators are used (Vickerman et al. (1999), see also Gutiérrez et al. (2009) for a recent application). The lack of theoretical foundations and thus the arbitrariness of the accessibility measurement and of the econometric specification remain, however, the weak points of this method (Bröcker, 1998c).

Regional input-output analysis builds upon the original multisectoral input-output framework of Leontief (1937, 1941). The interregional and inter-industry flows are represented here as a function of a set of exogenous parameters, including a transport cost matrix, and are determined subject to a set of general equilibrium constraints. Two examples of operational multiregional input-output models currently in use are the MEPLAN model (ME&P, 2001) and the STREAMS model (Leitham et al., 1999). The approach has two fundamental and related shortcomings: first, technical input-output coefficients are fixed, not reacting on relative prices, and second, the model is demand driven, having severe difficulties in handling supply restrictions or any economic impact which originates on the supply side of the economy.

Modern *computable general equilibrium (CGE) analysis* takes up the idea of mutual interdependence of all sectors of the economy put forward by the input-output analysis⁴, but it replaces the fixed coefficient assumption by price responsiveness of input-output relations. This does not only lead to higher flexibility in mimicking real adjustment processes, but it also allows for both sides of each market, supply and demand, to react fully to the external shocks. Naturally, prices play the main role in equilibrating the markets in this approach.

⁴ Chapter 2 discusses of the historical relation between the input-output analysis and the CGE approach.

One may regard a CGE model incomplete for analysing transport policies, when it does not address the important spatial features of interactions between economic agents. A distinctive feature of the *spatial computable general equilibrium* (SCGE) models is that firms, households, goods, and factors are distinguished by location, and the linkage of the economy with the transportation network is specified. Spatial spillovers arising from the changes in transport costs can be explicitly taken account of in this framework if the regional scale of the model is fine enough.

The advantages of using the SCGE approach to analyse the impacts of transport infrastructure policy have been demonstrated by several reviewers (Williams et al., 2002; Gunn, 2004; Laird et al., 2005; DfT, 2006). Main strengths of the approach mentioned there are theoretical consistency, incorporation of economy-wide effects of policies, avoidance of double counting, flexibility, significant amount of detail. Basing on these arguments, we are going to apply the SCGE methodology (reviewed in detail in Chapter 3) in this thesis.

As we mentioned earlier, the motivation to use advanced methods for the impact analysis of transport policies comes from the fact that the conventional cost-benefit analysis fails to take account of the indirect effects of such policies, the effects that arise due to market imperfections. Several studies mentioned below used the SCGE methodology to analyse these indirect effects. To illustrate the implications of the use of a more advanced methodology, these studies usually calculate a proportion (in %) of the indirect effects relative to the direct effects, or a ratio between the total effects and the direct effects (a *total benefit multiplier*).

Inspired by the *new economic geography* literature (Krugman, 1979, 1980, 1991), the first source of market imperfection that was included into such analysis was a certain degree of monopoly power on the product markets (implied by increasing returns to scale), leading to the *agglomeration economies*. Venables and Gasiorek (1999) analyse transport cost changes using an experimental SCGE model with monopolistic competition, and suggest that 30% share of indirect effects is likely to be exceeded in only a few cases. Bröcker and Schneider (2002) arrive at indirect welfare effects of about 20% using an SCGE model for the European regions, which is similar to the basic model of this thesis. Elhorst et al. (2004) obtain additional effects in the order of 30-40% with an SCGE model for the Dutch regions. Using an experimental urban CGE model, Venables (2007) finds a total benefit multiplier ranging between 1.25 and 5, depending on the chosen parameterization. Thus,

these values indicate that there is a risk of considerably underestimating the total benefits of infrastructure improvements, if conventional methods of evaluation are used.

Elhorst et al. (2004) argue that in addition to the imperfections on the product markets, the response of the *labour market* may be an important factor determining the size of the indirect effects. In their model, passengers are subject to the *costs of commuting*, and the changes in these costs due to infrastructure improvements affect their residential location decisions. Pilegaard and Fosgerau (2008) introduce search unemployment in their CGE model of the Danish economy, and find a total benefit multiplier from the reduction of commuting costs in the order of 1.3-1.5. Imperfections on the labour market, however, have not received much attention in analysing the impacts of the changes in the *trade costs* borne by the firms and households.

In this thesis, we will focus on the effects that large-scale transport infrastructure improvements are having on the trade costs, and the total economic impact thereof. The studies of the commuting costs mentioned above suggest that the factor market imperfections may play a particularly important role in the model-based evaluation. In Chapter 4, we therefore extend the existing static model developed by Bröcker (1998b, 1998c) by distinguishing between several factor markets. Our focus will be on the implications of the assumptions of partial capital mobility and wage rigidity for the evaluation of border-crossing infrastructure projects. In particular, we will introduce a negative relationship between the regional real wage and the unemployment rate, usually called the *wage curve* (Blanchflower and Oswald, 1994), into the model. We intend to show that including these assumptions substantially increases the magnitude of the indirect effects predicted by the model. We also identify and describe the mechanisms governing these effects. We will only look at the phenomena arising after the project completion, thus ignoring the effects during the construction phase.

Most of the existing applications of the SCGE modelling framework are static, *dynamic extensions* are still rare and “recursive” in most cases, which means to concatenate static equilibria for each period by the ad-hoc saving and investment functions. This is also true for the models used for transport policy analysis. However, a desirable feature of an economic model used for forecasting is the endogenous savings-investment behaviour of forward-looking agents. In particular, SACTRA (1999) recommendations for transport policy appraisal emphasize the need for incorporating endogenous dynamic mechanisms into the existing CGE models. The underlying idea is that in practice, many effects need time to

fully materialize, and the explicit time paths of these effects may be of interest to the policymakers. A particular point of interest here may concern the policy announcement effects. Using the aforementioned static model as a starting point again, we will in Chapter 5 make a first attempt to introduce *forward-looking dynamics* into the SCGE modelling framework by specifying the intertemporal optimization problems of the households and the firms. This framework also allows us to represent incomplete capital mobility in a more plausible way than in the static model by introducing the costs of investment. We will perform numerical simulations in order to study the properties of the model, and to understand the added value of this approach as compared to static analysis.

1.3. Outline of the thesis

We describe the general approach of CGE modelling in Chapter 2 by identifying its links with the general equilibrium theory and with the input-output modelling, and by summarizing the model-building process with a help of a nine-step algorithm. This chapter also introduces the main concepts that are distinctive of the CGE approach, and are routinely used by the author in the parts to follow.

Chapter 3 has three main goals. First, we describe the features that from our viewpoint distinguish modern SCGE models from the wide field of other CGE applications. Second, we discuss the specific assumption regarding the technology in the transport sector that is going to be applied in this thesis (the “iceberg” assumption), the motivation behind it, and the difficulties associated with its implementation. Third, we review the existing literature on the static SCGE modelling and classify the most relevant studies according to the way they incorporate spatial economic features.

Chapter 4 studies the implications of the specific assumptions about the structure of the factor markets (labour and capital) for the analysis of transport cost changes in the static SCGE framework. The trade-off between the unemployment rate and the workers’ remuneration is introduced via the region-specific wage curves. The values of the corresponding elasticities are gathered from the existing econometric studies for the European countries. Furthermore, we assume that a part of regional capital is perfectly mobile between countries and regions. We do extensive sensitivity analysis with respect to internal and external parameters of the model. The model is then employed to analyse the economic impacts of the *Fehmarn Belt railway axis* project, in particular the indirect effects thereof. For that,

the model is specified on a very fine regional scale (over 1400 regions) and is linked to an external transport network model.

Chapter 5 sets up a dynamic SCGE framework by assuming forward-looking behaviour of the firms and the households. The starting point is the open-economy version of the Ramsey optimal savings model. The evolution of the capital stock is assumed to be smoothed by the presence of adjustment costs. We present all the steps of the model setup and the accompanying derivations. The resulting mathematical problem is rather special and requires a tailor-made solution algorithm, which we describe in due detail. We then study the predictions of the model using an experimental 3-region setup, as well as a 10-region Fehmarn Belt simulation.

The findings of the thesis are summarized in Chapter 6, and a brief outlook of further research agenda is provided there.

Chapter 2. General equilibrium theory and computable general equilibrium modelling

2.1. Definitions

From an economic theory perspective, a *general equilibrium (GE) model* is a routinely employed, refined tool. At its heart lies an idea of countless economic agents acting in interdependent markets. It thus takes account of complex relationships in the economy and is hence a suitable tool for obtaining insight into economy-wide, direct and indirect, consequences of (for example, transport) policy. Broadly speaking, general equilibrium tries to give an understanding of the whole economy using a “bottom-up” approach, starting with individual markets and agents. One of the key elements of the GE theory is the assumption that the agents make choices individually and optimally.

Computable general equilibrium (CGE) models are often loosely defined as empirical counterparts of this theoretical framework. The most probable reason for such an interpretation is the presence of the words “general equilibrium” in the name. A more detailed and well-balanced specification is given by Thissen (2000). Combining and narrowing the definitions of Dixon and Parmenter (1996) and Dervis et al. (1982), he defines a CGE model as “the fundamental macro-economic equilibrium links among income of various groups, the pattern of demand, the balance of payments and a multisector production structure”. Moreover, such model incorporates a set of “equations describing the economic behaviour of the agents identified in the model and the technological and institutional constraints with which they are faced”.

An important point here is that a CGE model does not take the individual actors as the decision units, as would be the case in a purely microeconomic GE framework, but instead adopts a multisectoral approach. This quite often means that each particular population is represented by one aggregate household (consumer) and each sector by one aggregate firm (producer). This is an essential difference to the theoretical GE concept.

Because the relation between the general equilibrium theory and the CGE models is often misinterpreted, we will try in this chapter to clarify the historical linkages and the sources of important differences. The following two subsections shortly outline the history of general equilibrium analysis, focusing on the episodes that are decisive for understanding the origins of the basic approach and the structure of CGE modelling. After that, we continue

by reviewing the milestones in the literature defining the computational approach, as well as the basic algorithm of CGE modelling.

We do not intend to provide a complete survey of the huge literature constituting the general equilibrium theory. The history of general equilibrium analysis is described in much detail in Weintraub (1983), Samuels et al. (2003), Walker (2006), and shortly in every advanced-level textbook on microeconomic theory.

As for the CGE approach, a comprehensive survey is practically impossible, but instead different subgroups of models are chosen by the reviewers, who try to focus on one type of policy questions and/or one country at a time. Thus, separate surveys are available of CGE models studying tax policies (Shoven and Whalley, 1984), regional policies (Partridge and Rickman, 1998), development policies (Bandara, 1991), trade policies (de Melo, 1998), energy policies (Bhattacharyya, 1996), etc. A more general summary of the CGE approach is provided in the widely cited books by Dervis et al. (1982), Shoven and Whalley (1992), and Ginsburgh and Keyzer (2002).

2.2. The Walrasian general equilibrium model

General equilibrium theory seeks to explain the behaviour of supply, demand, and prices in the whole economy with several or many markets. The general equilibrium model of an economy is the product of nearly two centuries of conceptual innovation and continued intellectual refinement. As argued by Scarf and Shoven (1984, p. ix), its roots may be found in Adam Smith's description of the behaviour of capitalists motivated by considerations of profitability in the selection of economic activities. The elements of demand theory appear in John Stuart Mill's treatment of international trade and in his analysis of the response of economic agents to changes in taxes and import duties. The model reaches its mature form later in the nineteenth century in the work of Leon Walras (1874), who provided a general description of the functioning of a complex economic system based on the interaction of a number of interdependent economic agents.

As outlined by Walras, the basics of the model are the following: individuals are endowed with factors and demand produced goods; firms demand factors and produce goods with a fixed coefficients production technology; all agents are price-takers. *Walrasian (competitive) equilibrium* is defined as a set of factor prices and output prices such that the relevant quantities demanded and supplied in each market are equal to each other, i.e. both output

and factor markets clear. Competition ensures that price equals cost of production for every production process in operation.

More specifically, the following information is assumed to be given: consumer's preferences (utility functions or demand functions), endowments of factors, and production technology. From these components, one should be able to derive in equilibrium: (1) factor prices, (2) output prices, (3) quantity of factors, and (4) quantity of produced outputs. An equilibrium is defined when these components are such that (1) households maximize utility; (2) firms maximize profits; (3) factor and output markets clear.

A very important novelty at that time was that in the Walrasian equilibrium system there was no necessary direction of determination from one variable to another. It was a simultaneous system of equations where equilibrium prices and equilibrium quantities were determined jointly. One did not have to state, "prices determine cost of production" or "cost of production determines prices" etc. In equilibrium, price was equal to the cost of production, but this was obtained as a solution to a simultaneous system, and not from a causal relationship. The only exogenous data were preferences of households, endowments, and technology.

An alternative, but a very similar formulation of the general equilibrium model was given by Vilfredo Pareto (1906). He postulated that "the equilibrium results from the opposition between men's tastes and the obstacles to satisfying them". In his work, everything is cast in the "tastes-and-obstacles" structure (that is the signature of the Paretian system), rather than the demand and supply functions that the Walrasian model is built upon. As put by Koopmans (1957), "The emphasis is entirely on the existence of some set of compatible optimizing choices... The problem is no longer conceived as that of proving that a certain set of equations has a solution. It has been reformulated as one of proving that a number of maximizations of individual goals under interdependent restraints can be simultaneously carried out." A substantial improvement of Walrasian framework by Pareto was the explicit inclusion of profit-maximization by firms. A disputable point, however, was the reliance upon the assumption of differentiability of the various functions employed. The development of the Neo-Walrasian economics in the post-war period, notably the Arrow-Debreu model of the 1950s, retained the tastes-and-obstacles optimization structure of the Paretian system, but it essentially eschewed its differentiability assumptions and effectively reproduced the same results without it.

The Walrasian model fell into long disuse as general equilibrium theorists, particularly in the English-speaking world, opted for the Paretian system, and the study of efficiency issues. The original model was resurrected in Gustav Cassel's *Theory of Social Economy* (1918), but even after that, its analysis was confined to the small audience, which was predominantly German speaking. In the 1930s, a notable centre of intellectual activity in this respect was the Vienna Colloquium, where the Walrasian model was corrected and expanded by Karl Schlesinger (1935) based on the suggestions expressed by von Stackelberg (1933), Neisser (1932), and Zeuthen (1933). Most important improvements were the replacement of core equations by inequalities⁵ and the use of more rigorous mathematics (linear programming, constrained optimization). The model of general equilibrium as stemming from Walras was finally introduced into the mainstream English economic literature by John Hicks (1939) and Paul Samuelson (1941).

2.3. Existence vs. computability of equilibrium

The formulation of the general equilibrium model offered by Walras (1874) was the most mathematically elaborate of his time, and he alone among his contemporaries seemed to recognize the need for an argument demonstrating the existence of prices that would equilibrate the large number of decentralized decisions postulated in the model. He offered two lines of argument.

First, when translated into a formal mathematical system, the number of prices to be determined equalled the number of independent equations governing their determination, suggesting the possibility to solve the model as a simultaneous equations system. Walras was satisfied by this argument for existence, which, although it has considerable merit, is obviously incomplete without further analysis. Pareto (1906) was as well content to count equations and unknowns to verify the existence of equilibrium. Later studies of general equilibrium by Hicks and Samuelson also included the equation-counting step, but the context changed notably.

Samuelson (1941) set out the mathematical definitions of stability and equilibrium and formally defined comparative static analysis. As a starting point, he *assumed* the existence of equilibrium. He then linearized the non-linear equations appearing in the system using first-order Taylor expansion at an assumed equilibrium point. The Taylor series/Jacobian

⁵ Thus, the original system of equations was replaced by what is now called a complementarity system. We will discuss the notion of complementarity in Section 2.5.

(or Newton's) technique actually defined the conditions (namely, the non-singularity of a Jacobian) under which "equation-counting" provided necessary and sufficient conditions for the existence of a *local equilibrium*. The entire procedure was thus directed to exploring the properties of the model in the vicinity of an a-priori assumed equilibrium. A footnote in Samuelson's paper, however, warned that the stationary equilibrium might well be not defined.

In a later paper, Samuelson (1953), in order to show how the endogenous variables in his system are actually determined, makes sure that the constructed system is square by scrupulously counting equations (actually, complementarities) and unknowns. He does not discuss the problem of existence of equilibrium, but he is cautious to mention the possibility of non-unique solution if non-linear functions are employed.

The second existence argument offered by Walras is his famous *tâtonnement* (or groping) process in which tentative prices are revised according to the discrepancy between demand and supply aggregates. This process is globally stable provided either that the market excess demands exhibit gross substitutability or that they satisfy the weak axiom of revealed preference (Uzawa, 1960). Unfortunately, it is not possible to ensure these properties of the aggregate demand without putting serious restrictions on the individual demand functions, and thus the Walrasian *tâtonnement* does not provide a generally applicable procedure to compute equilibrium prices. A series of papers by Hugo Sonnenschein (1972, 1973), Rolf Mantel (1974, 1976), and Gerard Debreu (1974) showed that, with a sufficient number of consumers, aggregate excess demand is essentially arbitrary and hence the behaviour of the *tâtonnement* can be made to follow arbitrary curves. More specifically, the *Sonnenschein-Mantel-Debreu theorem* (as interpreted by Kirman (1992)) implies that only three properties will carry over from the individual's to the aggregate excess demand function: continuity, that the value of total excess demand must equal zero at all positive prices (Walras' law⁶), and that excess demand is homogeneous of degree zero (only relative prices count).

The first mathematically rigorous proofs of the existence of competitive equilibrium appeared only in the 1930s. Abraham Wald in a series of papers (1935, 1936a, 1936b) proved both existence and uniqueness of an equilibrium as defined by Schlesinger's (1935) equation system. The formulation however, employed inverse demand functions, where income and factor prices did not enter, and thus was not general enough.

⁶ This mathematical result was labelled "Walras' law" by Oskar Lange (1942).

The next important contribution to the field was due to John von Neumann (1937)⁷. This work contained the first use in economics of certain, now common, tools: explicit duality arguments, explicit fixed-point techniques in the equilibrium existence proof, and convexity arguments. This paper of von Neumann was not concerned with competitive equilibrium in the classical sense but with a program of maximal balanced growth in a closed production model. Its crucial element was the generalization of the *Brouwer fixed-point theorem*⁸ that would be the major mathematical tool in the later classical papers.

The existence problem for the general equilibrium model was finally solved during the remarkable burst of intellectual activity in mathematical economics that took place in the late 1940s and 1950s. Based on the work of Gerard Debreu (1952), Kenneth Arrow (1954, with Debreu), Lionel McKenzie (1954), and others⁹, the model was formalized with a high degree of precision and generality, and fixed-point arguments were used to demonstrate the existence of prices that simultaneously equated supply and demand for all commodities. A fundamental question in economic theory – the consistency of the general equilibrium model – was given a definite answer.

However, this remarkable achievement in pure theory came at high cost in terms of its practical implementation. The techniques used by Arrow, Debreu, and others in demonstrating the existence of equilibrium (topological fixed-point theorems of Brouwer, Kakutani, etc) utilized mathematical arguments that were fundamentally non-constructive (they did not give a specific recipe to calculate the equilibrium defined through a fixed point).¹⁰ These arguments thus gave no indication of the way in which the implied equilibrium could be used as a practical tool in the type of economic analysis that had provided the original motivation for the general equilibrium model.

Herbert Scarf, who set off to develop a computational algorithm to find the equilibrium implied by the Arrow-Debreu-McKenzie model, was already aware of this non-constructivity problem, and was therefore searching for an approximate solution. His algorithm for calculating the market clearing price vector (Scarf 1967a, 1967b; Scarf and Hansen, 1973) was the first practical, surely convergent method for computing general equilibrium prices and, equivalently, solving systems of nonlinear equations in \mathbb{R}^n . Its im-

⁷ Some economists consider this paper “the single most important article in mathematical economics” (Weintraub, 1983).

⁸ Every continuous function $F: B^n \rightarrow B^n$ defined over the unit ball B^n in the n -dimensional space has at least one fixed point (a point $x \in B^n$ for which $F(x)=x$) (ibid.).

⁹ Contributions of Nikaido (1956) and Gale (1955) are particularly noteworthy.

¹⁰ The impossibility to devise a constructive procedure (a computer algorithm) to determine the Brouwer fixed point is demonstrated e.g. in Velupillai (2006) and Tanaka (2008).

portant advantage over the traditional Newton's method was that no initial guess for the equilibrium was required, which was quite in the spirit of GE theory. Scarf's work was followed by the development of almost surely convergent homotopy methods for solving nonlinear equations (see Eaves and Schmedders (1999) for a review).

The connection of these methods to the theoretical concept of equilibrium (the fixed point), however, was not undisputed. Scarf's algorithm would narrow down the set of possible relative prices through a simplex method, which kept reducing the size of the 'net' within which possible solutions were found. The modeller then had to choose a cut-off, and thus get an approximate solution as the net never closed on a unique point through the iteration process. As Scarf notes in the classic book of 1973 (p. 16), "we have no assurance that the [chosen] sub-simplex... contains or is even close to a true fixed point of the mapping". Velupillai (2006) even argues that "the value determined by Scarf's algorithm has no theoretically meaningful connection with the fixed point for it to be referred to as an approximate equilibrium", and points that this issue still remains unresolved.

Although Scarf himself did not ever put together an applied model and solve it for the equilibrium using his algorithm, he clearly had applications in mind. His method was first used in a computational example by Shoven and Whalley (1972), and was extensively employed by Scarf's students and students' students¹¹. This approach was referred to as *applied general equilibrium modelling*. Building upon the original work of Arrow, Debreu, and others, these papers necessarily included an equilibrium existence proof for the model used. The calculations that followed aimed to assess the effects of a specific policy measure, like a reform of the tax system (Whalley, 1977) or quota liberalization (Feltenstein, 1983).

The first applications of Scarf's method, however, revealed severe limitations in terms of the feasible size of the underlying model and computational time. At the same time, the modellers that dispensed with explicit micro-foundations in favour of computational procedures that were fast (if not certainly converging) could already in the early 1970s solve a model with 35 disaggregated sectors in less than six minutes¹². Consequently, they could quickly provide a policymaker with important insights in the questions, for which the only alternative source of information would be pure guesswork. The success of this approach was built upon the original work of Wassily Leontief and Leif Johanssen, and we now want to discuss it in due detail.

¹¹ Timothy Kehoe, John Whalley, Andrew Feltenstein, John Shoven, Terje Hansen, to name a few.

¹² Taylor and Black (1974).

2.4. Genesis of the CGE approach

One dominant tradition in applied economic modelling originated with the seminal work of Leontief (1937, 1941), the implementation of the static *input-output model*. The initial goal of his work was the creation of a table of input-output accounts – an accounting system that encompassed “all branches of industry, agriculture, and transportation, and also the individual budgets of all private persons” (Leontief, 1951a, p.11). Once this huge project was underway, Leontief realized that in addition to the table, he needed a model for the underlying US economy. For this purpose, he set up his own structure for a “national account” of the economy, where all sectors produced goods or services that were consumed fully by another sector.

Besides taking an explicit *multisectoral approach*, Leontief had to further simplify the general equilibrium system to the extent necessary to derive a set of parameters for his model from a single observation of each of the inter-industry transactions in the economy. He therefore omitted the effects of limited factor supplies from the system. He also used the original Walrasian assumption of fixed coefficients of production instead of allowing for substitution among inputs. In thus eliminating all effects of prices on the composition of consumer demand, on the purchase of intermediate goods, and on the supply of labour and other factors, the Leontief model precluded many of the adjustments characterizing the Walrasian concept of general equilibrium.

The corresponding system of equations was linear, which was very important in the era when the computing capacities were severely limited. The assumption of fixed coefficients allowed estimating the unknown technological parameters from a single data point by simple calculations. Impact analysis and forecasting essentially involved inverting one single matrix.

At the end of the Second World War Leontief’s input-output estimates of the 1939 US economy (partly included in Cornfield et al. (1947)) were used to forecast steel demand in a non-war scenario. This was one of the few forecasts that suggested that steel demand would not fall as a result of the war ending, but would be strong – which turned out to be correct. Leontief (1951b) argued that this was one of the reasons why this form of analysis became important to the U.S. administration already then, and academics started adopting multisector input-output models for economy-wide analysis. Later, Chenery and Clark (1957) extended the original Leontief’s framework by adding behavioural equations to explain final demand (consumer demands were derived from an aggregate utility function),

by subdividing the economy into several regions, and by using multiperiod analysis to explain investment.

The first successful implementation of a numerical multisectoral model without the fixed-coefficients assumption of the input-output analysis is due to Johansen (1960). He used a model with nineteen production sectors, built upon Norwegian data from 1950, to identify the sources of economic growth in Norway over the period 1948-1953. Johansen retained the Leontief assumption in modelling demands for intermediate goods, but employed linear-logarithmic (Cobb-Douglas) production functions in modelling the substitution between capital and labour services and technical change. He also replaced the fixed-coefficients assumption for household behaviour by a system of demand functions originated by Frisch (1959).

Briefly, the solution method employed by Johansen is as follows: given a model with time-dependent parameters and an initial spot equilibrium, differentiate the model with respect to time and solve the linear system of equations to obtain a direction for the equilibrium route. Beyond this, Johansen, apparently, did not try to recover the equilibrium of the time-dependent economy (Eaves and Schmedders, 1999). He notes that his model (with a few exceptions) represents a formal analogy with the solution, which in theory is obtained under perfect competition. Nevertheless, the development path satisfying the equations of the model is not necessarily an optimal one.

Johansen's method was reintroduced by Taylor and Black (1974), who applied it to the model of the Chilean economy. In their paper, a set of equations characterizing the alleged equilibrium is written down and totally differentiated, and enough differential changes in exogenous variables are specified to permit inference of changes in the endogenous variables by the solution of a system of linear equations. This first contribution was followed by a rapidly growing number of papers that applied the same procedure, namely:

- 1) setting up a system of (nonlinear) equations characterizing an imputed equilibrium,
- 2) calculating the values of exogenous parameters based on the available data,
- 3) making sure that the system is exactly identified,
- 4) explicitly linearizing the model around the initial equilibrium, and
- 5) doing comparative static analysis by changing the values of exogenous variables.

This approach soon received the name of *computable general equilibrium modelling*¹³. The classical summary of the approach is by Shoven and Whalley (1984, 1992).

¹³ The name "computable general equilibrium" is due to Adelman and Robinson (1978).

This method of policy analysis became increasingly popular among international organizations and governments, also because many of the members of the CGE community (Hollis Chenery, Lance Taylor, Sherman Robinson, Kemal Dervis, and many others) eventually held positions as high-level policy advisers. When by the end of the 1980s the computational facilities improved enough to allow faster implementation of the Scarf-style algorithms, the original motivation for their development (Walrasian foundations and the existence proof of Arrow and Debreu) was widely perceived as having “no policy significance”¹⁴. The interest of policy makers was in comparative statics rather than existence. That is why the new solution methods were further applied in the same procedure as described above; only the linearization step could now be skipped.

The popularity of CGE modelling further expanded with the development of powerful modelling systems (GAMS, AMPL, GEMPACK) that were able to directly express the underlying mathematical problems (mostly nonlinear complementarity problems or constrained optimization problems) as part of their syntax and pass them on to the appropriate solvers. Included in this are so-called mini-languages, such as MPSGE (Rutherford, 1999), which allow particularly convenient formulation of certain types of models. For the very large problems, however, the linearization technique of Johansen could further be used, as is the case with the Australian ORANI model (Dixon et al., 1982) and its successors.

2.5. General structure of a static CGE model

We have in the previous section given a brief summary of the procedure underlying the construction of a typical CGE model. We will now provide some more detail about every step, and in doing so introduce such important notions in CGE modelling as benchmark equilibrium, complementarity, calibration, and closure.

The common algorithm of constructing a CGE model can be described as follows¹⁵:

- 1) define agents, factors, and commodities;
- 2) organize data in a benchmark equilibrium dataset;
- 3) specify technology and preferences, adopt functional forms;
- 4) choose market forms and define prices;
- 5) choose macroeconomic closure rules;
- 6) numerical specification;

¹⁴ Shoven and Whalley (1992), p. 21.

¹⁵ See Shoven and Whalley (1992) for a comprehensive discussion of various steps

- 7) choose a solution technique;
- 8) run the experiments;
- 9) sensitivity analysis.

In reality, the presented steps are interconnected, and often earlier steps need to be reconsidered if difficulties arise at later stages. We will now describe the content of these steps in some detail.

2.5.1. Agents, factors, and commodities

These choices vastly depend on the research question under investigation. If the focus is on the aggregate phenomena, it will probably be the case that few classes of agents, factors, and commodities will be introduced. First, a set of economic actors, whose behaviour will form the subsequent mathematical formulation of the model, is defined. A generally used assumption is that of a *representative household* and a *representative firm*.

A representative household approach means that all households of the same type are assumed identical. Each agent of a certain type is assumed to behave rationally and maximize his utility subject to the individual budget constraint. If the income distribution issues are of minor importance for the research question at hand, only one type of representative household per economy is introduced.

In the classical Arrow-Debreu-McKenzie approach, one would then sum up the choices of all identical households in the economy to generate the aggregate demand functions. In a CGE model, however, one starts with specifying the behaviour of the group. At this step, the thread connecting the two approaches is very thin. The sum of individuals' choices is mathematically equivalent to the decisions of one aggregate agent only if the individual demand functions are of very restrictive Gorman form, which in a special case is equivalent to the assumption of identical homothetic preferences (Gorman, 1953, 1961). Thus, assuming this form is necessary in order to stay consistent with the general equilibrium theory.¹⁶ Otherwise, the modeller has to start with devising behavioural rules for the aggregate of all individuals, just like Taylor and Black (1974) did, without making any reference to Walras or Arrow-Debreu framework.

In the case of the firms, the aggregation is very simple under perfect competition. If firms maximize profits taking prices as given, then the production side of the economy aggre-

¹⁶ The preferences that we assume in the models of Chapters 4 and 5 produce individual demand functions of Gorman form.

gates beautifully, with the sum of individual firms' choices equivalent to the choices of an aggregate firm (see MasCollé et al. (1995), Ch. 5.E.). This allows the modeller to treat the aggregate technology as if it were the outcome of decisions made by individual firms.

When specifying the agents acting in the economy, one should also define different *institutions*. These are different from the firms and the households in that they act on the macro-level. The phenomena associated with their behaviour are the budget deficit, tax revenue, public expenditure, savings-investment balance (in the static setup), trade deficit, etc. Institutions that can be introduced to allow for these phenomena include a government, a central bank, an external trading partner, etc.

To study the effects of tax policy and the provision of public goods, it is usually needed to explicitly introduce state, or government as a separate agent. If the structure of the taxation system has to be very detailed, several authorities dealing with different types of taxes are usually introduced (as in Löfgren et al. (2002)). Likewise, when the questions of external trade are involved, there will be a reason to introduce a *rest-of-the-world* region, probably characterized by more rough economic structure than the study area.

Unlike the firms and the households, the institutions do not have conventional objective functions. These vary significantly between models. The choice of rules for the macroeconomic agents is often referred to as a *closure* of the model, and we will discuss the corresponding choices a bit later.

The decision about the number of factors is dictated by the necessity to have e.g. a mobile and an immobile factor, skilled and unskilled labour, renewable and exhaustible resources, etc. In turn, the commodities introduced may be broad aggregates, like tradable and non-tradable goods, or sector-specific aggregates (e.g. metal products, food products), or even finer defined goods and services. These may or may not explicitly include money as one of commodities. The property rights for the factors have to be specified to identify the recipients of factor income. The transactions involving each factor and commodity specified are carried out in a separate *market*.

2.5.2. The benchmark equilibrium dataset

The starting point for creating a data structure underlying a CGE model is a table (or a set of tables) containing the monetary flows between the agents and the markets. Two alternative and commonly used methods to summarize these flows are the social accounting matrix (SAM) and the micro-consistent matrix (MCM). The common idea behind these two

approaches is the creation of a *benchmark equilibrium dataset*. In particular, the time point to which the data refer (called “base year”, “benchmark”, or “reference point” in different studies¹⁷), is assumed to be the initial equilibrium of the model, with which all consecutive solutions will be compared. Thus, the benchmark dataset has to be consistent with the general equilibrium requirements:

- 1) budget constraints should hold for all agents (“no loose ends” condition);
- 2) all markets should clear – summing over all agents, the value of sales must equal the value of purchases for all commodities and factors.

A SAM is a square matrix where every row has a corresponding column with the same name. All agents and all markets have their own row and column in a SAM. The rows identify the recipients, and the columns identify the payers of monetary amounts appearing in the cells of the matrix. A distinguishing feature of a SAM is that it has to be balanced: each row sum has to equal the corresponding column sum. Thus, all expenditures of every agent have to match the income, and the value of sales should equal the value of purchases on every factor and commodity market. In this way, the essence of general equilibrium is demonstrated – no “loose ends” are left. A SAM has an advantage of having a traditional input-output table documenting flows between industries as an integral part of itself.

An MCM, in turn, has markets in rows and agents in columns. Entries in the matrix can be positive (receipt of a given agent in a given market) or negative (expenditure, likewise). In a balanced MCM, all rows and columns thus sum up to zero, also representing the GE consistency. An MCM has an advantage of having a more direct link to the usual equations of zero profit and market clearing conditions. This method is also preferable for the cases where industry-commodity framework (defined below) is introduced.

In the multiregional models, additional data tables will be needed to describe the trade between areas, and the whole database may grow arbitrarily big (see e.g. the GTAP database (Center for Global Trade Analysis, 2005)).

2.5.3. Specification of technology and preferences

At this point, the mathematical formulation of the model is written down. The functional forms have to be chosen for the representations of preferences and technology. Very often,

¹⁷ We will use the terms “base year” and “benchmark” synonymously to denote the time point in the past to which the collected data refer. In contrast, “reference point” may be any time point in the past or in the future for which comparative policy simulations are performed. It may not coincide with the base year. Reference equilibrium dataset is constructed using the benchmark dataset and the rules of its evolution over time.

the dual concepts are applied here, and the basic constructs are thus the expenditure function and the cost function.

The major constraints on the specification of the functional forms in applied models are that they have to be consistent with the theoretical approach and analytically tractable (Shoven and Whalley, 1992). The first constraint involves choosing demand functions that are nonnegative, continuous, homogeneous of degree zero in prices, and satisfy the Walras' law. The second constraint requires that the demand and supply responses from the economy should be reasonably easy to evaluate for any price vector considered as a candidate equilibrium solution for the economy. This largely explains why the functional forms used are often restricted to the family of "convenient" forms (Cobb-Douglas, constant elasticity of substitution (CES), linear expenditure system, and several others). The general approach is to select the functional form that best allows key parameter values to be incorporated, while retaining tractability.

A device widely employed in applied models is to use hierarchical (or *nested*) functions. Under this approach, CES (or Cobb-Douglas) functions can be contained within other CES functions, and many layers of hierarchy can be employed. The benefit of this approach is that it greatly expands the number of elasticity parameters that can be used to replicate the estimates in the literature.

The choice of outputs and inputs for each activity also has to be done. When the firms are designed to produce more than one type of output, one can speak of the *commodity-industry framework*. In this case, the classical Leontief concept of the input-output table is not applicable, as no one-to-one correspondence between sectors and commodities is present. The input and output tables are then separated (see e.g. Löfgren et al. (2002)).

2.5.4. Market forms and prices

These choices are again dictated by the research questions under consideration, but also by the availability of data. With no firm-level data, for example, it will be hard to implement an applied model with the focus on an oligopolistic sector. All market forms apart from perfect competition require the knowledge of price elasticities of demand in order to determine the optimal pricing rules (e.g. through Amoroso-Robinson relation). Thus, this information should also be available.

The models based on new economic geography literature now often introduce a modern sector into the model, characterized by monopolistic competition. In this way, it is possible

to model the agglomeration effects (Fujita et al., 2000).

The knowledge of the price mark-ups together with the knowledge of the applicable taxes allows next to determine the relationships between producer and consumer prices. A commonly used units convention, originally adopted by Harberger (1959, 1962), is to choose units for goods and factors such that they have a price of unity in the benchmark equilibrium. For markets disturbed by mark-ups and taxes, the benchmark producer and consumer prices will, of course, differ from one another.

2.5.5. Closure rules

The formal introduction of the concept of a closure rule can be traced back to Sen (1963). Sen showed that in the static framework the necessary ex-post equality between savings and investment cannot be fulfilled when all the following conditions are satisfied: the factors are paid at their marginal productivity, household consumption is a function of real income, real investment is fixed, and the factors are fully employed. The equilibrium is achieved only by relaxing one of these constraints. The choice of the constraint to be dropped represents in fact the choice of the closure rule.

In mathematical terms, the model should consist of an equal number of independent equations and endogenous variables. The closure rule reflects the choice by the model-builder of which variables are exogenous and which variables are endogenous, in order to achieve ex-post equality.

Although the early work on macroeconomic closure focused on the savings-investment balance, Adelman and Robinson (1989) pointed out that there are three macro balances in any applied CGE model:

- 1) the government balance,
- 2) the external balance, and
- 3) the saving-investment balance,

and each of them can be a potential source of ex-ante disequilibria, which must be reconciled ex-post.

The selection of the closure rule is not only concerned with the technical solution of the identification problem described above but is also a reflection of the choice of theory. It specifies which functions need to be described explicitly and which variables are allowed to adapt to ensure that the macro balances hold. For example, the neoclassical theory would imply that labour is paid according to marginal factor productivity, and would spec-

ify a functional form for the real wage rate. The neo-Keynesian theory, on the other hand, would imply a fixed nominal wage rate and an endogenous price level determination. Thus, the choice of the closure rule necessarily affects the policy simulation results obtained with a CGE model.

2.5.6. Numerical specification

One can define three broad approaches to link a CGE model to the data:

- 1) calibration to a benchmark equilibrium dataset referring to a single year,
- 2) averaging across years,
- 3) econometric estimation.

Ideally, all parameters in the CGE model may be econometrically estimated, using simultaneous equation estimation methods that take into account the overall model structure. However, given the size of the CGE models, the required sophistication of techniques, the identification problems and the lack of data, this procedure is often regarded infeasible (Gunning and Keyzer, 1995). Therefore, the most commonly used procedure to determine the parameter values is calibration.

Calibration, as defined by Mansur and Whalley (1984), is the property of the model to reproduce the benchmark dataset as a model solution. This notion is tightly linked to the assumption of an initial “observable” equilibrium. In the process of calibration, the equations of the models are “inverted,” such that the parameters become the unknowns, and the endogenous variables become parameters with their values taken from the data or freely chosen (e.g. in the case of prices).

The calibration procedure implies that the parameters of the model are identified based on a single observation of the economy. This amounts to saying that absolutely no factors other than those already included in the model affected the values of the unknown parameters in the benchmark period and none are expected to affect them in any future period. This is a very strong assumption. The advantage of this assumption is, however, the parsimony of the data requirement – only one observation is needed, and the ease with which the values of the parameters can be determined. As argued by Lau (1984), some other problems with the calibration approach include the lack of a measure of the degree of reliability of the model and its parameters, and the impossibility to apply this method to estimate the elasticity (curvature) parameters.

Thissen (2000) proposed a refinement of the existing calibration approach, based on an estimation of the parameters using data for several years. The parameters are determined by minimizing an adjusted root mean square percentage error for the endogenous variables. Earlier versions of this *averaging approach* can be found e.g. in Feltenstein (1983). In this way, however, the identical satisfaction of the general equilibrium constraints in the benchmark period is lost.

2.5.7. Solution techniques

A modern CGE model is commonly formulated as a system of weak inequalities, with each inequality associated with a particular non-negative variable such as a price or quantity¹⁸. If a particular weak inequality holds as an equation, then the associated variable is allowed to be strictly positive. If it holds as a strict inequality, then the associated variable is zero. This is referred to as a *complementarity problem* in mathematics, and the associated variables are referred to as complementary variables. Calculating an equilibrium of a modern CGE model thus often involves solving a nonlinear complementarity problem.

The model is formulated as a square system consisting of two major building blocks: the market equilibrium constraints for the commodities and factors and the budget constraints for the agents (households and firms). In very general notation, we can write this system as (symbol \perp is connecting the complementary variables):

$$\text{For every product } i: \quad \text{Supply}_i \geq \text{Demand}_i \quad \perp \quad \text{Price}_i \geq 0$$

$$\text{For every factor } j: \quad \text{Supply}_j \geq \text{Demand}_j \quad \perp \quad \text{Price}_j \geq 0$$

$$\text{For every industry } s: \quad \text{Profit}_s \leq 0 \quad \perp \quad \text{Output}_s \geq 0$$

$$\text{For every household type } h: \quad \text{Expenditure}_h = \text{Income}_h$$

As the underlying demand functions are homogenous of degree zero in prices and income, the absolute levels of prices are not defined by this system. The solution is to fix the units of measurement by setting one price or a price index equal an arbitrary constant (usually, unity). This step is referred to as choosing the *numéraire* of the model. The model formulation is thus completed when the closure rules are specified, the price level is set, and one of the market clearing constraints is dropped due to Walras' law.

The past two decades have seen an enormous increase in the ability of modellers to solve large-scale complementarity problems, due not only to the phenomenal increase in com-

¹⁸ The original idea of the model formulation in terms of inequalities dates back to Schlesinger (1935).

puter speed, but also due to progress made in algorithms and software for complementarity problems. An important advance here was the implementation of large-scale complementarity solvers such as MILES (Rutherford, 1993), PATH (Dirske and Ferris, 1995), and SMOOTH (Munson et al., 2001). This improved ability to solve larger and more complex complementarity problems, of course, furthers the development of new applied economic models.

In the cases, when the solution of a CGE model is not expected to result in some goods not being produced or some possible trade links not being actively used, the model formulation in terms of a *square system of equations* may be sufficient. Then, standard Newton techniques using successive linear approximations to the nonlinear system can be employed.

An alternative method of the CGE model formulation involves solving *optimization problems* with complementarity constraints, typically termed mathematical problems with equilibrium constraints (MPECs) in the literature (Harker and Pang, 1988). This method dates back to Chenery and Usawa (1958), who suggested that a planning model could be formulated as either a maximization of the welfare obtainable from given resources, or the attainment of a given level of welfare with a minimum input of scarce resources. Ferris et al. (2005) show that such a problem essentially boils down to solving a standard nonlinear program. Modern MPEC solvers are available for all popular modelling environments such as GAMS, AMPL, or MATLAB. The applicability of these methods for CGE models is, however, not always straightforward, as a single function or variable to be optimized is often hard to determine, especially in the multiregional setup.

2.5.8. Running the experiments

After all previous steps are done, the modeller gets to the point when it is possible to run policy experiments and answer the research questions that motivated the construction of the model. A first important step is the *replication of the reference equilibrium*: it must be possible to get as a solution of the model the values of the endogenous variables that were used in the calibration step. If this step is successful, one moves on to solve for *counterfactual equilibria* by specifying changes to exogenous variables, and thus bringing the initial system out of balance. The task of the solver is then to adjust the values of endogenous variables such that the new “after-shock” or “policy scenario” equilibrium is attained. Further steps involve analysing the qualitative and quantitative results of these experiments and formulating policy recommendations.

2.5.9. Sensitivity analysis

One of the major criticisms of the CGE approach is the lack of a measure of the degree of reliability of the model and its parameters, which is usually present in the alternative, econometric approach. To partly respond to this critique, CGE modellers came up with the procedure called sensitivity analysis. This usually amounts to an additional series of experiments when the implications of the crucial assumptions of the model are being tested. Most commonly, a plausible range of values for an important parameter (e.g. a substitution elasticity in the utility function) is set, and the policy experiment is repeated for different values of this parameter inside that range. If the resulting output indicators do not change in an important way, the modeller may report that the model prediction is stable with respect to changes in that particular parameter. If the values of the output indicators change a lot, but at least the direction of change is preserved, it is often stated that the qualitative prediction of the model is stable.

2.6. Summary

The bottom line of this chapter, in which we discussed the historical linkages between the general equilibrium theory and CGE modelling, can be formulated as follows. CGE models are not true general equilibrium models if the latter is reserved for models devoted to the interaction of individual optimizing micro units in the economy. Starting from its true origins, the work of Leontief and Johansen, CGE modelling was quite distant from general equilibrium theory. Its focus was on the analysis of aggregate phenomena and its development was largely dictated by the advances in computer technology. Thus, any numerical exercise with a CGE model will have inevitable and unavoidable ad hoc aspects, divorced from general equilibrium theory. The construction of such models assumes a lot of freedom of choice for the modeller, and the particular assumptions made in every step may change the predictions of the model in an important way.

Chapter 3. Overview of the static SCGE modelling

Having described the general structure of a standard static CGE model in the last section, we now turn to the features specific to spatial CGE modelling. The concept of an SCGE model implies the distinction of commodities, factors, firms, and households by location. This alone, however, is not the main distinguishing feature. An SCGE model was probably first defined by Frisz et al. (1993), who thus denoted a CGE model including an explicit representation of a transportation network. As suggested by the further evolution of this framework, decisive for the ability of the SCGE models to bring forward new insights about the effects of policies is the incorporation of the fundamental principles of regional and spatial economics: factor mobility, economies of scale, and the presence of transport costs¹⁹. These ideas are also central to the modern trade and growth theory, and the new economic geography. The corresponding theoretical framework is largely based on the work of Paul Krugman (1979, 1980, 1991).

3.1. Key features of spatial economic models

The key theoretical assumptions that shape the spatial interactions in the modern regional science literature are the following:

1) Increasing returns to scale.

As Fujita et al. (2000, p. 2) put it, “any sensible story about regional development depends crucially on the assumption of increasing returns”. The cumulative processes that produce the remarkably uneven spatial distribution of economic activity and population in any country or region necessarily involve some form of scale economies.

A now widely used approach that allows incorporating scale economies into a spatial model while preserving much of the analytical ease of the perfect competition setup is the framework of monopolistic competition with free entry (originating from Chamberlin (1933)), whereby each firm produces a different brand of sectoral output. Then, within each (aggregate) sector, the whole spectrum of different products is produced in every region. This opens the possibility for intra-industry trade.

2) Preference for variety.

For a large pool of brands to sustain, the consumers have to distinguish them and treat them all as imperfect substitutes. This is the assumption made by Dixit and Stiglitz

¹⁹ Principles listed in Hoover and Giarratani (1999).

(1977) in their formalization of monopolistic competition model that explicitly involves “the desirability of variety”. Their initial contribution was followed by Krugman (1979) and Ethier (1982), who applied it to inter-industry trade modelling.

The combination of these two assumptions already leads to a model, which has a lot of explanatory power. Such a model would predict that a region with a bigger economy attracts more demand for intermediate and final goods, even without having a price advantage over other regions. In a traditional multiregional model, this result could only be achieved by using exogenous parameters of preferences and technology (through the commonly used approach due to Armington (1969)). Another implication is that firms and households gain from an increase of the number of brands, as this decreases their costs (we show the underlying derivations in Appendix A). This demonstrates the existence of *agglomeration economies* that is put forward as relevant by the new economic geography literature (Fujita et al., 2000). Not of least importance is also the fact that monopolistic competition may be simply a more plausible market structure for some industries.

3) Different factors of production have different degrees of interregional mobility.

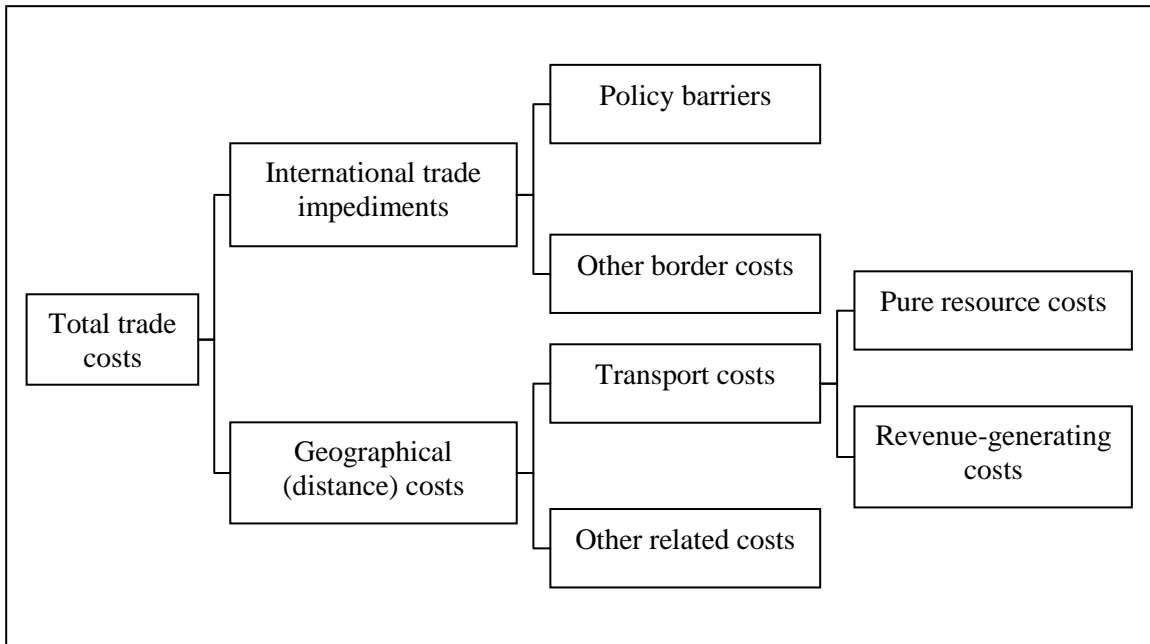
This ranges from complete immobility of land and natural resources to almost perfect mobility of certain types of investments. Capital mobility is an important element of international trade models since the seminal contribution of Mundell (1957). An important topic in regional economics is also the mobility of labour (migration). Factor mobility facilitates the distribution of the effects of various policy measures across space, and thus it must be taken into account when doing policy analysis.

4) Goods are not freely mobile.

Trade occurs in physical space and moving goods requires resources and time. The total trade costs can be thought of as consisting of several components. In this study, we will distinguish between the costs caused by the physical transfer of goods from the seller to the customer, and additional costs for overcoming international trade impediments (border costs).

We will refer to the first type of costs as geographical trade costs or distance-dependent costs. They include transport costs but also other costs correlated with distance (communication, logistics, insurance, travel costs in maintenance service, etc). Transport costs, in turn, consist of pure resource costs (fuel cost, vehicle operating costs, other costs of freight, as well as time costs), and revenue-generating costs (taxes, road tolls, rail network access charges, etc).

Figure 3.1.1 Components of the total trade costs



International trade impediments in turn contain policy barriers (tariffs and non-tariff barriers), language barriers, costs associated with the use of different currencies, contracting costs, and the like. Many of these cost components are unobservable.

As we will often refer to different components of the trade costs in the following discussion, we summarize the essential elements of this structure in Figure 3.1.1.

Later in this chapter, we intend to classify the available SCGE models according to the way they incorporate the listed principles of spatial economics. Because our focus is on the analysis of transport policy, we would like to first describe in more detail the alternative approaches used in the literature to incorporate the transport costs.

3.2. Approaches in modelling transport

In one of the early contributions to the SCGE modelling, Buckley (1992) distinguishes between an implicit and an explicit specification of **transportation demand**. According to this dichotomy, the main question is whether transportation is treated in the same way as any other production sector (*implicit method*), or its complementary nature is recognized and transport service is thus handled as origin-destination based margin (*explicit method*). In the first case, transportation (but also any other network service like wholesaling or communication) is treated as a commodity that can be directly consumed, traded or substituted interregionally. This method has its roots in the SAM-based modelling and can be

traced back to Round's (1988) procedure of including transfer costs in interregional SAMs. In the second case, demand for transportation is viewed as a derived demand, and its amount is directly linked to the flow of tradable products through a set of transportation coefficients. Let c_{rs} denote such a transportation coefficient, interpreted as the amount of transport service necessary to move a unit of a given commodity from r to s . Denoting commodity prices at origin and destination by p_r and p_{rs} , respectively, and the price per unit of transport service by p_t , the spatial pricing equation²⁰ would be:

$$p_{rs} = p_r + p_t c_{rs}. \quad (3.2.1)$$

Coefficients c_{rs} are usually treated as exogenous, and must be estimated or come from the model calibration. The price p_t depends on the technology used in the transport sector.

A good way to think about the origins of the two approaches described above is to compare the freight demand of a firm to a person's demand for short holiday trips with a car. While the first will be largely determined by the amount of goods that a firm wants to be moved from r to s , the second is dictated by preferences and income, thus being not very different from the demand for any other commodity. For the analysis of freight cost changes undertaken in the next chapter, the explicit method will be appropriate.

We thus discussed two alternative ways to represent the demand for transportation. Another object of choice for the modeller is the assumption about the **technology in the transport sector**. An obvious approach would be to construct the technology tree based on the information available in a SAM, exactly in a way it is done for the other sectors. However, if the model has very few sectors, but a lot of regions (as is the case for the model to be presented in the next chapter), adding an explicit transport sector would significantly increase the dimension of the mathematical system to be solved: the number of equations and the number of endogenous variables to be determined. In such cases, it became very common to use a shortcut solution proposed by Samuelson (1954), namely the "*iceberg*" *assumption*. This method allows incorporating transportation as an explicit element of the spatial structure of the model, without imposing any additional computational burden.

The "*iceberg*" model simply means that a certain percentage of the transported commodity itself is used up during transportation (Samuelson used an analogy with an iceberg "melting away"), and the amount of "melting" increases with distance travelled. The price of goods reaching the destination should then increase in order to leave the supplying firm with the same revenue. The firm will thus scale the mill price up by a factor $\tau \geq 1$, if the

²⁰ This simplified illustration, of course, ignores our discussion of different components of trade costs.

proportion of goods used up in initial amount is equal to $1 - 1/\tau$ ²¹. The value of the delivery, however, will stay the same. In terms of the pricing rule in Eq. (3.2.1), the iceberg assumption implies that $p_r = p_l$. Thus, we can rewrite this equation as

$$p_{rs} = \tau_{rs} p_r, \text{ where } \tau_{rs} = 1 + c_{rs}. \quad (3.2.2)$$

While the straightforward interpretation of the iceberg model is certainly sensible for the shipping of raw oil or gasoline, it may seem rather strange, if one thinks about the transport of building materials or machinery. A slightly more plausible interpretation would be to imagine that the transportation service is produced by the firm itself, using the same technology as is used to produce the supplied commodity. One should also keep in mind that making a delivery from r to s does not only involve transportation per se, but probably also other supplementary services, such as communication, storage, insurance etc. In the iceberg model, all these services can be treated as a joint product of the firm supplying the commodity (Bröcker, 1998a). These by-products are then used up completely during the delivery. Factor τ_{rs} can thus be interpreted as the ratio between the total value of the delivery, including these services, and the value of the delivered goods at mill prices. Correspondingly, $\tau_{rs} - 1$ is an ad-valorem tax equivalent of the mentioned costs.

The major justification for the iceberg assumption is, clearly, not observational, but analytical. As Krugman (1998) points out, this is a “technical trick” employed for reasons of modelling convenience, in particular because of “spectacular synergy between Dixit-Stiglitz market structure and ‘iceberg’ transport costs”. Krugman (1980) shows that the incorporation of the iceberg assumption within a Dixit-Stiglitz framework leads to a trade specification that is structurally consistent with a gravity model form.

Bröcker (1998b) further introduces a *modified “iceberg” assumption*. According to this approach, a composite of all available varieties of tradable goods is used up for transporting each single tradable good. The formal solution of the presented SCGE model turns out to be particularly easy to handle with this assumption.

A disadvantage of using the iceberg assumption is that it limits the possibilities for the analysis of phenomena inside the transport sector. Parameter τ_{rs} is purely exogenous by construction. It means that the shocks to the transport sector, such as infrastructure improvements, higher fuel prices, or introduction of emission taxes, have to be translated into

²¹ Denoting prices at origin and destination by p_r and p_{rs} , assume that x out of y units are used up. Then the firm will stay with the same revenue if $\frac{p_{rs}}{p_r} = \frac{y}{y-x} \Rightarrow \frac{x}{y} = 1 - \frac{1}{p_{rs}/p_r}$.

the values of τ_{rs} outside of the model. In order to be able to see the endogenous response of transportation activity to these shocks, the two options are: 1) the usual avenue of SAM-based modelling of technology (allowing for the response of the price p_i), and 2) the hybrid CGE-transport modelling (endogenizing the transportation coefficients). The examples of both methods are discussed in Section 3.4. Their common feature is that both are hard to implement when dealing with many regions.

Another problem with the iceberg assumption is that the formulation as in Eq. (3.2.2) merges all trade costs together. Thus, if several components of total trade costs (e.g. border barriers and distance costs) are assumed to be subject to individual shocks, factor τ_{rs} must first be correspondingly decomposed. We study this issue in the next subsection.

3.3. Parameterization of transport costs

The application of the iceberg approach requires knowledge of the mark-up factors τ_{rs} . For this purpose, the share of trade costs in the value of interregional trade flows must be evaluated. As total trade costs contain many unobservable elements, their value can only be inferred indirectly, for example, by setting up a theoretical trade model, and calibrating its parameters (including τ_{rs}) such that the theoretical trade flows match the observed trade flows.²² For the observable cost components, econometric methods can be applied. An excellent survey of these methods is by Anderson and van Wincoop (2004).

Further, in order to study the effects of transport policy in an applied model, one needs data about the size and composition of transport costs in the benchmark situation. These costs have to be separated from the total trade costs. We can in general distinguish between direct and indirect (inferred) measures of transport costs. Direct measures are based on surveys of original data sources. Indirect methods start by making assumptions about the appropriate model of trade or transport flow, as well as assumptions about the composition of the associated costs. Next, the underlying parameters are estimated or calibrated.

3.3.1. Direct measures of transport costs

Most accurate data would be obtained directly from the industry or from freight carriers. On the firm level, the data are distinguished by dozens of attributes, most important being

²² Because the exact procedure depends on the model used, we will not discuss this issue further here, but will return to it when describing our model calibration in Section 4.5.

the origin and destination of a trip, characteristics of the load, transportation mode, and route taken. Such information is of private nature, which means high time and monetary cost of initial data collection. In the multiregional modelling setup, the use of this option is thus unfeasible, unless a source containing readily aggregated data is available. Transport network models and their accompanying databases would be an ideal source of such information.

Alternatively, there are two sources of information on average transport costs. National customs data in some cases (e.g. U.S. Census; unfortunately, most of these cases are not European) still allow fine detail. Less satisfactory average ad-valorem transport costs are the aggregate bilateral c.i.f./f.o.b. ratios calculated from the trade statistics.²³ Such country-level averages are, however, not particularly useful for the analysis of infrastructure improvements, for which much finer level of spatial detail is needed.

3.3.2. Cost estimates from a transport model

A classical transportation planning model consists of four steps (see e.g. Ortúzar and Willumsen, 2001):

- 1) The *trip generation* step determines the frequency of incoming or outgoing trips in each zone by trip purpose, as a function of socio-economic factors.
- 2) The *trip distribution* step matches origins with destinations, often using a gravity model approach.
- 3) The *mode choice* step computes the proportion of trips between each origin and destination that uses a particular transportation mode. This model is often of the discrete choice form.
- 4) The *route assignment* step allocates trips between each origin and destination by a particular mode to a route. Often, Wardrop's (1952) principle of user equilibrium (equivalent to a Nash equilibrium) is applied here, wherein each traveller chooses the shortest (travel time) path, subject to every other driver doing the same.

The models used in the last two steps clearly require the knowledge of transport costs. The term used in transport models is *generalised cost*, that is, the sum of monetary and non-monetary costs of a trip. Monetary (or “out-of-pocket”) costs include costs of fuel, vehicle operating and depreciation costs, road tolls, and the like. These cost figures can be based on original data surveys as well as involve averaging. Non-monetary costs refer to time

²³ IMF (www.imf.org) reports these ratios for many countries and years in the Direction of Trade Statistics (DOTS) and the International Financial Statistics (IFS).

spent undertaking the trip. Obviously, the state of infrastructure is likely to have a considerable effect on the time costs. Time is converted to a monetary value using a “value of time” parameter, which is often based on a qualified guess rather than proper estimation.

A major requirement to a transport model would thus be to deliver estimates of generalised costs between relevant pairs of regions, which would be sensitive to changes in the infrastructure network. Then an introduction of a new transport link or an upgrade of an existing one would lead to a change in these costs and an SCGE model could be asked to quantify the arising economic effects. Constructing a link between the two models is however a non-trivial task (indeed, there is a general problem that economic and transport modelling are still poorly integrated (Preston, 2001)).

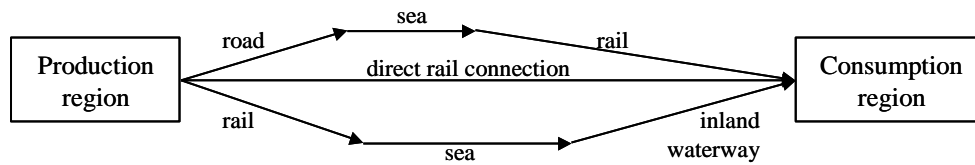
Further, for the application of the iceberg approach, we would like to know the ratio between the transportation expenditure per annum between the relevant pairs of regions and the value of the respective trade flow. If possible, the separation of this ratio into individual components (pure resource costs, payments to the public budget, other related costs) should also be done. Thus, in addition to costs per transported unit in the reference and in the policy scenario situation, the transport model would have to provide the reference physical trade flows (in terms of transported units) between any production region r and consumption region s (we will refer to this combination as a *production-consumption (P/C) pair*). The following difficulties may arise here:

1) Conflict in the treatment of regions.

One potential problem is the conceptual difference between, to put it in simple terms, economic and transport accounting. The important notion here is that of a *transshipment point*. Quite obviously, the amount of goods that are directly transported from region A (origin) to region B (destination) need not be the same as the amount of goods produced in A and bought in B for final or intermediate use. One should take into account the fact that there may in practice exist several routes (origin-destination (O/D) chains) connecting a P/C pair, and some of these may involve transportation mode change in-between. Transshipment points are then the nodes in the transport network where the mode change takes place. Figure 3.3.1 illustrates this situation.

The presence of transshipment points is a problem for the calculation of transport cost changes, if a transport model can only provide cost information for O/D pairs and not P/C pairs. In the situation depicted in Figure 3.3.1, suppose that only the direct rail connection is upgraded, and as a result, the costs per trip on this link go 10% down. It

Figure 3.3.1 Multiple transportation routes



would then be a mistake to apply this number as a reduction of the distance cost factor for trade flows between the two regions, because the true cost reduction is less due to the existence of other routes.

The problem posed by the O/D-based cost estimates can be solved by using an additional source with detailed information that allows transforming them into the P/C-based costs. Bröcker et al. (2009) show how this can be done using the ETIS database (ETIS-BASE Consortium, 2005) as such an additional source of data.

2) Inconsistencies between trade and transportation data.

Difficulties may come from both sides. One problem is that there is usually no data on interregional trade, and ad-hoc methods (often based on gravity approach) are employed to derive interregional trade flows from country-level flows and regional data on GDP and value-added. Then, one can easily imagine that this would give a result inconsistent with transport statistics. In particular, zero-valued flows will not be correctly placed. This could, however, be easily corrected if explicit use is made of the data on transportation flows (e.g. from the aforementioned ETIS database) in deriving the interregional trade flows. This information itself must of course be checked for reliability.

A more serious problem is the situation where the available transport model provides low quality (e.g. many gaps, implausibly low or high values, etc) or simply no information on the interregional transport flows. Then one is forced to look for alternative sources of data on benchmark transportation expenditures. Apart from employing another transport model (which may well be very expensive), a possible solution would be to use the distance cost mark-ups derived from an econometrically estimated distance function. Our experience from the research projects mentioned in Chapter 1 suggests that this last type of problem is very likely to arise. That is why, an alternative method to infer transportation expenditures must be considered, that involves econometric modelling of trade flows.

3.3.3. Inference of trade cost components from a gravity model

The idea behind this method is that trade costs may be derived from an economic model linking trade flows to observable variables. As many trade models lead to gravity-like structure of theoretical trade flows (Deardorff, 1998), gravity models²⁴ have been widely used to estimate various components of trade costs (see Hummels (2007) for a recent survey).

Anderson and van Wincoop (2004) list the following prerequisites for a trade model to have a gravity-like structure:

- separable preferences and technology for each region (leading to “trade separability”),
- the aggregator of traded varieties across countries is identical and of CES form (with the elasticity of substitution σ), and
- ad-valorem tax equivalents of trade costs (that we defined as $\tau_{rs} - 1$ above) do not depend on the quantity of trade.

Then, the theoretical trade flow x_{rs} (in value terms) between locations r and s takes the following form:

$$x_{rs} = A_r \tau_{rs}^{1-\sigma} B_s, \quad (3.3.1)$$

where A_r gathers all variables characterizing the exporting region, B_s does so for the importing region, and τ_{rs} can be thought of as a trade cost function, gathering all variables to which trade barriers are related (distance, adjacency, preferential trade membership, common language, etc). In the gravity regression, A_r and B_s enter as country-specific fixed effects.

For the ease of econometric estimation, usually multiplicative form of the components of τ_{rs} is assumed. Recalling the scheme in Figure 3.1.1, we can notice that this formulation allows separating the effect of distance on trade costs from other effects (border barriers), namely:

$$\tau_{rs} = f(g_{rs}) \delta_{rs}, \quad (3.3.2)$$

where $f(g_{rs})$ is a function of distance, and δ_{rs} is a term capturing all other observable trade costs. Components of δ_{rs} are accounted for by including dummy variables for com-

²⁴ See Leamer and Levinsohn (1996) for an overview of these models.

mon border, common language, common currency, membership in trade blocks, and the like, in the gravity regression.

If more reliable information from direct measures or transport model estimates is not available, $f(g_{rs})$ has to serve as a proxy for the geographical trade costs. For the econometric estimation of Eq. (3.3.1), one has to assume a particular functional form of this distance function.

Since 1970s, the extensive empirical work on the composition of transport rates (Bayliss and Edwards, 1970; Jansson and Shneerson, 1985, 1987; Tyler and Kitson, 1987; Savage, 1997) reported economies of distance and scale in transportation. That is why in most models of spatial pricing the delivered prices of goods are typically assumed to be concave with distance. The traditional explanation (see e.g. Alonso, 1964) for such a form is the presence of both fixed and variable components in transport costs. This explanation gains even more ground if a broad concept of distance-related costs is accepted, including the communications and other costs associated with trade, which are likely to exhibit network externalities (see Harris, 1995).

By far the most common assumption in the literature is the concave form $f(g_{rs}) = g_{rs}^\rho$, where $0 < \rho < 1$. This approach is criticized by Grossman (1998), who argues that a more reasonable assumption is $f(g_{rs}) - 1 = g_{rs}^\rho$, meaning that the ad-valorem rate is increasing in distance, but at a diminishing rate. Given any of the alternative assumptions, the values of parameters of interest are obtained from estimating a linearized Eq. (3.3.1) with OLS or by applying nonlinear methods. For the model in Chapter 4, we also use an assumption that the transport costs are increasing in distance, but employ a functional form more appropriate for the model at hand.

Note that gravity estimation does not help to divide distance costs into parts (pure resource costs, revenue-generating costs, other related costs). However, for the type of analysis we have in mind, it is desirable to have a possibility to separate the effects of shocks to different cost components. In the absence of reliable data on the transportation flows, however, such disaggregation becomes hard. We describe our ad-hoc approach to deal with this problem in Section 4.5.

3.4. Review of relevant studies

The spatial CGE modelling is a recent and growing field of research. We summarize several earlier models that we consider particularly relevant for our study in Table 3.4.1. This table has two parts. In the first part, we describe the way transportation service is modelled. In the second part, we focus on other relevant spatial features. In the following, we shortly review these and other related studies.

The special treatment of transportation sector in the CGE framework, namely the direct linkage of movement services to the actual products moved, can be traced back to Buckley (1992) and Wigle (1992). These were the first papers to consider the explicit specification of transportation demand in a multiregional setting and to check the implications thereof.

In Buckley's "interregional CGE model" for the USA, trade (also intraregional) requires a fixed ratio of transport services to the quantity of goods shipped. Destination prices are thus determined according to a rule similar to (3.2.1). The structure of the economy is SAM-based, multisectoral, and an Armington assumption of imperfect substitution between goods coming from different origins is applied. The transportation service itself remains an untraded good. It is generated in the region of origin. The new approach is then compared to the "traditional" specification (where transportation is handled as a direct intermediate input or an element of final demand) for the case of productivity increase in the transportation sector.

Wigle (1992) aims to compare the effects of tariffs in the presence or absence of transportation costs using a SAM-based interregional CGE model for Canada. This paper also includes the comparison of an explicit ("distance" or "spatial") and implicit ("point") formulation of the transportation demand. In the explicit formulation, costs are calculated as the product of (commodity-specific) transportation margins, representative distances and corresponding quantity flows. The total demand for transportation service is then equal to final demand (for personal travel) plus intermediate demand for goods delivery.

The advantage of the explicit method, as reported by Buckley (1992), is the prevention of over/under production of transport services through the implementation of direct link to trade flows. In addition, one is sure that the end users of products purchase a correct amount of these services for delivery of their bundle of goods. Finally, a much clearer picture of consumption and production activities emerges. Several later studies that included an explicit formulation of transportation demand into a SAM-based CGE model are Haddad & Hewings (2001) and Lofgren & Robinson (2002). The latter study also com-

compares the explicit (“spatial”) and implicit (“non-spatial”) specification of transportation and finds that the spatial model is able to capture a diverse pattern of regional impacts.

A common drawback of the aforementioned studies is that the non-trivial procedure of determining the transportation coefficients remains explained. As these models are SAM-based, one can assume that in all cases the coefficients were calibrated using the data about the transport service sector that is contained in the SAM. However, taking into account that regional input-output tables and regional margins data are normally not available and have to be constructed using intricate procedures, it is hard to say without knowing the details what thus constructed transportation coefficients actually represent.

In contrast, a branch of research that we are turning to now puts major focus on representing the transportation sector as realistic as possible. The conceptual framework implies the integration of a CGE model including a transport service sector with an engineering-type transport network model. Such a framework was first described by Roson (1993) and Friesz et al. (1993). The resulting model had to determine the quantities of goods to be produced and shipped, their mill and destination prices, and the paths by which goods are to be delivered. It was thus well suited for evaluating potential impacts of transport infrastructure investments.

The empirical applications of this methodology had to struggle with problems of lacking data, inconsistencies between transport and economic accounting, not to say about the computational difficulties. The bold task of fully integrating the two types of models and filling them with data is not yet solved. We review the approach of Roson (1996) below. Other studies not discussed here, but which adopt other alternatives to confront these problems are Elbers (1996), Friesz et al. (1998), and Kim et al. (2004).

Roson (1996) studies the interaction between the economic and the transport system by integrating a multiregional CGE model with a freight network equilibrium model. The operational model, called MITER, is designed to analyse how demand for freight transport is generated by trade relationships among regions, how transport costs vary to match demand and supply of transport infrastructure (including the possibility of congestion) and how transport costs influence economic competitiveness of regions and industries. A SAM-based CGE model and a network model are linked by expressing trade flows in quantity units. The transportation coefficients are endogenous and are updated so as to balance the demand and (fixed) supply of infrastructure on each link of the transport network.

Table 3.4.1. The classification of relevant models

Study/ Model used	Study area	Link between trade and demand for transport	Provider of transport service (for explicit method)	Technology in the transport sector	Source of data on transportation coeffi- cients
Buckley (1992)	3 US regions	Explicit vs. Implicit	Region of origin	Nested CES	Not specified
Roson (1996) / MITER	20 Italian regions	Explicit	Region of origin	Leontief	Integrated network model
Hertel et al. (1997) / GTAP	Up to 87 regions of the world	Explicit, transport merged with other mar- gins	Global sector	Nested CES	Calibrated to match the estimated cif/fob ratios
Bröcker (1998) / CGEurope	800 European regions	Explicit	Region of destination	Modified iceberg	Estimated distance function
Venables and Gasiorok (1996)	22 regions (Spain and Portugal)	Explicit	Region of origin	Iceberg	Linear function of dis- tance
Caspersen et al. (2000) / BROBISSE	3 Danish regions	Explicit	Nation-wide sector	Modified iceberg	Data on value-to- weight ratios and trans- port costs
Oosterhaven et al. (2001) / RAEM 1	548 Dutch municipali- ties	Explicit	Region of destination	Iceberg	Estimated distance function
Ivanova et al. (2002) / PINGO	19 Norwegian counties	Explicit	Nation-wide sector	Nested CES	Input from a transport model
Kim et al. (2004)	4 Korean regions	Implicit, accessibility index enters the pro- duction function		Accessibility index is updated by investment	Exogenous path of in- vestment expenditure
Thissen (2004, 2005) / RAEM 2.0	40 Dutch regions	Explicit	Nation-wide sector	Nested CES	Input from a transport model

Table 3.4.1. The classification of relevant models (continued)

Study/ Model used	Agglomeration effects	Factor mobility between regions	Unemployment	Applicable to analyse effects of infrastructure projects	Solution method / Software
Buckley (1992)	No	No	No	No	Iterative adjustment/ not specified
Roson (1996) / MITER	No	No	No	Yes	Johansen method /GAUSS
Hertel et al. (1997) / GTAP	No	Capital, Labour	No	No	Gragg's method / GEMPACK
Bröcker (1998) / CGEurope	Yes, Dixit-Stiglitz	No	No	Yes	Iterative / MATLAB
Venables and Gasiorok (1996)	Yes, Dixit-Stiglitz	Capital, Labour	No	Yes	Not specified
Caspersen et al. (2000) / BROBISSE	No	Capital	Yes, employing labour-leisure choice	Yes	Path solver / GAMS
Oosterhaven et al. (2001) / RAEM 1	Yes, Dixit-Stiglitz	Labour	No	Yes	Path solver / GAMS
Ivanova et al. (2002) / PINGO	No	No	No	Yes	Path solver / GAMS
Kim et al. (2004)	No	Labour	No	No	Path solver / GAMS
Thissen (2004, 2005) / RAEM 2.0	Yes, Dixit-Stiglitz	Labour	Yes, employing search theory	Yes	Path solver / GAMS

The network model includes route choice (based on Wadropian user equilibrium), modal split (using fixed shares), and congestion mark-ups that increase with growing transport flow. The equilibrium solution is achieved by iterating between the submodels until convergence is achieved. The simulation results show that constraints in the supply of transport infrastructures may have a significant impact on national and regional economic performance, as well as on social welfare.

The last approach may be considered a compromise between the desire of having a realistic representation of transportation as a resource-using activity linked to actual trade flows and the technical difficulty of implementing a fully integrated CGE-transport network model. The key to this approach is the use of the simplifying assumption of iceberg transport costs, and the division of labour between the transport and the economic model. We will stick to this method in the modelling exercises of the next two chapters.

Venables and Gasiorek (1996) use a spatial CGE model for Spain and Portugal to evaluate the impact of several road projects financed by the European Commission. This is the first application of an SCGE model employing the elements of the new spatial economics literature: the Dixit-Stiglitz framework and iceberg-type transport costs.²⁵ Facing the lack of interregional trade data, the authors develop a calibration procedure, where the relationship between the distance and the transport costs is adjusted until the model is able to replicate data on aggregate trade volumes well enough. In general, the data requirements of this model are quite modest, while the attained insights are important.

The results are presented in forms of multipliers, which show the real income effect of a project relative to the direct impact (value of direct transport cost savings). The size of thus computed indirect effects is not negligible. Further analysis shows that transport infrastructure projects may have very localized effects, but in many cases, they may produce significant spillover effects throughout the neighbouring and even quite distant regions. The latter is for example the case for the completion of the M-40 ring road around Madrid: because it acts as a link for several major Spanish motorways, it has strong spillover effects for large parts of the Iberian Peninsula. Further, Venables and Gasiorek (1999) look in detail at the implications of imperfect markets assumption and conclude that the standard tools of cost-benefit analysis that are used for project appraisal may not be accurate. Namely, if production is undertaken by imperfectly competitive firms, then the real income gains from policy

²⁵ The underlying theoretical framework was first described by Bröcker (1995).

measures in transport may exceed those that would be calculated by standard CBA techniques by up to 30%.

The studies discussed so far (with an exception of Wigle (1992)) are all based on single-country models, and the international trade impediments are not really an issue there. In a multi-country setup, the composition of the costs of spatial interaction must however be taken account of. We discussed the appropriate methodology in the last section. The use of gravity regressions to estimate the total trade margins in a multi-country CGE model was pioneered by the developers of the GTAP model (Hertel, 1997). The scale of the GTAP model is however too big to allow for the analysis of transport infrastructure improvements, and, in addition, all margins are simply merged together.

Bröcker (1998b, 1998c) introduces an SCGE model for 800 regions covering the entire European space and the rest of the world. The model includes consistent treatment of trade cost components entering via a modified iceberg formulation, and explicit gravity-based estimation of the distance function. As a result, the modeller is able to study the regional effects of changes in international trade impediments as well as in the interregional transport costs. In addition, a calibration procedure for an interregional trade matrix is suggested, based on a constrained gravity approach. The fine spatial detail of the model (facilitated by modest data requirements) allows it to be linked to a transport network model and be used to analyse the impacts arising from the completion of the major European transport corridors. The high level of sectoral aggregation (only two sectors per region) and the lack of dynamics are indicated as the most important shortcomings of the model.

Building upon the work of Venables and Gasiorek (1996, 1999) and Bröcker (1995, 1998c), country-level SCGE models have been developed for Denmark (Caspersen et al., 2000), Norway (Ivanova et al., 2002), and Sweden (Hussain, 1996; Hussain and Westin, 1997). One strand of modelling effort has to be particularly noted, namely the development of the RAEM model for the Netherlands (Oosterhaven et al., 2001; Thissen, 2004, 2005; Ivanova, 2007). This model is subject to continuous improvement process and is the most detailed of all available models. The latest innovations concern the introduction of recursive dynamics and detailed treatment of passenger transport, interregional migration, and public sector. Outside Europe, SCGE models for transport policy analysis have been recently developed in Japan (Miyagi and Honbu, 1996; Sato and Hino, 2005), South Korea

(Kim et al. 2004), and China (Ando and Meng, 2006). Most of these models are implemented in GAMS.

In the next two chapters, we present the extensions of the *CGEurope* model introduced in Bröcker (1998b, 1999c). The first extension concerns the study of the adjustment processes in the factor markets. Few of the reviewed papers pay explicit attention to capital and labour markets. Venables & Gasiorok (1999) and Caspersen et al. (2000) allow for capital mobility in their models but they do not comment on the implications of this assumption. Kim et al. (2004), as well as the developers of the RAEM model, introduce interregional labour mobility, which enables them to study the effects of certain policy measures on the commuting patterns. Thissen (2004) in addition allowed for unemployment and search for jobs à la Pissarides (2000), however the calibration of the matching functions remained unexplained. Meanwhile, the incorporation of mobile investment and labour supply response was always mentioned as desirable by the reviewers evaluating the relevance of the SCGE models for policy analysis (Williams et al., 2002; Gunn, 2004; DfT, 2006). In the following, we intend to introduce these elements in a multiregional, multi-country setup.

3.5. Summary

The purpose of this chapter was to link the model to be presented in the following to the existing literature, and to provide some background information about various model components and the important assumptions employed. As should be clear from the literature review, the application of the SCGE modelling for transport policy analysis is still a young field and a lot of progress can still be made. The biggest challenge is to create a framework for the consistent integration of economic and engineering-type transport models. Beyond that, little is known still about the implications of particular assumptions about the factor markets for the SCGE model-based evaluation of transport projects. We are going to study this issue in the next chapter. After that, we will turn to discussing the dynamic SCGE modelling in Chapter 5.

Chapter 4. Investigating the role of assumptions about the factor markets in the static SCGE framework

This chapter contains a comprehensive discussion of the modelling framework and policy simulation results contained in Korzhenevych and Bröcker (2009). There, we suggest an extension of the static *CGEurope* model introduced in Bröcker (1998b, 1998c) concerning the treatment of the factor markets.

After presenting the overall model structure and the new elements in the first three sections, we discuss the calibration procedure in sections 4 and 5, and do sensitivity tests with respect to internal and external parameters in section 6. Then, the model is used to analyse a real example of infrastructure improvement, namely the implementation of the project no. 20 from the Van Miert priority list (High-Level Group, 2003), which contains the construction of the fixed link across the Fehmarn Belt.

4.1. Description of the core model elements

Bröcker (1998b) introduces a spatial general equilibrium model for a closed system of regions covering the whole world. All of regions are treated separately and are linked through endogenous trade. The number of regions is only limited by the data availability. The study area is Europe, with the focus on the EU. The inference method is comparative statics, which means that in each model run two equilibria (reference and policy scenario) are compared.

In each region r belonging to county k there is assumed to dwell a set of homogenous households, owning a bundle of primary production factors (a composite of land, labour, and capital), which are used by regional firms for production of goods. Two types of goods are distinguished: local and tradable. Local goods can only be sold within the region of production, while tradables are sold everywhere in the world, including the own region.

Producers of local goods combine primary factor services, local goods, and tradables, using a Cobb-Douglas technology with region-specific cost share parameters. The output of locals is assumed completely homogeneous, and is produced under constant returns to scale. The firms in the local sector take prices for inputs as well as for their output as given, and they do not make any profits.

Instead of directly selling this output of local goods to households or other producers, firms

can use it as the only input needed to produce tradables. The respective technology is increasing returns to scale. Tradable goods are modelled as being close but imperfect substitutes, following the approach of Chamberlinian monopolistic competition. Different goods stem from producers in different regions. Therefore, relative prices of tradables do play a role. Changes of exogenous variables (e.g. transportation costs) make these relative prices change and induce substitution effects. For producers of tradables, only input prices are given, while the output price can be set under the framework of monopolistic mark-up pricing. Due to free market entry, however, profits are driven to zero, as they are in the market for locals.

Households are assumed to act as utility maximizers, taking all prices as given. Utility emerges from consumption (in fixed income shares) of local goods and a CES-composite of tradables, consisting of all, regionally produced and imported variants. Utility is modelled following the Dixit-Stiglitz (1977) approach, such that households appreciate a higher number of variants of tradables. The same income spent on more diverse variants means higher utility for the households. In other words, they share the “love for variety”. For the sake of simplicity, all components of final demand, that is private and public consumption and investment, are subsumed under household demand. There is no explicit consideration of a separate public sector.

Apart from factor income, disposable income contains a positive or negative net transfer payment from the rest of the world, depending on whether the national current account with respect to all other countries has a surplus or a deficit in the benchmark situation. These transfers are held constant (in real terms) in our simulations. They are negligible with regard to quantitative results, but are needed for keeping budget constraints closed. One more source of income is the exogenously specified regional share of total revenue from charges in transport.

In addition to distinction of goods, factors, firms, and households by location, the costs for goods movement are explicitly incorporated into the model. They depend on geography as well as on the national segmentation of markets. It is assumed that the total trade costs for goods to be delivered from region r to region s amount to a share $\tau_{rs} - 1$ in the traded value, $\tau_{rs} > 1$ denoting the trade cost mark-up factor. The way trade costs are modelled resembles the “iceberg” approach (Samuelson, 1954).

Two kinds of trade costs are introduced: costs related to geographic distance (transport costs and other related costs), and costs for overcoming impediments to international trade.

The first are modelled under the assumption that geographical costs are increasing with distance but at a diminishing rate. The change of these costs constitutes the policy scenario.²⁶ The values for the second type of costs are calibrated within the model and include tariffs, but also (and more importantly in the EU case) all costs stemming from non-tariff barriers, like costs due to language and currency differences, costs for bureaucratic impediments, time costs spent at border controls, and so forth.

From a theoretical point of view, the model relies strongly on Shoven-Whalley (1984, 1992) approach to general equilibrium modelling, even though it does not assume perfect competition on all markets. In doing so, the suggestion of Venables and Gasiorek (1999) is taken account of, who show that the estimated welfare impact of trade cost reductions can change dramatically with a deviation from the perfect competition assumption.

4.2. Assumptions about the factor markets

Two facts about the European economies that are not reflected in the original model by Bröcker (1998b) but are of constant concern to the policymakers are unemployment and capital mobility. In this section, we suggest a way to incorporate these facts into the spatial CGE model. Later in this chapter, we will analyse the implications of these assumptions for the analysis of transport infrastructure policy.

In the basic model²⁷, labour effort is a part of regional composite factor service and is assumed to be fully-employed, labour market being cleared by a flexible wage. Of course, this is an extremely unrealistic representation of European regions. A more realistic approach is to introduce market imperfection in the form of unemployment. In order to allow for a gap between supply and demand on the labour market, we need to relax a corresponding assumption of the neoclassical Walrasian model. We have to assume that market forces are constrained by a certain degree of **wage rigidity**.

Many alternative models of wage rigidity can be considered at this point, ranging from simple minimum wage specification (Stigler, 1946) to efficient bargaining (McDonald and Solow, 1981) or search and matching models (Pissarides, 1984). Maechler and Roland-Holst (1997) provide a menu of labour market specifications, with numerical examples of how each of them can be implemented in a prototype CGE model. The difficulty of apply-

²⁶ In case of infrastructure improvement, the analysis thus only concerns the phenomena arising after the project completion, and ignores the construction phase.

²⁷ In this chapter, we will refer to the model described in Bröcker (1998b) as “the basic model”

ing these recipes in our multiregional setup is that the implementation of any theoretical model would require knowledge of rather subtle parameters, such as probability of being fired, index of bargaining power, base effort level, etc, for which little data can be found and thus no justified method to differentiate these parameters across regions can be designed. This difficulty motivated us to search for a simpler approach that would be very parsimonious in data requirement, but still allow the incorporation of employment response in the SCGE framework.

Based on these considerations, we find the approach of Blanchflower and Oswald (1994) particularly useful. In their study, the empirical responsiveness of workers' remuneration to the state of the labour market is captured by the coefficient on (log) unemployment rate in an equation for (log) real earnings. The estimate of this coefficient is strictly negative, suggesting a downward sloping relation between unemployment and wages that the authors called "*the wage curve*". Simply put, according to the wage curve, a worker earns a lower wage the higher the (contemporaneous) unemployment rate is in his labour market, all else equal.

One way to provide an intellectual rationale for the wage curve is by appealing to efficiency wage theory. The well-known characteristic of efficiency wage analysis is that firms set pay in an environment where the wage influences productivity. Shapiro and Stiglitz (1984) is an archetypal case. In equilibrium, firms try to maximize profits and workers choose how hard to work. If the costs of shirking at work are low, employees put in little effort. The outside rate of unemployment plays a role, because it determines the ease with which a fired worker can get another job. In a highly depressed labour market, the employees are frightened of losing their jobs, and so put in high effort even if pay is comparatively low. Put differently, a marginal rise in unemployment leads to a corresponding marginal fall in the level of wages. The reason is that firms can reduce pay slightly while maintaining a motivated workforce. Unemployment is a discipline device: when it is high, the generosity of workers remuneration can be low. Hence, there is an efficiency wage interpretation of a negative dependence between wages and unemployment.

Blanchflower and Oswald (1994) suggested a methodology to estimate the degree of this dependence using panel data regressions. Following their original contribution, dozens of papers appeared that documented the existence of this empirical relationship for many countries.²⁸ These were supported by a handful of theoretical papers that derived the foun-

²⁸ The recent reviews of this literature are Nijkamp and Poot (2005) and Blanchflower and Oswald (2005).

dations for a wage curve from the search theory (Sato, 2000) or efficiency wage theory (Campbell and Orszag, 1998). Although the issue of the theoretical background remains a disputed one, the empirical strength of the approach makes it a very useful shortcut that can be used in an applied CGE model.

Following Blanchflower and Oswald (1994), we introduce a regional wage-fixing curve in our model:

$$\frac{w_r}{G_r} = \mathcal{G}_r u_r^{\zeta_r}, \quad (4.2.1)$$

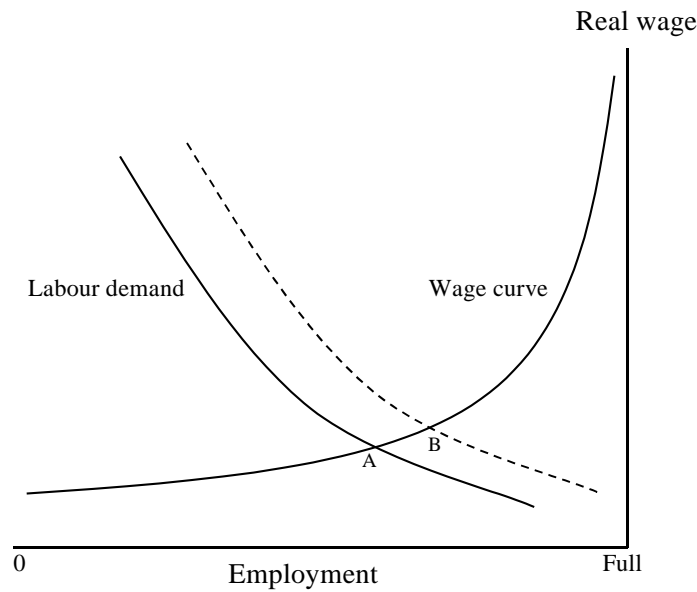
where in the left-hand side expression regional wage w_r is corrected for regional price index G_r to give the real wage; \mathcal{G}_r is the shift coefficient, corresponding to the regional dummy in the wage curve regression; u_r is the regional unemployment rate, and ζ_r is the unemployment elasticity of pay.

The country-level values of ζ_r are taken from the rich wage curve literature. Table 4.2.1 summarizes the results of our literature survey. The values range from -0.52 for Latvia to -0.02 for Norway. However, many estimates lie close to -0.1 , a remarkable similarity discovered by Blanchflower and Oswald. The wage curve tends to be flatter in Scandinavian countries known for highly regulated contract systems, while allowing for more wage adjustment in the former socialistic countries.

To see how the infrastructure policy imposes response in the regional labour market, con-

Table 4.2.1. Available estimates of the unemployment elasticity of pay for the study area

Country	Source	Value	Country	Source	Value
Austria	Nijkamp and Poot (2005)	-0.068	Latvia	Blanchflower (2001)	-0.520
Belgium	Janssens and Konings (1998)	-0.054	Netherlands	Nijkamp and Poot (2005)	-0.185
Bulgaria	Blanchflower (2001)	-0.206	Norway	Nymoen and Rødseth (2003)	-0.020
Czech Rep.	Galuščáck and München (2005)	-0.112	Poland	Blanchflower (2001)	-0.127
Denmark	Nymoen and Rødseth (2003)	-0.032	Portugal	Montuenga et al. (2003)	-0.055
Estonia	Blanchflower (2001)	-0.291	Romania	Kallai and Traistaru (2001)	-0.140
Finland	Nymoen and Rødseth (2003)	-0.027	Russia	Blanchflower (2001)	-0.175
France	Montuenga et al. (2003)	-0.213	Slovakia	Blanchflower (2001)	-0.186
Germany	Blien (2003)	-0.092	Slovenia	Simončič and Pfajfar (2004)	-0.100
Great Britain	Bell et al. (2002)	-0.120	Spain	Montuenga et al. (2003)	-0.126
Greece	Guichard and Laffargue (2000)	-0.330	Sweden	Nymoen and Rødseth (2003)	-0.046
Hungary	Kertesi and Kollo (1997)	-0.110	Switzerland	Nijkamp and Poot (2005)	-0.164
Italy	Montuenga et al. (2003)	-0.070	Turkey	Ilkcaracan and Selim (2003)	-0.088

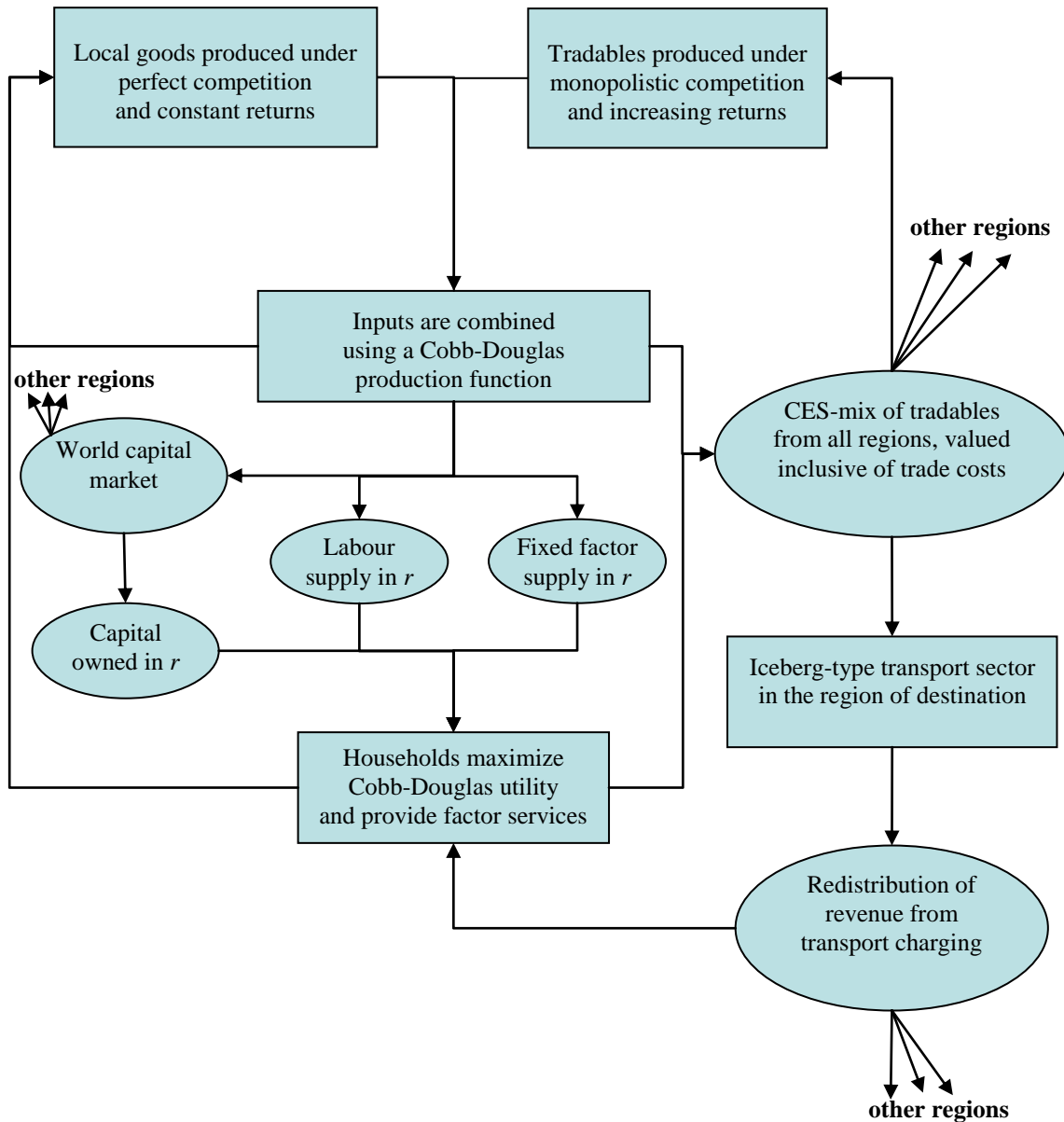
Figure 4.2.1. Labour market response

sider Figure 4.2.1. In this example, improved accessibility increases demand for region's output, causing regional factor demands to increase. Labour demand schedule shifts outwards, and the equilibrium moves from point *A* to point *B*. In contrast to fixed employment assumption, here only a part of adjustment is done by wages, the degree of rigidity set by the exponent appearing in the wage curve equation. The rest of adjustment is accomplished by an increase in employment level.

Few examples of the application of the wage curve equation in the CGE modelling are Roson (1998) in a multisectoral model of Italy, and Annabi (2003) in the experimental models with different labour market regimes. To our knowledge, there was no previous attempt to collect the estimates from the wage curve literature and use them in a multi-country setup.

Another stylised fact about the European economies, not reflected by the basic model, is a certain degree of **capital mobility**. The theoretical models allowing for commodity movements (trade) as well as some degree of international capital mobility date back to a seminal contribution of Mundell (1957). Today there exist several widely used methods to account for international capital flows in a static CGE model. Shoven and Whalley (1992) use an exogenous capital ownership scheme, through which regions get income from the factors located abroad. Hertel (1997) introduces "investment good" which enters regional utility and production functions, and is collected and redistributed by the "global bank". This approach is taken by the researchers using the GTAP model described in Hertel's book. Decaluwe et al. (2004) follow essentially Ricardian approach by assuming that

Figure 4.2.2. Monetary flows in region r



movement of physical capital is governed by differences in international rates of return, and that total capital stock is fixed. We will take a similar approach.

A second change to the framework of the basic model is thus to assume that a certain fraction of regional capital stock is (freely) mobile internationally. It can move (following higher return) to other regions. We assume that there is a single rental τ clearing the market for this homogeneous factor. The total stock of mobile capital is assumed to be fixed.

Because we allow the amount of mobile capital employed in the region, K_r^e , to differ from the capital stock owned by the inhabitants of the same region, K_r , we need to take account of international income flows. Thus, when calculating household income, besides the fixed

transfer and the regional share of revenue, the amount of $(K_r - K_r^e) \cdot \iota$ must be added to the regional GDP. Capital owners themselves, however, are assumed not to move between regions. For the lack of other information, K_r and K_r^e are assumed to coincide in the benchmark equilibrium.

The schematic representation of the extended model is in Figure 4.2.2. In the following section, we are formalizing the model, including the two innovations discussed above.

4.3. Formal setup of the SCGE model

4.3.1. Households

Preferences of the aggregate household in region r are represented by a two-level utility function. The upper nest is of Cobb-Douglas form and determines the choice between the local goods and the composite of all tradable goods, with their constant value shares given by ε_r and $(1 - \varepsilon_r)$, and their prices being p_r and q_r , respectively. The natural regional price index corresponding to the preference structure of households is the unit expenditure function

$$G_r = p_r^{\varepsilon_r} q_r^{1-\varepsilon_r}. \quad (4.3.1)$$

The lower-level symmetric CES function aggregates the \bar{l} varieties of tradables from all locations having prices $c_{r,1}, \dots, c_{r,\bar{l}}$ in region r , to a composite tradable:

$$q_r = \phi \left(\sum_{i=1}^{\bar{l}} c_{r,i}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}, \quad (4.3.2)$$

with σ denoting the elasticity of substitution between different brands of tradables, and ϕ being a scaling parameter fixing the units of measurement for the composite tradable.

Households get their income N_r from three sources. First, they receive all factor income from domestically owned factors, which includes the income from capital employed abroad. Note that the sum of payments to the primary factors employed in the region comprises the regional GDP, Y_r . The income of domestically owned factors will then be given by $Y_r + \iota(K_r - K_r^e)$. Second source of income is the regional share of total revenue from charges in transport, R_r . This payment is determined using an exogenous revenue redistribution rule, which is a policy variable in our model. At last, each region gets a fixed trans-

fer X_r . In this way, we represent the fact that the trade account may be unbalanced in the benchmark. We assume that the surplus countries pay a transfer equal to their benchmark trade surplus to deficit countries, such that each deficit country receives an amount sufficient to remove the trade imbalance. Transfers are distributed among regions within a country in proportion to their GDPs. Thus, the composition of households' income is as follows:

$$N_r = Y_r + t(K_r - K_r^e) + R_r + X_r.$$

Note that the sum of X_r across all regions is always zero by construction. These transfers are kept constant in real terms. Fixing transfers in real terms is the same as fixing them in nominal terms and scaling prices such that the overall price index remains unchanged. As an overall price index (which thus plays the role of a *numéraire*), we use the weighted average of G_r over all regions, the weights being the base-year GDPs.

4.3.2. Firms

In the local sector, the representative firm of region r operates with constant returns-to-scale technology, combining local goods, tradable goods, and primary factors. The upper nest of a two-level production function is Cobb-Douglas with shares of primary factors, local goods, and tradables being α_r , β_r , and γ_r . These shares add up to 1. The output price p_r , which equals the minimal unit cost, is then

$$p_r = \frac{1}{v_r} \omega_r^{\alpha_r} p_r^{\beta_r} q_r^{\gamma_r},$$

parameter v_r being the level of regional productivity, and ω_r denoting the composite factor

price. Introducing new parameters, $\eta_r = \frac{\alpha_r}{\alpha_r + \gamma_r}$ and $\tilde{v}_r = v_r^{-\frac{1}{\alpha_r + \gamma_r}}$, and solving for p_r yields

$$p_r = \tilde{v}_r \omega_r^{\eta_r} q_r^{1-\eta_r}. \quad (4.3.3)$$

The lower-level symmetric CES nest for tradables is assumed to be the same as the one for the households, with the elasticity of substitution σ .

The primary factors lower-level nest is Cobb-Douglas, with shares of immobile factors (excluding labour), mobile capital, and labour denoted by κ_r , χ_r , and θ_r , respectively. The composite factor price is then:

$$\omega_r = h_r^{\kappa_r} t^{\chi_r} w_r^{\theta_r}, \quad (4.3.4)$$

where h_r , l , and w_r are the corresponding factor prices, and $\kappa_r + \chi_r + \theta_r = 1$.

The value of total output of local goods, denoted by P_r , can be easily related to the regional GDP value (sum of payments to primary factors), using the Cobb-Douglas share of the primary inputs: $Y_r = \alpha_r P_r$.

In the tradables sector, the different brands of output are produced by firms acting under monopolistic competition with free entry. The production of a given variety of a tradable good requires a certain amount of fixed cost as well as variable cost, all composed of the local goods. The optimization procedure described in Appendix A, leads to the following expression for the output (mill) price of a tradable variety:

$$\tilde{p}_r = \mu p_r, \text{ where} \quad (4.3.5)$$

the constant $\mu > 1$ is a price mark-up, being a function of the elasticity of substitution σ and the parameters of the cost function. Further, it is shown in Appendix A, that the output per firm, denoted by x , is a constant, not depending on the equilibrium solution of the model. Let l_r denote the number of different brands of tradable goods produced in region r . Then the total output value of tradables in r (valued at mill prices), S_r , is

$$S_r = l_r \cdot x \cdot \tilde{p}_r. \quad (4.3.6)$$

The value of tradables supply is easily related to regional income. Using the zero-profit constraint of the tradables sector, we can express S_r as a difference between the total output value of local goods, and the value of local goods use in consumption (share ε_r of regional income N_r) and production of local goods themselves. Thus, we obtain

$$S_r = P_r - \beta_r P_r - \varepsilon_r N_r = \frac{1}{\eta_r} Y_r - \varepsilon_r N_r. \quad (4.3.7)$$

In a similar way, we can express the value of demand for tradables from the side of households and production firms, D_r (not including the demand of the transport service):

$$D_r = \gamma_r P_r + (1 - \varepsilon_r) N_r = \left(\frac{1}{\eta_r} - 1 \right) Y_r + (1 - \varepsilon_r) N_r = S_r + (N_r - Y_r). \quad (4.3.8)$$

4.3.3. Factor markets

The immobile factor is assumed to be fully employed and its market cleared by a flexible rental h_r . As the corresponding supply amount H_r is fixed, the Cobb-Douglas technology

implies the following equilibrium condition:

$$H_r = \frac{\kappa_r Y_r}{h_r}. \quad (4.3.9)$$

The homogeneous mobile factor market is cleared by the single rental ι , which is equalized internationally. The equilibrium condition follows from the assumption of the fixed total factor stock:

$$\sum_r K_r^e = \sum_r K_r. \quad (4.3.10)$$

The amount of capital employed in individual regions is also determined through the Cobb-Douglas cost function:

$$K_r^e = \frac{\chi_r Y_r}{\iota}. \quad (4.3.11)$$

Equilibrium in the labour market is defined by the intersection of the wage curve and the labour demand curve. Inserting the numbers of employment E_r and fixed labour force L_r into the wage curve equation of section 4.2, we get:

$$\frac{w_r}{G_r} = g_r \cdot \left(1 - \frac{E_r}{L_r}\right)^{\zeta_r}. \quad (4.3.12)$$

On the other hand, given the Cobb-Douglas functional form, the wage rate is

$$w_r = \frac{\theta_r Y_r}{E_r}. \quad (4.3.13)$$

These two equations determine the equilibrium employment level and the wage rate.

By our definition, the expressions for regional GDP Y_r and regional income N_r thus are:

$$Y_r = h_r H_r + \iota K_r^e + w_r E_r \quad (4.3.14)$$

$$N_r = h_r H_r + w_r E_r + \iota K_r + R_r + X_r = Y_r - \iota(K_r^e - K_r) + R_r + X_r. \quad (4.3.15)$$

4.3.4. Trade costs and the market for tradables

We assume trade costs to have the structure as described in Figure 3.1.1. We take the ‘‘iceberg’’ approach and model the total trade costs arising during the transfer of goods from s to r by applying a mark-up factor $\tau_{sr} > 1$ to the mill price of the tradables produced in s , \tilde{p}_s . This mark-up is constructed as a product of two components: distance (or geographical) cost factor $f_{sr} > 1$ and international impediments factor $\delta_{lk} > 1$ (letting region r belong to country k and region s to country l). We will assume that the change of distance costs

will come from three sources: the resource costs change, the revenue-generating costs (infrastructure charges and taxes) change, and the change of costs of business passenger travel (representing other distance-related costs). We thus disaggregate f_{sr} as follows: $f_{sr} = 1 + z_{sr} + r_{sr} + j_{sr}$, where $z_{sr} > 0$, $r_{sr} > 0$, and $j_{sr} > 0$ are the ad-valorem rates of revenue-generating costs, resource costs, and business passenger costs, respectively.

We can now turn to the valuation of the trade flows. If subscript i refers to a variety stemming from region s and used in region r , the price $c_{r,i}$ in region r , including all relevant costs (thus we will refer to it as *inclusive price*), is

$$c_{r,i} = \tilde{p}_s \tau_{sr} = \tilde{p}_s \delta_{lk} f_{sr} = \tilde{p}_s \delta_{lk} \cdot (1 + j_{sr} + r_{sr} + z_{sr}). \quad (4.3.16)$$

Note that for all goods i stemming from some region s the prices $c_{r,i}$ are the same and are given by Eq. (4.3.16). Also, note that by this definition the revenue-generating charges amount to $\tilde{p}_s \delta_{lk} z_{sr}$ per unit of transported good.

As there are l_s different brands of tradables produced in s , after inserting the expression for $c_{r,i}$, Eq. (4.3.2) becomes

$$q_r = \phi \cdot \left(\sum_s l_s (\tilde{p}_s \tau_{sr})^{1-\sigma} \right)^{\frac{1}{1-\sigma}}.$$

Now take Eq. (4.3.6) for region s , solve for l_s , insert into the last equation, and gather all constants in a new parameter $\tilde{\phi}$. This yields

$$q_r = \tilde{\phi} \cdot \left(\sum_s S_s p_s^{-\sigma} \tau_{sr}^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \quad (4.3.17)$$

We can now derive the expressions for the trade flows and the equilibrium conditions for the tradables market.

Let T_r denote the total demand in r for tradables in real terms (including the demand for doing the transport service). Let $d_{r,i}$ be the demand for a specific good i (produced in some region s) per unit of T_r . According to Shephard's lemma, $d_{r,i}$ is the derivative of the minimal unit cost of tradable composite q_r with respect to price of good i . Hence, by Eq. (4.3.1),

$$d_{r,i} = \phi^{1-\sigma} \left(\frac{q_r}{c_{r,i}} \right)^{\sigma}.$$

The total value of trade flow t_{sr} from s to r (valued at mill prices) is then

$$t_{sr} = \tilde{p}_s l_s d_{r,i} T_r = S_s (p_s \tau_{sr})^{-\sigma} m_r,$$

where we again made use of Eq. (4.3.6) and collected all variables with index r or without an index in an auxiliary variable m_r .

To formulate the equilibrium condition, we have to take account of the transport expenditure. Following Bröcker (1998b), we assume that trade costs for goods arriving in r (exclusive of charges) are paid to a zero-profit “transport service”, doing the job by consuming composite tradables, composed in the same way as the composite tradables used by households and firms. Then, the total value of all flows to region r , valued at mill prices plus per unit charges, equals D_r , the value of demand of firms and households for tradables in r , valued at inclusive prices. The value of charges can be calculated as the number of transported units $\frac{t_{sr}}{\tilde{p}_s}$ times the per unit charge $\tilde{p}_s \cdot z_{sr} \cdot \delta_{lk}$. Introducing $\tilde{z}_{sr} = z_{sr} \cdot \delta_{lk}$, the equality

$\sum_s t_{sr} (1 + \tilde{z}_{sr}) = D_r$ must thus hold. Then, the expression for the trade flow becomes

$$t_{sr} = \frac{S_s (p_s \tau_{sr})^{-\sigma}}{\sum_j S_j (p_j \tau_{jr})^{-\sigma} (1 + \tilde{z}_{jr})} \cdot D_r. \quad (4.3.18)$$

The amount of revenue collected from charges on transport is given by

$$F_{sr} = t_{sr} \tilde{z}_{sr}. \quad (4.3.19)$$

The amount of revenue accruing to every region, R_r , is determined by applying an exogenous redistribution rule, denoted by Ψ , to the revenue matrix F that has F_{sr} as its elements:

$$R_r = \Psi_r(F). \quad (4.3.20)$$

Our default rule assigns half of revenue from transport charges to the country hosting the producing region and half to the country hosting the consuming region. The total revenue collected by each country is then distributed among the regions in this country proportionally to their GDPs.

Finally, the equilibrium condition, written in value terms, requires equality of supply of tradables and demand for tradables stemming from a region r , both valued at mill prices:

$$S_r = \sum_s t_{rs}. \quad (4.3.21)$$

Table 4.3.2. Endogenous variables and equations of the model

Equation	3	4	7	8	9	10	11	12	13	15	17	18	20	21
Variable	ω_r	h_r	S_r	D_r	Y_r	t	K_r^e	w_r	E_r	N_r	q_r	t_{sr}	R_r	p_r
Type	P	P	V	V	V	P	Q	P	Q	V	P	V	V	P

This completes the model formulation. All equations and endogenous variables are for convenience summarized in Table 4.3.2. We suppressed the chapter and section number, as all equations come from Section 4.3. For each of the endogenous variables we indicate its type, namely, whether it is a price (P), a quantity (Q), or a value (V).

Supplementary variables G_r and F_r , that are themselves functions of the listed endogenous variables, are given by Eqs. (4.3.1) and (4.3.19), respectively. Exogenous variables and parameters are $\varepsilon_r, \eta_r, \tilde{v}_r, \kappa_r, \chi_r, \theta_r, K_r, L_r, H_r, X_r, \vartheta_r, \zeta_r, \sigma, \tilde{\phi}, \tau_{sr}, \tilde{z}_{sr}, \Psi$.

Note that we did not use the complementarity syntax in the model formulation, as we do not expect any of the activities to shrink to zero because of the simulated policy shocks. The solution method employs iterative adjustment. The model calibration is discussed in Sections 4.4 and 4.5.

4.3.5. Welfare measurement

Utility changes of the households due to simulated changes in the transport costs come from the production side and the consumption side. On the production side, a better access of firms to input and output markets for tradables increases the factor return, thus bringing a higher income to the household. On the consumption side, a better access to the supply of tradables reduces prices and increases the available product diversity. The utility need not increase everywhere, however; a region making only little use of a new link but trading intensively with those regions making much use of it could suffer from the fact that demand for its output will shift away to other, better accessible places.

A standard way to quantify utility gains and losses is by employing Hicksian measures of relative welfare change (relative equivalent variation (*REV*) or relative compensating variation (*RCV*)). Having introduced an interregionally (and internationally) mobile factor, however, we need to be careful in defining a proper regional welfare measure. The fundamental problem is how to treat the income of domestically owned factors employed elsewhere. From the point of view of the household owning some factors abroad, it is still a part of his personal income. However, a policymaker in the respective region may well

regard this factor outflow as a pure loss if the capitalist moves away together with his ownership. The difference between these two welfare evaluations will of course depend on the amount of factors actually moving between regions. We choose to assume that income from factors employed elsewhere is repatriated to the region of ownership, and that capital owners do not move between regions.

As the welfare effects of transport cost changes are expected to be small, we can use the change of log real regional income between situations 1 (policy scenario) and 0 (reference) to approximate the standard Hicksian measures of relative welfare change:²⁹

$$REV_r \approx RCV_r \approx \log(N_r^1 / N_r^0) - \log(G_r^1 / G_r^0), \quad (4.3.22)$$

where nominal income is denoted by N_r , and G_r is the same price index as in the wage curve equation. This measurement of aggregate welfare is valid, as we assume all households to have identical homothetic preferences.

We assume that no additional welfare gains or losses arise due to the change in unemployment rate. Most importantly, we assume that there is no considerable welfare loss associated with moving from unemployment to employment (e.g. potential leisure loss). In doing so, we follow the arguments widely accepted among the experts studying the problems that people experience during unemployment. A consent among psychologists (see e.g. Waters and Moore, 2001; Macdonald and Siemon, 2000) is that the majority of unemployed people suffer from economic deprivation, lack of meaningful leisure activity, “loss of identity”, and deterioration of psychological health in general. From this point of view, it would be wrong to assume that the unemployed person would enjoy having more free time (for the “demoralization” argument see also Layard et al. (2005, Ch. 5)).

As mentioned in Chapter 1, the outcomes of policy simulations performed using the SCGE approach are often summarized by comparing them with the outcomes of the conventional cost-benefit analysis. For this purpose, the monetary measure of the total economic impact (e.g. the equivalent variation) is compared with the measure of the direct effect (benefits for transport users). The latter can be calculated using the concept of the transportation consumers’ surplus TCS (Jara-Diaz, 1986). In the empirical applications, however, the approximation of the TCS is used, expressed by the “rule of half” (see Small and Verhoef, 2007, Ch. 5). According to this concept, the demand for transport is assumed to be linear with very little loss of accuracy, and the direct effect ΔW_{rs} on the link from r to s is approximated using the following formula:

²⁹ The proof is an exercise in microeconomic calculus, see Appendix A.

$$\Delta W_{rs} = \frac{1}{2} (x_{rs}^1 + x_{rs}^0)(p_{rs}^0 - p_{rs}^1), \quad (4.3.23)$$

where $x_{rs} = \frac{t_{rs}}{\tilde{p}_r}$ denotes the transported quantity and $p_{rs} = \tilde{p}_r \tau_{rs}$ denotes the destination price in the reference (0) and policy scenario (1) situations.

A summary measure of indirect effects can now be defined, the “total benefit multiplier” *TBM* (see Copenhagen Economics, 2004), which is given by the ratio of the sum of total economic effects as measured by the equivalent variation EV_r (defined in Appendix A) and the sum of the direct effects given by (4.3.23), for all regions:

$$TBM = \frac{\sum_r EV_r}{\sum_r \sum_s \Delta W_{rs}}. \quad (4.3.24)$$

We will report this measure in the parts of analysis where the size of the indirect effects will be of interest to us. Note that it is possible to suggest a region-specific benefit multiplier:

$$BM_r = \frac{EV_r}{\sum_s \Delta W_{rs}}. \quad (4.3.25)$$

The latter indicator, however, does not measure the regional direct effect properly, assigning all link-specific effects to the region of origin. We will not use it in our analysis.

4.4. Links with the transport model

The source of freight and business passenger cost data for the empirical applications included in this study is the *Trans-Tools* model (Trans-Tools Consortium, 2006; TENconnect Consortium, 2008), which is being developed in a series of research projects supported by the European Commission. More specifically, we use the output of the assignment module developed at the Danish Technical University. In broad sense, the route assignment problem there is solved using the concept of stochastic user equilibrium with congestion (Danzon and Sheffi, 1977; Sheffi and Powell, 1981). The specific problem formulation for Trans-Tools is based on Nielsen (1997) and Nielsen et al. (2002).

An important step in linking a transport network and an SCGE model is to make sure that the level of spatial detail is comparable. The assignment module of Trans-Tools is based on actual European transport networks, specified for several modes of transport (road, rail, air, inland waterways, short sea shipping). Every such network is a set of links (connec-

tions) between the nodes of the network (railway stations, ports, road junctions). Each node is defined to belong to a specific zone (region), for which socio-economic data is available. Because the transport networks are very detailed, the corresponding zonal structure must also be as fine as possible. The highest level of detail allowed by Eurostat data on GDP, employment, etc, is NUTS3³⁰. That is why both Trans-Tools and our SCGE model are built on NUTS3-level data.

The output of assignment module relevant for our SCGE model includes (for every P/C pair at NUTS3 level):

- Average (across all routes and commodities) generalised freight cost per ton, in 2005 Euros, divided into pure resource cost part and payments to the public budget³¹;
- Freight flow per year, tons;
- Average generalised cost of business passenger travel per trip, in 2005 Euros, divided into same two parts;
- Business passenger flow per year, trips.

Unfortunately, the Trans-Tools model is still under development and not all output data are entirely consistent with the stylised facts from the transport statistics. A drawback most important for our model is that the aggregate transportation expenditure indicators, calculated from the data listed above, in some cases strongly (by 50-75%) underestimate the share of these costs in the value of trade or GDP suggested by country-level statistics (European Communities, 2008) or reported by empirical studies (such as Anderson and van Wincoop, 2004). As the benchmark levels of transportation expenditure are important for our analysis of the effects of transport policy measures, we thus cannot use the values of this indicator coming directly from Trans-Tools for calibrating the model parameters. Instead, we take an approach described in Section 3.3.3, namely, inferring distance costs from a gravity-type model.

Beyond the distance cost factors, another parameter that could be directly taken from the Trans-Tools output is the revenue collected from public charges on transport, F_{sr} . As absolute levels of collected revenue cannot be regarded as reliable for the same reasons mentioned above, we prefer to assume that no such revenue is collected in the benchmark. In other words, all costs are considered private, and thus no revenue redistribution is possible.

³⁰ NUTS stands for “Nomenclature of territorial units for statistics”, this is the official EU delineation of regions for statistical purposes. The list of NUTS3 regions is in Appendix B.

³¹ These payments consist of road use charges (such as urban toll rings in London or German Maut) and extra fuel taxes beyond normal value-added tax.

This essentially means that we do not distinguish between the cost components j_{sr} , r_{sr} , and z_{sr} at the calibration stage. F_{sr} and \tilde{z}_{sr} are thus equal to zero in the benchmark.

However, we will use Trans-Tools data for calculating the shares of individual components of distance costs (resource costs, charges and other costs) in the future year, as well as for calculating the relative changes in these costs due to policy scenario implementation. Then also the additional revenue collected due to scenario implementation could be calculated, and redistributed according to an appropriate rule. The mentioned drawbacks of the data are expected to have minor impact on the calculation of these parameters.

4.5. Calibration

At the end of Section 4.3, we have listed the exogenous variables and parameters of the model. The aim of the calibration procedure is to endow them with values. The comparative statics experiments in this chapter will be carried out for the year 2020. To describe the future reference economic situation we need a consistent database for a recent benchmark year (2005 in our case), as well as predictions of GDPs and trade impediments for the period until 2020. All shares and elasticity parameters are fixed based on the data for 2005. However, trade costs, factor stocks and productivity parameters have to be calculated based on the assumptions made for the future year.

4.5.1. Share parameters of technology and preferences

The national accounts data for 32 European countries (country list is in Appendix B) and the “rest of the world” region are extracted from GTAP database, version 6 (Center for Global Trade Analysis, 2005). From this source, we obtain the country-specific shares in gross output of factor costs and of intermediate input of services (as a proxy for non-tradable goods). Similarly, the share of non-tradables in consumption is approximated by the expenditure share for services. Further, we obtain the shares of primary factors in the total factor cost. We assume that 50% of capital is mobile, and that there are no capital shifts between regions in the benchmark ($K_r^e = K_r$). The cost share of the fixed factor is constructed from GTAP data as a sum of shares of land, natural resources, and the remaining 50% of capital.

As the respective data is available only for countries, not regions within countries, we assume the share parameters not to vary across regions within a country. This fixes the pa-

parameters $\kappa_r, \chi_r, \theta_r, \eta_r$, and ε_r . Sensitivity analysis shows that deviations from these specifications in a plausible range are non-critical for our conclusions.³²

4.5.2. Parameters of the distance function

The distance-dependent trade costs f_{rs} are, as the name says, modelled as a function of geographical distance g_{rs} (measured as truck travel time). A plausible assumption is that f_{rs} is increasing with distance, but at a diminishing rate. Following Bröcker (1998b), we assume the following form:

$$f_{rs} = \exp(\xi g_{rs}^{\varpi}) \quad (4.5.1)$$

with parameters $\xi > 0$ and $0 < \varpi < 1$.³³ Now, note that Eq. (4.3.18) suggests a gravity form of the trade equation:

$$t_{rs} = A_r \exp(-\sigma \xi g_{rs}^{\varpi}) M_{kl} B_s,$$

where $A_r = S_r p_r^{-\sigma}$, $B_s = \frac{D_s}{\sum_j S_j (p_j \tau_{js})^{-\sigma}}$, and $M_{kl} = \delta_{kl}^{-\sigma}$.

A standard procedure involving an OLS estimation of the log-linearized trade equation is not applicable here, because some of the trade flows may be zero. For consistent estimation, allowing for zero-valued trade flows, the equation should be rewritten as

$$t_{rs} = \exp(a_r + b_s - \sigma \xi g_{rs}^{\varpi} - \sigma \tilde{\delta}_{kl}), \quad (4.5.2)$$

with $a_r = \log(A_r)$, $b_s = \log(B_s)$, and $\tilde{\delta}_{kl} = \log(\delta_{kl})$.

Bröcker (1998b) estimates Eq. (4.5.2) by a non-linear regression using data on European international trade for 1995 (37 countries), because interregional trade data on a sub-national level are lacking. He receives highly significant and robust estimates for $\sigma \xi$ and ϖ . To receive an estimate for σ , a wage function may be estimated based on Eq. (4.3.3). These two estimation procedures are in detail described in Bröcker et al. (2009), and we only use the estimates reported there: $\varpi = 0.58$, $\xi = 0.03$, $\sigma = 12$.

³² Letting regional parameters η_r and ε_r vary randomly in the range $\pm 10\%$ around their country-specific mean values, and repeating calculations 1000 times, the resulting coefficients of variation of the aggregate indicators (indicators to be presented in Section 4.6) are all less than 0.01.

³³ This function is not globally concave, but is concave for the range of values of the distance measure in the data: 0-30000 minutes of truck travel time.

4.5.3. Trade calibration: base year

International trade data comes from the UN Comtrade database (United Nations). For our model, however, we need an interregional trade matrix. Such data is not directly available. That is why we apply the calibration procedure as described in Bröcker (1998b). We combine the country-level data with regional data in the NUTS3 classification stemming from the NewCronos database (Eurostat). This source provides us with the values of regional GDPs Y_r for the benchmark year. Using the Eqs. (4.3.7) and (4.3.15), we can express regional tradables supply as $S_r = \left(\frac{1}{\eta_r} - \varepsilon_r \right) Y_r - \varepsilon_r X_r$ (recall the assumption of no revenue redistribution in the base year). The value of regional trade deficit X_r is obtained by distributing national trade balance deficit across regions within a country proportional to regional GDPs. Tradables demand is then $D_r = S_r + X_r$.

Now we are able to formulate a system of calibration equations that would be solved simultaneously for trade flows and international trade impediments:

$$\left\{ \begin{array}{l} t_{rs} = A_r \exp(-\sigma \xi g_{rs}^{\sigma}) M_{kl} B_s, \\ \sum_r t_{rs} = D_s, \\ \sum_s t_{rs} = S_r, \\ \sum_{r \in \mathcal{K}, s \in \mathcal{L}} (t_{rs} + t_{sr}) = E_{kl} + E_{lk}, \quad k \neq l. \end{array} \right. \quad (4.5.3)$$

The unknowns are the flows t_{rs} and factors A_r , B_s , and M_{kl} . k (l) is the country that region r (s) belongs to, \mathcal{K} (\mathcal{L}) is the set of regions in country k (l). We assume symmetry of trade barriers, $\delta_{kl} = \delta_{lk}$. E_{kl} is exports from country k to country l , data coming from UN Comtrade. The last equation in the system is the calibration equation for trade barriers requiring that international trade flows for any pair of countries in the benchmark equilibrium coincide with the observations.

Under consistency of the data, this system is well known to have a solution, unique in t_{rs} , that can be efficiently found by generalised iterative scaling (Darroch and Ratcliff, 1972). Consistency here means that supply equals demand for the whole world, and countries export less than they produce and import less than they use, all with respect to the tradables sector. The solution provides unique values for international impediment factors δ_{kl} . The

solutions for row and column multipliers A_r and B_s are unique up to a constant scaling factor.

4.5.4. Trade calibration: future year

We will perform policy experiments taking year 2020 as a reference, i.e. we will compare a hypothetical world of 2020 that has a respective policy measure (an infrastructure project) implemented with another hypothetical world without this policy. The situation “without” is constructed by first recalibrating the trade matrix for 2020. To do this, we assume that all share parameters, the parameters of the wage curve, unemployment rates, and the parameters of the distance function remain unchanged, that the GDPs increase according to the exogenous growth rates, and that the border barriers within the EU decline. Then, the remaining parameters are calibrated.

In order to proceed in a similar fashion as in the previous step, we have to update the values of regional GDPs in the future year. For that, the official country-level GDP growth projections of the European Commission (Mantzios and Capros, 2006) were used. No convergence or divergence is assumed among regions within each country. Then we update the values of regional supply and demand for tradables.

Next, we need to make assumptions about the development of the calibrated trade barriers δ_{kl} for the period until 2020 (the distance costs however remain unchanged). For this we consider country aggregates: EUS15 (“old member states”), EUS12 (“new member states”), and EU27 (the whole EU). In the current situation, border impediments are considerably lower for the EUS15 countries than for the EUS12 countries, but we assume that after the accession to the EU the new member states gradually catch up and their trade integration increases. We therefore assume that the impediments to trade within the group of new member states, and between EUS15 and the new member states, in our scenario year 2020 will on average be equal to the average of the impediment to trade within EUS15 in 2005.

Then the calibration is done using the system (4.5.3) with one modification: there is no adjustment to the observed international trade flows. Instead, estimates of these flows are the outcome of calibration, resulting from the predicted impediments. To put it differently, for 2005 we know international trade flows and infer on border barriers, while for 2020 we know impediments and infer on international trade flows.

4.5.5. Calibration of remaining parameters: future year

Note that the calibration procedure in the last step also determines regional prices p_r , but only up to a positive multiplier (see the formula for the row multiplier A_r). Thus, the price level remains arbitrary. We fix it by requiring that the GDP-weighted average price is equal to one. Then we calculate prices q_r by Eq. (4.3.17), fixing the arbitrary scaling factor $\tilde{\phi}$ such that prices of tradables are equal to one on average as well. Assuming all factor prices to equal one initially, we can now use Eqs. (4.3.9), (4.3.11), and (4.3.13) to determine the reference factor stocks K_r , L_r , H_r . Productivity parameter \tilde{v}_r is then determined from Eq. (4.3.3). Finally, base-year regional unemployment rates from the NewCronos database are used to determine the position parameter of the wage curve \mathcal{G}_r for all regions through Eq. (4.3.12).

Now all model parameters are specified and we are ready to do sensitivity tests and compute the results of policy scenarios.

4.5.6. Introducing transport policy shocks

In order to incorporate transport policy measures into the model, we go back to the expression for the inclusive price in (4.3.16), and introduce three shock parameters there, Δr_{sr} , Δj_{sr} , and Δz_{sr} , corresponding to the three components of distance costs that we look at (freight costs, business passenger costs, and charges):

$$c_{r,i} = \tilde{p}_s \delta_{lk} \cdot (f_{sr} + r_{sr} \cdot \Delta r_{sr} + j_{sr} \cdot \Delta j_{sr} + z_{sr} \cdot \Delta z_{sr}). \quad (4.3.16')$$

Resource parts of freight costs and costs of business passenger travel (time costs, fuel costs, vehicle operating costs) change due to the construction of the new transport links or due to the upgrade of the existing ones: the trip may become shorter, faster, and the road quality might have improved. Introduction of the new road pricing rules, new tolls, or emission taxes leads to the changes in the revenue-generating costs.

Parameters Δr_{sr} , Δj_{sr} , and Δz_{sr} are calculated as relative changes in the per unit (ton or trip) costs produced by the Trans-Tools model. In order to add all these changes together, we need to infer on the benchmark levels of the ad-valorem rates r_{sr} , j_{sr} , and z_{sr} . These are not calculated directly from the Trans-Tools data, because of the inconsistencies mentioned above, but are computed by applying the shares of these cost components to the

estimated total distance cost mark-up:

$$r_{sr} = (f_{sr} - 1) \cdot s_{sr}^r, \quad j_{sr} = (f_{sr} - 1) \cdot s_{sr}^j, \quad z_{sr} = (f_{sr} - 1) \cdot s_{sr}^z,$$

where

$$s_{sr}^r + s_{sr}^j + s_{sr}^z = 1.$$

Here, s_{sr}^r is the share of the resource costs of freight transport, s_{sr}^j is the share of the resource costs of business passenger travel, and s_{sr}^z is the share of the collected revenue in total distance cost, all calculated from Trans-Tools base-year (2005) data. We can now rewrite the expression for the inclusive price as:

$$c_{r,i} = \tilde{p}_s \delta_{lk} \cdot \left(f_{sr} + (f_{sr} - 1)(s_{sr}^r \cdot \Delta r_{sr} + s_{sr}^j \cdot \Delta j_{sr} + s_{sr}^z \cdot \Delta z_{sr}) \right) \quad (4.3.16'')$$

Apart from modifying the expression for the inclusive price, we have to correspondingly update the expressions for the trade flows in (4.3.18) and the collected revenue in (4.3.19), which become:

$$t_{sr} = \frac{S_s (p_s \tau_{sr})^{-\sigma}}{\sum_j S_j (p_j \tau_{jr})^{-\sigma} (1 + \tilde{z}_{jr} + d\tilde{z}_{jr})} \cdot D_r \quad (4.3.18')$$

and

$$F_{sr} = t_{sr} (\tilde{z}_{sr} + d\tilde{z}_{sr}), \quad (4.3.19')$$

where we introduced $d\tilde{z}_{sr} = \delta_{sr} (f_{sr} - 1) s_{sr}^z \Delta z_{sr}$. Note that \tilde{z}_{sr} is equal to zero in the benchmark according to our calibration.

4.6. Sensitivity analysis

We will perform sensitivity analysis with respect to two groups of model parameters: 1) those describing the policy measures (external parameters), and 2) those describing the structure of the underlying economy (internal parameters). Specifically, we will investigate the sensitivity of the model with respect to the shock parameters and with respect to the assumptions about the factor markets.

The two key model elements describing transport policy measures are the change of the transport costs relative to the reference scenario, and the revenue redistribution rule. As the transport costs have two main components: pure resource costs and payments to public budget, respectively, the effects of changes in these two components may be analysed individually. Actually, we can test three types of policy scenarios: pure infrastructure sce-

nario (only resource costs change), pure pricing scenario (only charges change), and a combination of the two.

The second part of sensitivity analysis will be performed in order to test the implications of the different assumptions about the capital and labour markets in the model.

The capital market plays an important role in the transmission of the economic effects across space, as it enables the relocation of economic activity based on the relative attractiveness (for example in terms of accessibility) of different regions. We will experiment with different degrees of capital mobility and document the implications for policy assessment. Our default assumption here is that 50% of regional capital is internationally mobile.

The labour market is known to be characterized by a certain level of wage rigidity that varies between regions. High wage rigidity means that the adjustment of the labour market to the policy shock is going mainly through the change in (un)employment level, while little rigidity implies that most of the shock is absorbed by the changing wages. In the sensitivity analysis, we will look at the implications of different assumptions about the form of the wage curve on the effects of policy scenarios. The default value for the wage curve elasticity is -0.1 for all regions.

The direction of response of the regional economic activity to the introduction of wage rigidity and capital mobility is easy to guess. Either of assumptions opens an additional source of inputs for production that can be used to meet the increased demand for tradable varieties from the other regions (for example following the reduction of the transport costs), which would increase the economic effect. However, it is hard to say a priori which of the assumptions is more important in quantitative terms and how the interplay between these elements is realized. We will try to answer these questions using the numerical simulations.

We will pay separate attention to the question of the magnitude of the indirect welfare effects predicted by the model, and to the dependence of these predictions on the new assumptions about the factor markets.

4.6.1. Sensitivity with respect to transport policy parameters

We will start by testing several homogeneous policy scenarios (implying equal relative transport cost changes for all P/C pairs inside the study area) under the default values of internal parameters. We will only look at the results for country aggregates: EUS15 (“old member states”), EUS12 (“new member states”), and EU27 (the whole EU). For the sensi-

tivity runs, we will assume specific values for parameters Δr_{sr} and Δz_{sr} (value of 0.01 corresponding to 1% increase in the overall distance costs), while setting $\Delta j_{sr} = 0$.

Tables 4.6.1-4.6.3 show the results of the first set of sensitivity tests for the three key output indicators of the model: **real GDP**, consumers' welfare (measured by **real income**), and **unemployment rate**. We should note that the weighted averages of GDP effects are calculated using reference GDPs as weights, while population is used as weights for calculating the average welfare and unemployment effects. With this rule, the EUS12 will always have a bigger impact on the aggregate value of welfare effect in EU27, than on the aggregate GDP effect.

The qualitative interpretation of these results is straightforward. The output indicators are equally sensitive to the increases and the decreases of the distance costs. Increasing the test value of cost change 5 times leads to roughly proportional increase of all output indicators, which is due to linear-homogenous forms used to describe technology and preferences.

The general tendency is also quite clear: trade costs reduction decreases the price of the composite tradable in the given region and makes it a relatively cheap input in the Cobb-Douglas production function, which allows firms to choose a higher production level by substituting towards this input. On the other hand, the affected regions can charge higher prices (\tilde{p}_r) for tradable varieties, which leads to an increase of price of output and thus of factor prices. These two main effects lead to an increase in GDP and income. All these mechanisms are reversed in the case of trade costs increase. The exact values of the indicators, however, deserve a detailed investigation.

Analysing the impacts of cost changes specified as the percentage change of the reference distance costs, we can expect the resulting levels of GDP effects to be in some correlation with the reference shares of distance-related costs in GDP. Our calculations based on the estimated distance function suggest that these costs amount to almost 7% of GDP within the EU. There exist variations across countries here. In particular, the share of distance costs in the new member states is notably larger than in the old member states, and amounts to 11% on average, which is likely due to the lagging technology in the logistics and the lack of cost-efficient vehicles, but also due to the state of transport infrastructure.

Having these numbers in mind, we can infer that the GDP effects resulting from a homogenous 1% distance cost reduction scenario should be at least in the order of 0.07% for the whole EU. That would hold if the cost change would immediately affect the value of

Table 4.6.1. Sensitivity of GDP effects to homogeneous transport cost change for EU27

Type of scenario	Cost change	Real GDP effects, %		
		EUS15	EUS12	EU27
Pure pricing scenario	+1%	-0.144	-0.348	-0.160
	-1%	0.145	0.349	0.161
	+5%	-0.717	-1.724	-0.794
	-5%	0.728	1.761	0.808
Pure infrastructure scenario	+1%	-0.134	-0.325	-0.149
	-1%	0.135	0.326	0.150
	+5%	-0.667	-1.607	-0.740
	-5%	0.689	1.680	0.777

trade and leave other economic links untouched. In fact, Table 4.6.1 suggests that the GDP effects exceed this tentative threshold. The reported values are roughly twice as large. It means that numerous interdependencies in the economy give rise to various indirect effects, the magnitude of which is comparable with the effect of directly applying the cost changes to the value of trade. These indirect effects result from the monopolistic competition on the market for tradables and from the wage rigidity introduced via the wage curve. They are facilitated and reinforced by the interregional linkages in the form of trade and capital mobility. We evaluate these effects in more detail in the following.

Important to note is also the fact that relative GDP effects for the “new member states” are larger than for the EU as a whole. Using the same logic as above, this can to a large extent be related to the higher share of geographical costs in the GDP. In this homogenous cost change scenario, the same argument will apply to explain differences across individual countries or regions. Other factors that determine the variation in the GDP effects are the differences in the unemployment rates, the mobile capital share, and the pattern of trade.

Note also that the effects of equally strong decrease of resource costs and increase of charges do not cancel out completely. The effects of a pricing scenario are always stronger, which is due to the change in the value of collected revenue, and thus in households’ income. The difference in the effects of the two types of scenarios is much more pronounced if we look at the response of the welfare measure in Table 4.6.2. However, as we have constructed the shock to the revenue-generating charges in correspondence to the percentage change of the distance-dependent costs, we can easily explain this difference. Indeed, the amount of revenue collected from the 1% cost change in the pricing scenario is in the same order of 0.07% of GDP for the EU27, and this number can simply be subtracted from the

Table 4.6.2. Sensitivity of welfare effects to homogeneous transport cost change for EU27

Type of scenario	Cost change	Real income effects, %		
		EUS15	EUS12	EU27
Pure pricing scenario	+1%	-0.041	-0.100	-0.053
	-1%	0.041	0.098	0.052
	+5%	-0.212	-0.519	-0.272
	-5%	0.197	0.472	0.251
Pure infrastructure scenario	+1%	-0.113	-0.239	-0.138
	-1%	0.113	0.240	0.138
	+5%	-0.562	-1.190	-0.686
	-5%	0.575	1.231	0.704

real income response to reveal the pure cost change effects (which then become close to the values from the infrastructure scenario). Of course, the slight difference between the benchmark GDP and income, and the response of the price index make this estimate a rough one, but we see that this method helps quite well to explain the values in Table 4.6.2.

We also see from Tables 4.6.1-4.6.2 that, for the case of the resource cost change, the responses of GDP and real income lie close to each other. Equation (4.3.15) provides a clear explanation for this fact. In the absence of revenue flows, the difference between income and GDP effects is only due to capital in- or outflow and its magnitude is thus largely determined by the share of the mobile capital.³⁴

The last output indicator we look at in this first set of sensitivity tests is the unemployment rate. To get an idea of what the magnitude of its response to the change of transport costs should be, we can consider the following chain of thoughts. The immediate effect of the simulated policy shock is the change of the prices of tradable goods, which are linked to the transport cost components through Eq. (4.3.17). According to this formula, if the trade cost mark-ups are all multiplied by a constant factor, the price of tradables will also be scaled by the same factor (linear homogeneity). Ignoring for a moment the variability of transport cost margins across countries and regions, we can roughly estimate the change in the trade cost mark-up by inserting the values of $\Delta r_{sr} = 0.01$ and $f_{sr} = 1.09$ (trade-weighted average for EU27) into Eq. (4.5.5). The rough estimate of the change in factor τ_{sr} is then equal to 0.083%. The effect on the consumer price index will be further reduced by applying the share of tradable goods in the consumption basket (around 40%). The ef-

³⁴ Another element of income, the interregional transfer, is fixed in real terms and thus has only a negligible effect on the difference between the GDP and income effects.

Table 4.6.3. Sensitivity of unemployment rate to homogeneous transport cost change for EU27

Type of scenario	Cost change	Unemployment rate effects, % points		
		EUS15	EUS12	EU27
Pure pricing scenario	+1%	0.066	0.170	0.086
	-1%	-0.065	-0.169	-0.086
	+5%	0.329	0.855	0.433
	-5%	-0.325	-0.837	-0.426
Pure infrastructure scenario	+1%	0.061	0.158	0.080
	-1%	-0.061	-0.158	-0.080
	+5%	0.307	0.796	0.404
	-5%	-0.308	-0.799	-0.405

fect on real wages of a 1% increase in transport costs will thus be in the order of -0.033%. To assess the effect on the unemployment rate, we divide this number by the default wage curve elasticity of -0.1 , and get a tentative value of $+0.33\%$. Thus, an average unemployment rate of 9% for EU27 would go up roughly 0.03 percentage points. This is the order of magnitude we should expect.

In fact, the values in Table 4.6.3 are roughly 3 times larger than what our line of argument above would suggest. However, the order of magnitude and the sign of effects is as predicted. We see also that the difference between the effects on EUS12 and EUS15 is not negligible, which can be explained by higher average unemployment rates in the EUS12 in the base year.

Caspersen et al. (2000) integrate the classical labour-leisure trade-off in their model, and as a consequence, the transport cost reduction leads to a decline in labour supply in the affected regions. In our case, such effect is ruled out by the assumption of the wage curve.

A further set of test model runs studies different assumptions about the *revenue redistribution rule*. In the case where revenue is just used to cover the income losses caused by the increase of charges, all welfare effects would be very close to zero. However, revenue is normally not allocated according to where the “damage” happened. Our default rule assigns half of revenue from transport charges to the country hosting the producing region and half to the country hosting the consuming region, and then allocates the country totals proportionally to regional GDPs. As a further test, we can check the implications of collecting the total revenue in a single European “pot”, and then distributing this money to regions Europe-wide. At least three alternative options for a possible redistribution rule can

Table 4.6.4. Sensitivity of welfare effects to revenue redistribution rule (in the case of 5% cost increase in the pricing scenario)

Parameter	Test value	Real income effects, %		
		EUS15	EUS12	EU27
Revenue redistribution rule	Proportional to GDP	-0.190	-0.894	-0.329
	Proportional to population	-0.206	-0.100	-0.185
	Inversely proportional to GDP per capita	-0.241	0.759	-0.044

be checked. The reallocation scheme choice is not expected to have strong influence on the distribution of GDP and employment effects, but it can significantly influence the response of the welfare measure. We perform the analysis for the case of a homogenous 5% increase of the costs in the pricing scenario.

As can be seen from Table 4.6.4, distribution based on population shares is advantageous for the EUS12, as these countries have a bigger weight in terms of population than in terms of GDP, compared to EUS15. Even more advantageous for the EUS12 is the redistribution inversely proportional to GDP per capita. This scheme in a sense displays the desirable outcome from the point of view of the social and economic cohesion objective (as mentioned in Chapter 1), although it may well be a disputable point, whether pricing policy in transport should at all be in any way related to cohesion considerations.

4.6.2. Sensitivity with respect to internal parameters

The second large set of test cases that we look at concerns the parameters that are internal to the model and that determine the response of the factor markets to the policy shocks.

The first parameter is the **elasticity of the wage curve**, or the unemployment elasticity of pay. This parameter shows the percentage by which the real wage rate in the region changes as a response to a 1% increase of the unemployment rate. The analysis performed by Blanchflower and Oswald (1994) suggests that the value of this elasticity is very often close to -0.1. Thus, the wage rate falls by only 10% if the unemployment rate doubles. This illustrates, for instance, the fact that the labour markets in most EU countries are subject to significant wage rigidity, because of the organized wage setting through the labour unions.

For the purposes of sensitivity analysis, we will assume that the value of this elasticity is the same in the whole study area of EU27. Table 4.6.5 shows the effects of a 1% resource cost increase under different values of this elasticity. Apart from the overall GDP response, we provide its decomposition into four components. We will discuss these results in detail.

Table 4.6.5. Sensitivity of the GDP components and the TBM to the elasticity of the wage curve (in the case of 5% resource cost decrease)

Parameter	Test value	Real GDP response for EU27, %	TBM	Change of GDP components, % of real GDP			
				Labour income components		Income of employed capital	Income of the fixed factor
				Real wages effect	Employment effect		
Elasticity of the wage curve (unemployment elasticity of wages)	-0.01	1.311	2.80	0.076	0.546	0.336	0.353
	-0.05	0.917	2.00	0.159	0.266	0.240	0.252
	-0.10	0.777	1.71	0.180	0.177	0.205	0.215
	-0.20	0.678	1.51	0.214	0.098	0.179	0.188
	-1.00	0.574	1.29	0.240	0.023	0.152	0.159
	-5.00	0.548	1.23	0.246	0.005	0.145	0.152
	-10.00	0.544	1.22	0.247	0.002	0.144	0.151

The overall effect on GDP is increasing when we shift from very flexible wages to very rigid wages, with notably larger response at the low absolute values of the test parameter. This is an interesting finding that gives us an idea of how important the assumption of wage rigidity is for the numerical outcomes of policy experiments. We see that the absolute value of GDP response goes up roughly 40%, compared to the case with flexible wages ($\zeta = -10$), if we assume the threshold value of -0.1 for the wage curve elasticity. If $\zeta = -0.05$, the increase is already 70%. 100% difference is achieved by setting this elasticity to -0.03 . If we now turn to the estimated values of the wage curve elasticity in Table 4.2.1, we will see that some estimates do lie as low (in absolute terms) as -0.03 for some very regulated labour markets. Thus, there we have a danger of underestimating the overall impact of a policy measure by as much as 100% if the labour market is assumed to be free of rigidities.

In order to explain this pattern, we have to recall the arguments we used in order to predict the order of magnitude of the unemployment rate response. Transport cost reduction has the main effect on the relative prices of goods, reducing the consumer price index in the directly affected regions. Other things equal, the real wages will thus go up. Moreover, the increased demand from other regions for the products of the directly affected regions creates an incentive for the firms there to expand production. These two effects create conditions for the entry of the additional labour force out of unemployment. The expansion of production can thus be realized at a higher scale than with fixed employment, and the factor payments (GDP) increase correspondingly.

Looking specifically at the indirect effects, the results in Table 4.6.5 confirm the point made by Elhorst et al. (2004) about the important role that the assumptions about the behaviour of the labour market play in determining the size of the economy-wide effects. Assuming flexible wages, the model predicts indirect effects in the order of 20% of the direct effects, which resembles the results of the previous studies using a similar model (Bröcker and Schneider, 2002). These arise from the monopolistic competition on the tradables market, “love for variety”, and the resulting effects on the consumers and the firms (which we called *agglomeration economies* in Chapter 3). Setting the elasticity of the wage curve in the range predicted by the empirical studies increases the magnitude of the indirect effects drastically. These additional effects coming from the changes in employment levels are much stronger than the effects brought about by the agglomeration forces only, and are in the order of 50% of the direct effects for the default value of the elasticity. Similar values have been found by Pilegaard and Fosgerau (2008), who analysed the impact of infrastructure improvements on commuting behaviour using an experimental CGE model with search unemployment. Such large values of indirect effects mean that conventional CBA analysis would significantly underestimate the benefits from transport projects, and would thus introduce a bias into the decision-making process.

Individual components of GDP are affected proportionally to the overall response. However, it is worthwhile to further decompose the effect on labour income, and to see that the burden of adjustment shifts from the wages to the level of employment as we move from high to low absolute values of wage curve elasticity. The value of -10 is sufficiently close to an assumption of perfectly flexible wages, and little adjustment of employment is observed. At the low end of elasticity values, however, the overall level of economic activity is mostly affected by the movements in the level of employment. An interesting finding is that at the value of -0.1, the response of GDP through wages and through employment (in the sense of Table 4.6.5) is almost the same, which could add to the long list of findings that have made it almost a magic number in the wage curve literature.

The responses of mobile capital income and fixed factor income are always close to each other, because the main component of fixed factor is immobile capital, and it is in relation of 50/50 to mobile capital by default. The ratio between the sum of these two effects and the effect on labour income corresponds to the average ratio between total capital and labour income for the EU27, which is in the order of 1.2 according to the GTAP data.

Table 4.6.6. Sensitivity of unemployment rate to the elasticity of the wage curve (in the case of 5% resource cost decrease)

Parameter	Test value	Unemployment rate response, % points		
		EUS15	EUS12	EU27
Elasticity of the wage curve (unemployment elasticity of wages)	-0.01	-1.012	-2.157	-1.238
	-0.05	-0.497	-1.229	-0.642
	-0.10	-0.308	-0.799	-0.405
	-0.20	-0.183	-0.504	-0.246
	-1.00	-0.043	-0.125	-0.059
	-5.00	-0.009	-0.026	-0.012
	-10.00	-0.005	-0.013	-0.006

The response of unemployment rates in Table 4.6.6 essentially follows the same pattern as already described in our discussion of Table 4.6.2. This indicator is of course much more sensitive to the changing form of the wage curve than the overall indicator of GDP. For the low absolute values of the wage curve elasticity, the effects in the order of 0.5-1.5 percentage points of unemployment rate are definitely not negligible (the assumed trade cost reduction is however also very considerable).

Appearing in the wage curve equation, the reference value of the **unemployment rate** itself is one of the factors determining the magnitude of the economy's response to the policy shock. For the lack of other information, in our numerical experiments we assume that the regional rates of unemployment in 2020 will be the same as in the benchmark year 2005. It is however worthwhile to check the sensitivity of the welfare effects with respect to this assumption.

We thus ran additional experiments, assuming different values of average base-year unemployment rates for the study area. Intuitively, one can expect that the larger the labour market imperfection (the higher the unemployment rate), the larger the indirect effects of the transport policy shock would be. Our calculations confirm this intuition. First, the calculated indirect welfare effects are positively correlated with the benchmark unemployment rates (correlation coefficient of 66%). With the default value of the wage curve elasticity ($\zeta = -0.1$) and the average unemployment rate calculated from the data for 2005 equal to 9%, the total benefit multiplier is equal to 1.71 (see Table 4.5.6). Scaling the projected unemployment rates down such that the average rate falls to 8% gives $TBM = 1.68$, and scaling it up to the average of 10% gives $TBM = 1.75$. The influence of the moderate changes in the benchmark unemployment rate is thus quite small. However, if we assume

Table 4.6.7. Sensitivity of the GDP components and the TBM to the share of mobile capital (in the case of 5% resource cost decrease)

Parameter	Test value	Real GDP response for EU27, %	TBM	Change of GDP components, % of real GDP			
				Capital income components		Labour income	Fixed factor income
				World interest rate contribution	Capital in-flow contribution		
Share of mobile capital in total capital	1%	0.550	1.53	0.001	0.002	0.256	0.291
	5%	0.565	1.54	0.003	0.012	0.263	0.287
	10%	0.583	1.56	0.006	0.024	0.271	0.281
	15%	0.602	1.57	0.009	0.038	0.280	0.275
	25%	0.645	1.60	0.017	0.067	0.299	0.261
	35%	0.693	1.64	0.026	0.101	0.321	0.245
	50%	0.777	1.71	0.042	0.163	0.357	0.215
	65%	0.897	1.80	0.065	0.244	0.411	0.178
	80%	1.059	1.93	0.097	0.355	0.481	0.127
	95%	1.301	2.10	0.145	0.519	0.584	0.053

that the future unemployment rates will be significantly lower, say in the order of 3%, the value of the *TBM* will drop to 1.4.

The next internal parameter we will look at is the **share of mobile capital** in the total capital. There are no reliable estimates of this share even on country basis, and we would like to see how sensitive the results are to the changes of our default value of 50%. We expect that with our guess we be rather on the high end of reasonable values. From our viewpoint, 100% of capital region-wide cannot be assumed mobile even in the long run, because of the inevitable installation costs and further market imperfections. The more probable values would lie substantially below 100%. The test case is again a 5% resource cost decrease for EU27, and the outcomes are reported in Table 4.6.7.

As in the case with the wage curve elasticity, we can see that the GDP response and the total benefit multiplier change significantly if we move between the two extreme assumptions of almost complete capital mobility and little capital mobility. The reason for this pattern is the connection between the capital availability and the production possibilities of the firms. Infrastructure improvements reduce the trade costs for the affected regions and make their products more affordable. Capital flows to these regions because the increased demand for their products creates a tendency for regional factor returns to rise. The availability of additional capital then allows the firms in the regions enjoying accessibility improvements to further expand production and thus respond to an increase of demand from

the other regions. The inflow of capital also makes other factors more productive, thus increasing the factor income and thus the effect on the households. The size of these effects is positively correlated with the assumed share of mobile capital in the factor income.

Again, we can decompose the response of capital income into its components and check that the burden of adjustment is mainly carried by the actual capital movements. However, we see that a stable part of capital income adjustment (about 25%) is actually realized through the change of the world interest rate, which is simply due to the fact that the whole EU economy is a big enough part of the world economy. Another interesting finding is that the GDP response is quite sensitive to the increase of mobile capital share at the high end of the tested values (in the range 50%-95%), but is less so in a more probable range of values at the lower end (15%-35%). This suggests that various indirect effects are magnified in the presence of capital mobility, whereby the link is probably not linear.

Finally, we would like to compare the predictions of the model extended by the new assumptions of wage rigidity and capital mobility with the predictions of the previous version of the model without these assumptions. We start with the base case of flexible wages and low capital mobility and consequently introduce the default assumptions about the factor markets that we used in this sensitivity analysis framework. Table 4.6.8 documents the results.

We see that in the basic setting with negligible effects on employment and capital movements, the response of GDP is close to the tentative threshold of 0.07% that we referred to earlier, and the indirect effects only amount to 20%. Both our default assumptions about the factor markets seem to extend the GDP effects equally strong, and they reinforce each other in combination, so that the impact of the two modifications together is larger than the sum of the additional impacts they cause individually.

Table 4.6.8. Sensitivity of the key indicators to the combinations of assumptions about the factor markets (in the case of 1% resource cost decrease)

Experimental setting		TBM	Response of indicators for EU27			
Wage curve elasticity	Share of mobile capital		Real GDP, %	Real income, % of real GDP	Income of foreign capital, % of real GDP	Unemployment rate, % points
-10.0	1%	1.19	0.084	0.084	0.000	-0.001
-0.1	1%	1.53	0.110	0.110	0.001	-0.057
-10.0	50%	1.23	0.109	0.086	0.029	-0.001
-0.1	50%	1.71	0.150	0.124	0.041	-0.084

Under the default values of the wage curve elasticity and the share of mobile capital, the indirect effects amount to 70% of the direct user benefits. This is of course an immense difference to the basic setting and a strong signal about the importance of incorporating these features for the quality of numerical outcomes of the model. As the values of the *TBM* in Table 4.6.8 suggest, the degree of wage rigidity seems to play a more important role in determining the size of indirect effects than the degree of capital mobility. Under the flexible wages, switching between the assumptions of rather mobile and rather immobile capital does not make the share of indirect effects deviate much from the 20% benchmark. In contrast, when the degree of wage rigidity is high, the degree of capital mobility becomes a much more important factor in determining the overall impact (see Table 4.6.7), higher mobility corresponding to higher share of indirect effects. This deserves additional explanation, as one cannot view the increase of capital mobility as an additional market imperfection (which, as we noted, facilitate the emergence of indirect effects).

The presence of a mobile factor of production can however be viewed as an additional channel through which the spatial spillover effects may arise. The spatially connected markets in our model are initially characterized by a market imperfection in the form of monopolistic competition. Capital mobility means that the resulting agglomeration effects can now be distributed in space more easily, not only through trade, but also through the reallocation of resources. This additional effect from capital mobility is reinforced when all markets are characterized by even more market imperfection, now including the labour market.

As no additional revenue is generated in this scenario, we can also demonstrate the relationship between the response of GDP and real income. For this we calculate the change in real income as a percentage of reference real GDP (see Table 4.6.8). Then the two indicators have common basis for comparison. Now we see that the amount of added value generated by foreign capital roughly corresponds to the difference between the change of GDP and income³⁵.

4.7. Experiment description and simulation results

In this section, we apply our model in order to analyse the economic effects of the *Fehmarn Belt railway axis* project. It includes the construction of a fixed rail-road link across

³⁵ As foreign income accrues abroad, we have to subtract this effect from GDP to get the value for the households' income.

the Fehmarn Belt as well as the update of the access rail routes on the German and Danish side (including the Hannover-Hamburg/Bremen railway). The future update of the related road infrastructure is also foreseen but is not included into this project. According to the contract between the states of Germany and Denmark (BMVBS, 2008), a fixed link (the form – a bridge or a tunnel – is still to be decided upon) will replace the existing ferry service between Puttgarden (Kreis Ostholstein, DE) and Rødby (Storstrøms Amt, DK) by the year 2018. The project is a part of the trans-European networks in transport (TEN-T). It appears as one of the priority projects in the Van Miert Report (project no. 20).³⁶ We have chosen this case because several studies analysed it before³⁷, and we thus have a base for (at least, qualitative) comparison.

The *Fehmarn Belt railway axis* project will be financed by the governments of Germany (15%) and Denmark (85%). As of year 2009, the estimated budget for construction works is €5600 mln. It is not our purpose here to make a proper evaluation of this infrastructure project (mainly, because of the preliminary nature of the Trans-Tools data). Our aim is to use it as an illustration of the various points made in the previous section on sensitivity analysis.

The fixed link and the updated access routes represent an infrastructure improvement in the already closely integrated markets of (in particular, northern) Germany and Denmark. The welfare impacts of this project are thus expected to be quite small compared to the size of the affected economies. The biggest direct effect of the fixed link is due to the achieved time savings (the usual ferry waiting and transfer time is considerably reduced) and increased flexibility. The toll for crossing the fixed link will remain at the level of the current ferry service, so the out-of-pocket costs are not affected much by the link itself. The main benefit for Germany will come from the update of the access routes, where the connection on the axis Bremen-Hamburg-Lübeck-Puttgarden will be substantially improved. The project may also be a success for the further integration of the German market with the markets in the other Nordic countries (Sweden, Norway, Finland) via the Danish-German link.

Several types of effects will be at work when the project implementation is simulated. First, the fixed link will lower the costs associated with the transportation of goods across the Fehmarn Belt. Lower prices for final products and especially lower costs of business travels will make the export markets more available for the companies on the both sides of

³⁶ We will refer to this whole package of infrastructure improvements as the “Fehmarn Belt project” for the sake of brevity

³⁷ The cost benefit analysis of the fixed link was done by Cowi (2004). Several studies employed the SCGE framework of Bröcker (1998c): Copenhagen Economics (2004), Barten et al. (2006).

the link. This will induce the *substitution effect*: firms in the directly affected regions will be able to export more or charge higher prices for their products, while the regions adjacent to previously used routes (mainly, the Great Belt area in Denmark) may even suffer losses from trade flows shift. The expansion of activity in the directly affected regions has a further consequence, as these firms will increase demand for the local goods as well as for the intermediate products from the other regions. Hence, through the *income effect*, also more distant regions will be able to benefit from the project. As the regions become “closer” to each other, the producers will be exposed to stronger competition. In the monopolistically competitive tradables sector, this will mean an *increase in the variety* of available products, which will benefit the consumers and firms. Finally, the *employment effects* and larger *regional spillover effects* brought about by the new assumptions of wage rigidity and capital mobility also to a large extent shape the overall economic impact.

We will perform calculations with the model described in Section 4.3, as well as with the basic model (without capital mobility and wage curve) and an intermediate version, where only capital mobility was allowed for. We find it convenient to introduce short names for the different model runs. We will refer to the basic model as *Model 1*. The extensions of the basic model will be labelled *Model 2* (capital mobility only) and *Model 3* (capital mobility and wage curve).

The source of scenario data is the Trans-Tools model, used in the way described in Section 4.5.6. We first tried to run the project implementation scenario using both the resource cost changes and the changes in infrastructure charges. However, the resulting spatial pattern of the effects could not be regarded as reasonable (see Table A.1 in Appendix A). According to the cost data, the resource cost decline was almost exactly counteracted by an increase in charges for the links inside Denmark. This produced an implausible bias in the results to the detriment of Danish regions.³⁸ That is why we decided to illustrate the functioning of the model by only using the resource cost change information.

We start by presenting the spatial distribution of the estimated impacts. Figure 4.7.1 displays the predicted pattern of welfare effects of the Fehmarn Belt project, as calculated by the extended model (*Model 3*), on the NUTS3 level of detail. We can see that relatively large positive welfare effects (>0.05%) are predicted only for a few regions, mostly those directly touched by the update of the infrastructure. Table 4.7.1 provides details about the effects on selected regions, as coming from the three model versions defined above. Strong

³⁸ This must be a consequence of a misspecification in the assignment module operated by the Danish Technical University. It was not possible to obtain the corrected cost matrices for the purposes of this thesis.

Table 4.7.1. GDP and welfare effects in selected regions in year 2020

Region	Country	Real income effects, %			Real GDP effects, %		
		<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model1</i>	<i>Model2</i>	<i>Model3</i>
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Bremen, Kreisfreie Stadt	Germany	0.049	0.049	0.087	0.049	0.067	0.118
Hamburg	Germany	0.050	0.050	0.078	0.049	0.069	0.106
Stade	Germany	0.039	0.040	0.061	0.039	0.054	0.083
Lübeck, Kreisfreie Stadt	Germany	0.063	0.063	0.098	0.063	0.087	0.134
Ostholstein	Germany	0.041	0.042	0.065	0.041	0.057	0.088
Kobenhavn City	Denmark	0.064	0.066	0.132	0.066	0.083	0.164
Københavns Amt	Denmark	0.081	0.082	0.164	0.083	0.104	0.204
Frederiksborg Amt	Denmark	0.077	0.078	0.156	0.079	0.099	0.194
Roskilde Amt	Denmark	0.102	0.103	0.204	0.104	0.131	0.255
Vestsjællands Amt	Denmark	0.102	0.103	0.203	0.104	0.131	0.254
Storstrøms Amt	Denmark	0.116	0.117	0.229	0.118	0.148	0.286
Skåne Län	Sweden	0.048	0.049	0.088	0.049	0.062	0.112
Västra Götalands Län	Sweden	0.023	0.024	0.050	0.024	0.031	0.064

local effects are predicted for German, Danish, and Swedish regions. We will analyse this table gradually. For the moment, we can concentrate on column 5, corresponding to Figure 4.7.1. Among the areas directly affected by the new infrastructure the strongest welfare impact (0.23%) is predicted for the Storstrøms Amt. We discuss the model output country-by-country in the following.

Germany accounts for 52% of the total welfare effects. Small relative gains ($>0.01\%$) can be found as south as the region of Bielefeld. Strongly affected regions of Bremen, Hamburg, and Lübeck get shares of total project benefit for Germany that are about 8-10 times higher than their respective shares of German GDP. Because the economic links between the regions in the northern Germany are quite strong, many areas enjoy at least small gains due to project implementation. Still, some regions in Eastern Germany suffer very small welfare losses that realize due to the reallocation of trade flows from the Scandinavian countries.

Denmark accumulates 33% of the total welfare effects, whereas the regions in western part of the country suffer slight welfare losses (-0.02% on average). The positive effects on Danish regions are quite evenly spread in the eastern part of the country, the shares of benefits exceeding shares in GDP only 2-3 times. Although the relative effects on the Danish regions reported in the table above are all of comparable size, the absolute effects vary a lot. In fact, 70% of the total welfare effect on Denmark accrues to the Copenhagen area.

The study of Copenhagen Economics (2004) suggested the presence of significant economic effects of the project implementation in the Nordic countries (Sweden, Finland and Norway). We can confirm this finding in particular for the case of Sweden, where the region of Skåne Län, connected by the Øresund bridge to Denmark, enjoys a quite high gain from the project (0.088%). Certain time savings brought about by the construction of the fixed link are also noticed for the regions that are located further to the north and in the area stretching towards Stockholm and further to the Finnish border. Sweden and Norway together account for 15% of the total project benefits.

Another important indicator to look at is the regional GDP. The pattern of trade is decisive for the magnitude of GDP effects. The regions that trade intensively using the routes that are being upgraded are likely to gain a lot, while other regions may even suffer losses from the reallocation of trade flows. Figure 4.7.2 displays the predicted distribution of GDP effects. It is easy to notice that the spatial pattern is not different from the welfare impacts in Figure 4.7.1. A somewhat different pattern could be expected if we took account of the infrastructure charges and the corresponding revenue collection and redistribution.

In the absence of revenue flows, the main factor that makes GDP effects and welfare effects differ is the capital mobility. We would like to discuss this point in detail for the case under study by comparing the results from alternative model setups.

Figure 4.7.3 illustrates the point made in the previous section that the GDP effects and the welfare effects roughly coincide in the absence of capital flows (panel *a*), while a wedge arises between the two if we allow for capital mobility (panel *c*). In the basic model, the only difference between regional income and GDP, the international transfers, are fixed in real terms. In the case of the model with mobile capital, however, regional factor payment contains an additional amount of $(K_r^e - K_r) \cdot \tau$, which is not fixed. If the amounts of capital moving internationally are small (as is the case in our experiment), the loss of some domestic factor income and the gain from foreign factor ownership roughly cancel out, and the welfare response stays close to the prediction of the basic model. The GDP figures, however, reflect the introduction of capital mobility in that the range of predicted values expands notably (panels *b* and *c*). Both negative and positive effects become stronger.

Figure 4.7.1. Prediction of regional welfare effects for 2020 with Model 3

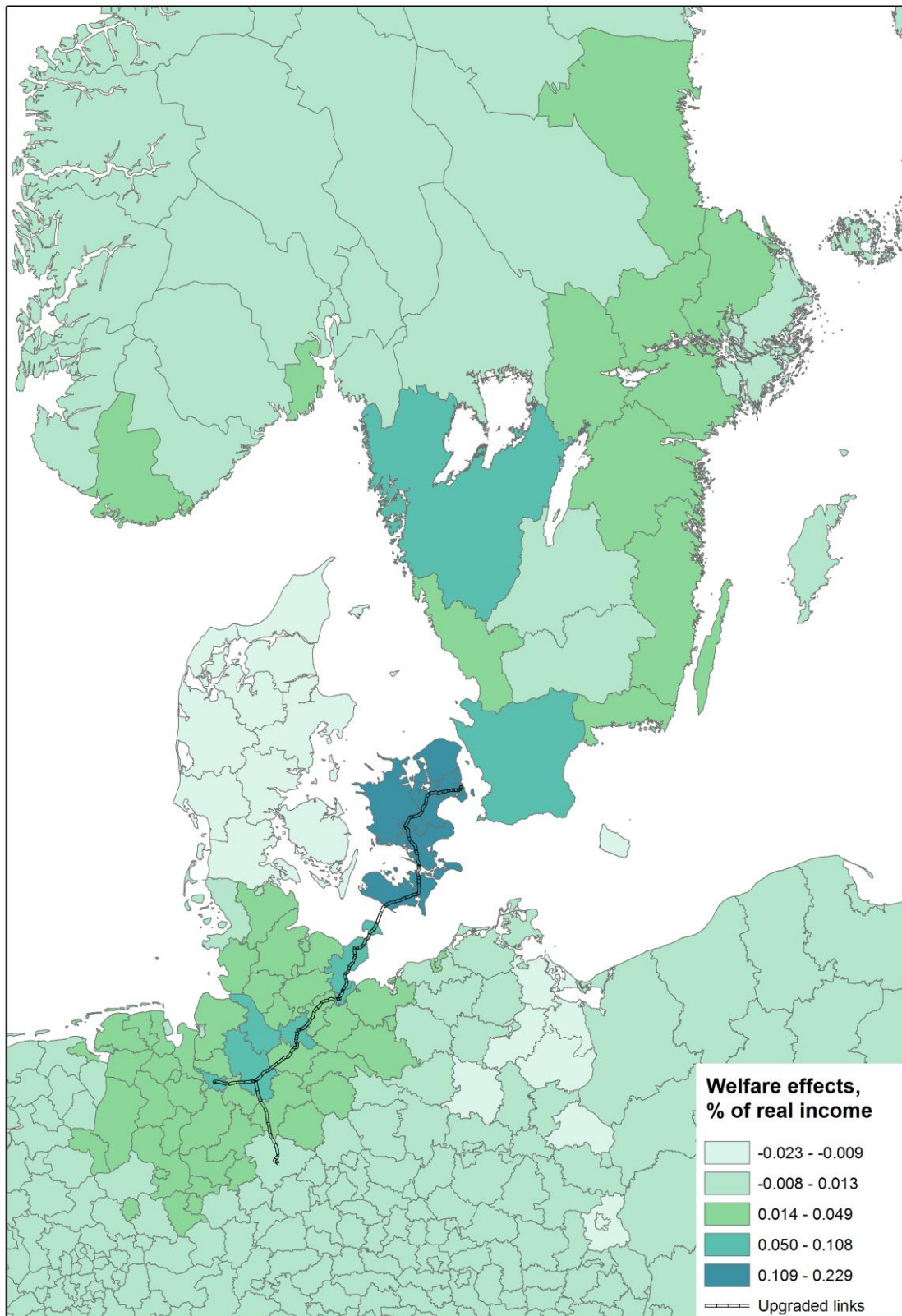


Figure 4.7.2. Prediction of regional GDP effects for 2020 with Model 3

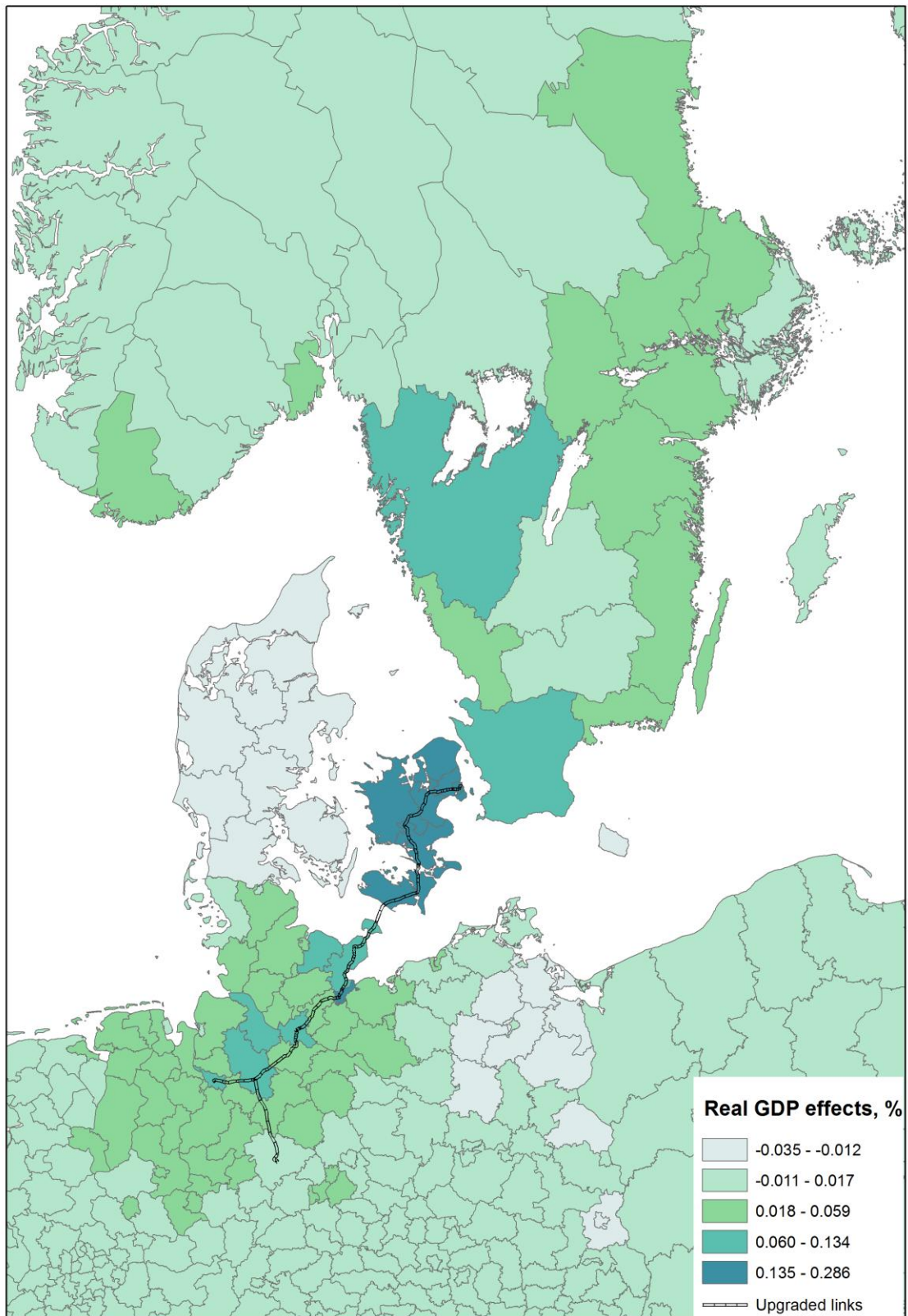


Figure 4.7.3. Comparison of different model runs

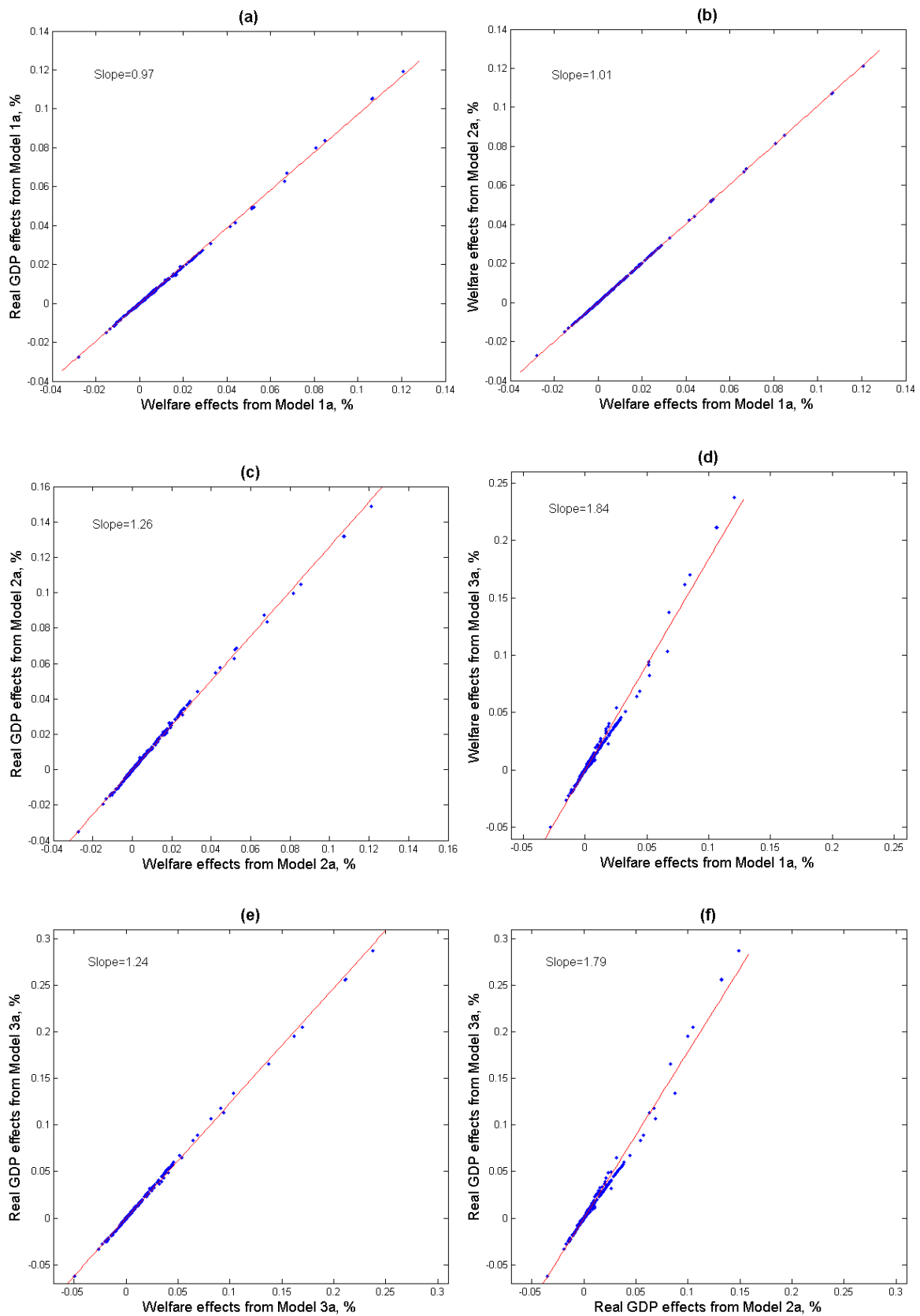
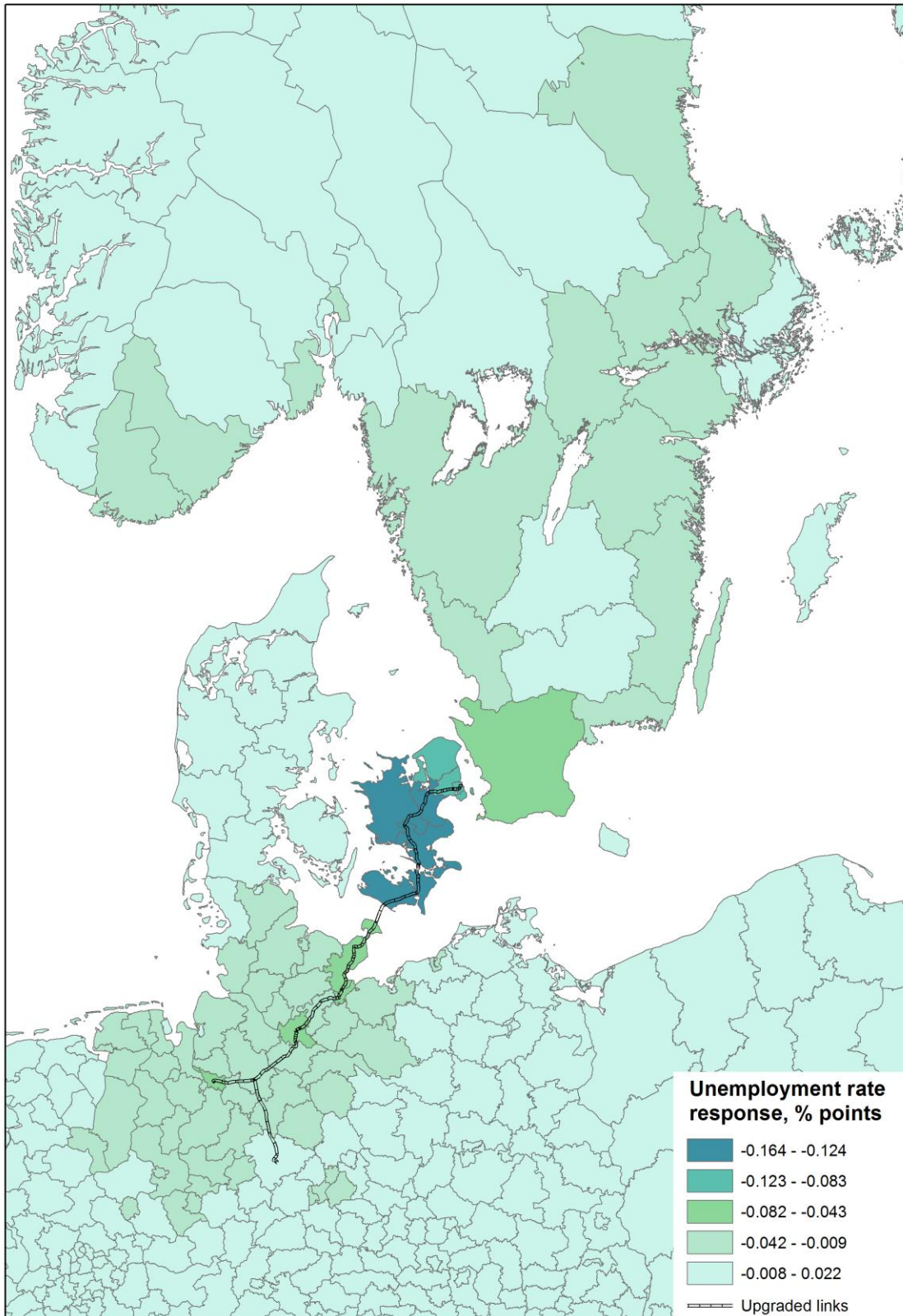


Figure 4.7.4. Prediction of unemployment effects for 2020 with Model 3



As noted above, the reason for this effect is the wider scope of production possibilities of firms. The size of this effect depends on the assumed share of mobile capital in the factor income. The average value of this share is 20-25%, so according to Eq. (4.3.11) we can expect the change in the regional capital stock to be in the order of one quarter of initial GDP response. Noteworthy, panel *c* shows that the real GDP impacts are scaled on average with a factor 1.26. Columns 6 and 7 of Table 4.7.1 illustrate this finding.

Further extending the model to allow for labour market imperfection appears to be important also for welfare effects prediction (see columns 4 and 5 of Table 4.7.1, and panel *d* in Figure 4.7.3). The range of computed values expands further in comparison to the model with factor mobility only. The estimated slope coefficient is equal to 1.8. Quite importantly, the effects on real income and real GDP are related in a similar way, as in the case of the model with factor mobility only (see panel *e*). Note that this multiplier is much smaller for the Danish regions that have the additional revenue from charges in transport as the primary source of welfare improvement.

Columns 7 and 8 of Table 4.7.1 further document the effect of wage rigidity assumption for GDP prediction. We can actually see that German regions are affected less strongly in relative terms than Danish and Swedish regions. Building the ratios from the numbers in the two columns gives 1.5 on average for Germany and 1.9 for Denmark and Sweden. The explanation for this fact is the difference in the wage curve elasticities (-0.032 for Denmark, -0.046 for Sweden, -0.092 for Germany). We already noted in the previous section that more wage rigidity means a stronger response of the regional GDP to the trade cost reduction.

Regional unemployment rate responses are displayed in Figure 4.7.4. The pattern is almost identical to that of GDP effects. The highest impact is predicted for the Storstrøms Amt region in Denmark (-0.16 % points).

One of the criteria determining the inclusion of an infrastructure project into the priority list of the European transport policy is the presence of “European added value”, that is, benefits to countries (EU members) other than those where the project is built. In the case of Fehmarn Belt project, we can identify quite substantial benefits for Sweden, and some small positive spillover effects for Belgium and the Netherlands. The presence of these effects could be a reason for investing parties (Denmark and Germany) to ask for the financial involvement of the European Community. The size of the potential annual subsidy compensating for the generated spillovers could be evaluated on the basis of the size of

generated welfare effects accruing to other members. Based on our calculations with *Model 3*, this would amount to €28 mln or 0.5% of the project cost per annum. Compared to the annual rate of return to the investors (sum of welfare effects for Germany and Denmark, as a share of project cost), which is equal to 8%, the amount of the potential subsidy is not critical but might still be a matter of the political debate.

Finally, one issue of constant political concern in the EU is a problem of promoting regional cohesion. A policy that creates additional welfare in relatively rich regions at cost of poorer regions would be violating this objective. In our case, correlation analysis suggests that there is no strong evidence of violation of cohesion objective. For the extended model, the correlation between reference GDP per capita and percentage increase of employment level is equal to -9.6% . The correlation coefficient between the reference GDP per capita and welfare change due to policy implementation is around $+10\%$ for all three models. Approximately equal correlation coefficients are found if we substitute real income effects with effects on real GDP. This is obvious, given strong correlation between real GDP and real income effects, presented in the Figure 4.7.3.

4.8. Summary

In this chapter, we have introduced regional employment response as well as a certain degree of factor mobility into a static SCGE model used to study the effects of transport policy measures. Labour market was modelled by specifying a wage curve for each region in the study area. The country-specific wage curve elasticity values were taken directly from the studies reporting such estimates.

The implications of these assumptions were first checked using a set of sensitivity tests. We found that the numerical results of the model are substantially influenced by the introduction of these additional elements. In particular, the size of the predicted indirect effects increases considerably. The direction of change and the order of magnitude is plausible and can be intuitively verified. This implies the importance of incorporating these assumptions for the purposes of transport project evaluation. The calculations using the updated methodology were demonstrated on the example of the analysis of the *Fehmarn Belt railway axis* project.

Chapter 5. Forward looking dynamics in spatial CGE modelling

This chapter takes the basic model of Bröcker (1998c) as a starting point and sets up a dynamic equilibrium framework by assuming households to maximise a utility functional over time, taking their respective intertemporal budget constraints, prices and interest rates varying over time and space into account. Similarly, firms maximise present firm values. Response of capital stocks to shocks is smoothed by assuming the existence of adjustment costs for the capital stock. Like in the static model of the previous chapter, we assume monopolistic competition in the tradables sector. Because of increasing product diversity on the dynamic equilibrium path, the model belongs to the category of semi-endogenous growth models in the sense of Jones (2005).

In the next section, we shortly review the literature on dynamic CGE modelling. We proceed by specifying the spatial dynamic CGE model in Section 5.2. The two consecutive sections describe the solution algorithm and the calibration procedure. The results of numerical experiments are presented in Section 5.5. Section 5.6 concludes.

5.1. Selected literature review

Many early CGE models were static in nature, i.e. they were used to evaluate the effects of policy shocks by comparative static analysis. Although the limitations of this approach were immediately obvious in certain applications, such as tax policy analysis, the methodological problems associated with tracing out the dynamic path of the modelled economy turned out to be substantial and not easy to solve. That is why the explicit considerations of intertemporal efficiency and equilibrium started to appear in the CGE literature much after the first contributions of Johansen and his followers.³⁹

Before the appearance of fully dynamic models, however, some shortcut methods were developed. The first approach, employed e.g. by Sheshinski (1978), Kotlikoff (1979), and Summers (1981) in their numerical exercises with an extended optimal savings model, limited itself only to finding a solution for the position of the economy in its long-run steady state. In the steady state, by construction, the role of expectations and the process of economic adjustment could not be considered. However, this approach could be used to

³⁹ Short surveys of intertemporal CGE modelling are provided, for example, by Dixon and Rimmer (2002), and Brunner and Strulik (2002). A more comprehensive review of this literature can be found in Ginsburgh and Keyzer (2002).

infer the long-run effects of the changes in the economic environment, including most fiscal policies.

The solution for the dynamic transition path connecting the before- and after-shock steady states, presents much more imposing problems than finding the single equilibrium, because of the interdependencies between the values of variables at different points in time. The complexity of the exercise can however be allayed by making a simplifying assumption that economic agents behave as if economic conditions were not changing. This assumption of “myopia” or “static expectations” allows solving for the dynamic path of the economy recursively, year after year, without regard to the impact of future conditions on current behaviour.

Miller and Upton (1974) provided perhaps the first dynamic simulations based on a life cycle model assuming static expectations. Several widely cited CGE models employing this type of assumption are Fullerton et al. (1978, 1983), Goulder et al. (1983), and Ballard et al. (1985). There, the static equilibria are connected to each other through capital accumulation. Each single-period equilibrium calculation would begin with an initial capital service endowment. Savings in the current period would augment the capital service endowment available in the next period. In the base-case sequence, the economy is assumed to be on a balanced growth path, where the capital endowment grows at the same rate as the effective labour force. The alternative dynamic sequences are compared by calculating the present value of the stream of welfare gains, as measured by equivalent or compensating variation.

Non-recursive specifications involving forward-looking expectations can be traced back to dynamic economy-wide planning models (e.g. Adelman and Thorbecke, 1966). A feature of dynamic equilibrium in these linear models was a requirement of intertemporal consistency of the capital structure. However, as in other Leontief-type models, price-responsive behaviour was given almost no role. An early example of a non-recursive model with price-responsive behaviour is Dervis (1975). The later development of modern, non-recursive CGE models can be followed through Chao (1982), Lipton and Sachs (1983), Auerbach and Kotlikoff (1983), Ballard and Goulder (1985), Bovenberg (1985), and Goulder and Summers (1989).

Beyond the usual differences in research focus and assumptions about particular markets, two types of dichotomies can be traced in this literature. First, the forward-looking households can be modelled either using a Ramsey (1928) concept of an infinitely lived agent

(ILA), or through the overlapping generations (OLG) approach stemming from Allais (1947). OLG models are preferable when important intergenerational issues have to be highlighted, which is often the case, for instance, in the studies of tax systems. The ILA approach is computationally less demanding. Otherwise, the two approaches are very similar. The second type of dichotomy concerns the numerical approximation strategy employed, meaning either a complete linearization around the steady state or a search for a nonlinear solution of a model.⁴⁰

Auerbach and Kotlikoff (1983) present the first “life cycle dynamic simulation model” that numerically solved for the economy’s path under the assumption that households (modelled by the OLG approach) and firms rationally take account of future changes in economic conditions. Auerbach et al. (1983) and Auerbach & Kotlikoff (1985) are more elaborate versions of the same model. The consequent summary of this model development contained in Auerbach and Kotlikoff (1987) is one of major contributions that made dynamic CGE models a widely used instrument for economic policy analysis.

The agents in the Auerbach-Kotlikoff model have *perfect foresight*: they make decisions based on correct expectations of future economic variables. The authors admit that the assumption of perfect foresight is an extreme one, but argue that it appears to be a useful benchmark for analyzing behaviour because deviations from rationality are not likely to be systematic. In contrast, the assumption of myopic expectations would imply that all households are irrational in a particular way.

The economy in Auerbach and Kotlikoff (1987) is composed of three aggregate sectors: government, household, and industry (thus, the multisectoral production structure of planning models is abandoned). The household sector is, at any time, made of fifty-five overlapping generations of individuals that differ only in labour endowments. The households maximize their lifetime utility, made of consumption and leisure, subject to individual budget constraints. Firms employ capital and labour and do “smooth” investment decisions taking the adjustment costs into account, as in Abel (1981) and Summers (1981). The government sector is modelled in detail enough to allow for taxes of all sorts, investment incentives, and a social security system in the form of retirement benefits. Government actions are restricted by the requirement that the present value of tax collections must equal the present value of public spending. The model is formulated as a big system of nonlinear

⁴⁰ Another major matter of choice would be of deterministic versus stochastic model, but this issue is beyond the scope of this thesis. Our focus is on deterministic models. Dynamic stochastic GE models are reviewed e.g. in Cooley (1995).

difference equations. The iterative solution method employed allows to solve for the before- and after-shock long-run equilibrium of the model, as well as for the transition path that the economy takes between these two steady states.

The OLG framework for tax policy analysis has gained great popularity in applied work, mostly in the fields of public finance, international trade, and environmental policy. Examples include Ballard (1990), Keuschnigg and Kohler (1995), Broer and Lassila (1997), Rasmussen and Rutherford (2004), and Farmer and Wendner (2004).

Another branch of dynamic CGE literature incorporating perfect foresight assumption is based on the ILA approach and can be traced back to Ballard & Goulder (1985) and Bovenberg (1985). Basing upon the earlier analytical studies of Brock & Turnovsky (1981) and Abel & Blanchard (1983), these models were fully intertemporal and examined short-run impacts of policy shocks as well as the transition path to the new steady state. Some models of this type (Bovenberg 1985, 1988; Wilcoxon 1985, 1987) used formulation in discrete time and performed the linearization around the steady state. Other studies, such as Chao (1982), Goulder and Summers (1989), and Bovenberg & Goulder (1991) solved for a nonlinear transition path of the economy.

All contributions mentioned so far dealt with single-country models. The development of consistent dynamic CGE models incorporating several or many regions has been considerably delayed due to additional computational difficulties arising when spatial dimension is added to the model. Three lines of research have to be mentioned here.⁴¹

The first is connected with the development and application of the MS-MRT model (Bernstein et al. (1999), Lau et al. (2002), Böhringer and Welsch (2004)). The model divides the whole world into 10 geopolitical regions connected by endogenous trade. Consumption and investment decisions of the aggregate economic agents are based on rational expectations of future prices. Investment takes place as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous world interest rate such that the marginal productivity of a unit of investment and marginal utility of a unit of consumption is equalized within and across countries. The model is solved in 5-year intervals spanning the horizon from 2000 to 2030. All regions grow at non-uniform rates over this 30-year horizon. Terminal capital stocks are “purchased” by the representative agent in the respective region. The terminal condi-

⁴¹ We omit the discussion of recursive-dynamic multiregional models, such as EPPA (Babiker et al., 2001), FEDERAL-F (Giesecke and Madden, 2003), or MMRF-Green (Adams et al., 2000).

tion for each region requires that growth rates of investment and consumption are the same in the last period. Thus, there is no common steady state for all regions and no convergence towards it in this model. It is solved as a large mixed complementarity problem in discrete time.

The second branch is based on a computational method proposed by Mercenier and Michel (1994). The basic idea is to solve a large-scale intertemporal decision program directly by mathematical programming techniques instead of solving the system of first-order conditions. The first application of this method for solving a multiregional dynamic CGE model is due to Diao and Somwaru (2000). There are eight macro-regions in the model. Firms and households are characterized by perfect foresight. Household's income is consumed or saved in the form of equity in domestic firms or foreign bonds. Home firm equities and foreign bonds are assumed to be perfect substitutes. Through equity purchases by households, the world "pool" of savings is channelled to profitable investment projects without regard to the national origin of savings. Investment is smoothed by the presence of capital adjustment costs. Before any policy shock, the world is evolving along a balanced (equilibrium) growth path. After-shock equilibrium is achieved when the system goes back to the steady state. The terminal period is chosen when the steady state for the main variables is asymptotically approached. The recent application of a similar model is due to Gaitan and Lucke (2007).

Finally, the third approach we would like to mention is represented by the G-Cubed model developed by McKibbin and Wilcoxon (1999). As in the aforementioned models, saving and investment are resulting from forward-looking intertemporal optimization. Unlike most other studies, however, the model parameters are determined by estimation rather than calibration. Furthermore, G-Cubed distinguishes between financial and physical capital. Financial capital is perfectly mobile between regions and sectors, and is driven by forward-looking investors who respond to arbitrage possibilities. Physical capital, in contrast, is immobile once installed. Investment in capital stock is subject to rising marginal costs of installation. The model is solved by linearizing the system of difference equations around the steady state and finding an expression for the stable manifold.

The size of the regions in the mentioned models is very large, while the sectoral detail is considerable. These models are used to study a variety of policies in the areas of environmental regulation, tax reform, monetary and fiscal policy, and international trade. However, regarding the focus of this thesis, these models are not applicable for studying the

spatial effects arising due to transport policy measures, such as infrastructure improvements.

The dynamic models including explicit spatial considerations are very rare. The only spatial dynamic CGE models (models incorporating the spatial features listed in Section 3.1) known to us are Sundberg (2005) and Ivanova (2007). They are at the same time the only dynamic CGE models applicable to the study of regional effects of transport infrastructure policy. However, none of these models includes forward-looking expectations of firms and households in a consistent way.

Sundberg (2005) describes a 3-region experimental model designed to test the implications of alternative assumptions about expectation formation. It is based on the open-economy optimal savings model with iceberg transport costs. Only the households make intertemporal decisions in this model. The solution strategy for the forward-looking formulation employs a direct Newton method as in Gilli and Pauletto (1997). The results are however not entirely plausible. The model formulation involving perfect foresight is characterized by extremely slow convergence and uneven transition of consumption and investment. The reasons for the strange behaviour are not explained, and that is why we consider the task of introducing forward-looking expectations in this paper as incomplete.

Ivanova (2007) presents an extension of the RAEM model for the Netherlands (RAEM 3.0)⁴², which includes all the spatial features of the previous versions (see our discussion in Section 3.4). Current version incorporates backward-looking expectations. The introduction of full dynamics and forward-looking expectations into the model are mentioned as the directions of further development of the model.

5.2. Model formulation

The model we are going to describe is a dynamic version of the basic static model (Bröcker, 1998b) already discussed in Chapter 4. Therefore, we will concentrate on the dynamic elements of the model and only shortly revise other parts. The basic setup is an open-economy version of the Ramsey optimal savings model, combined with the adjustment costs for investment framework, as presented e.g. in Barro and Sala-i-Martin (1995, Ch. 3). Thus, both households and firms make intertemporal decisions in our model, and they are all characterised by perfect foresight. As in the static model, the neoclassical struc-

⁴² A smaller dynamic model called “RAEM-light” has been applied in several research projects in Japan, see e.g. Koike and Kawamoto (2006).

ture is altered by the introduction of monopolistic competition in the tradables sector. The intertemporal problem is formulated in continuous time. Explicit expressions or dynamic equations for consumption and investment are derived in the sections to follow. Model variables are denoted by Latin letters and have a regional dimension. Exogenous parameters mostly do not have a regional index, and are denoted by Greek letters. Exceptions are explicitly mentioned.

5.2.1. Building blocks

5.2.1.1. Consumption

Below we describe the aggregate household formulation of the consumption decision. There are n_r regions in the model. An aggregate household in region r maximizes the present value of a weighted sum of total future flows of utility. Future utility is discounted with a rate of time preference $\rho > 0$. Assuming that utility is given by a constant intertemporal elasticity of substitution function, and the corresponding elasticity value is given by $\varphi > 0$, the present value of total utility is

$$U_{r0} = \int_0^{\infty} \frac{C_{rt}^{1-1/\varphi} - 1}{1-1/\varphi} e^{-\rho t} dt, \quad (5.2.1)$$

where C_{rt} is the Cobb-Douglas consumption index, denoting the amount of composite consumption (consisting of local and tradable goods with constant value shares) in region r at time t .

Before we formulate the corresponding budget constraint, it is necessary to say a few words about the pricing system. Similar to the static setup, the absolute prices are not defined by the equations of the general equilibrium system. We would be actually free to set the time path for one nominal variable and to measure prices at every moment against this chosen numéraire. It proves convenient in our case, if a bit unconventional, to normalize prices at every moment such that the nominal interest rate always equals the subjective discount rate ρ . In addition, the absolute level of prices at one single point in time should be fixed (we will fix the nominal values of asset holdings at $t=0$). Of course, the choice of a numéraire has no effect on the evolution of real magnitudes such as the level of consumption, or relative prices.

Households are competitive in the sense that everyone takes as given the nominal interest rate ρ and the wage rate W_{rt} that is paid per unit of labour service L_{rt} . Each individual is

assumed to provide one unit of labour service inelastically, so that L_{rt} grows with the exogenous rate of population growth n . Labour is assumed to be immobile, and initial population is given by \bar{L}_r .

Households hold assets in the form of shares (ownership claims on firms' net cash flows) or loans. We denote the value of regional assets by A_{rt} . Two forms of assets are assumed to be perfect substitutes as stores of value, so they must pay the same nominal rate of return, ρ . Total income received by an aggregate household is the sum of labour income $W_{rt}L_{rt}$, and financial or interest income (which can be positive or negative), ρA_{rt} . Denoting the regional consumer price index (CPI) by G_{rt} , the consumption expenditure is equal to $G_{rt}C_{rt}$. The flow budget constraint is then⁴³

$$\dot{A}_r = W_r L_r + \rho A_r - G_r C_r. \quad (5.2.2)$$

The savings are thus given by the difference between total income and consumption expenditure, and can be positive or negative. Now, we can formulate an optimal control problem for the aggregate household, of maximizing (5.2.1) subject to (5.2.2), the stock of initial assets \bar{A}_r , and the “no-Ponzi-game” condition (see e.g. Barro and Sala-i-Martin, 1995, p. 62), restricting the households borrowing. The first-order conditions, derived by applying the standard techniques of optimal control lead to the following⁴⁴:

1) The optimality condition for consumption:

$$\hat{C}_r = -\varphi \hat{G}_r. \quad (5.2.3)$$

This condition is known as the Euler equation or the Ramsey rule of optimal saving. It tells that the pattern of consumption is determined by the direction of movement of the CPI, and is opposite to it.

Note that the standard textbook formulation of the Ramsey rule would be $\hat{C}_r = \varphi(i_r^c - \rho)$, i_r^c being the real interest rate in terms of consumables. Note also that i_r^c can be defined as a difference between the nominal interest rate and the rate of change of CPI (inflation rate). The consumers thus tend to postpone consumption the more to the future, the lower the inflation rate and the less they prefer present to future consumption (that is, the lower is ρ). By our choice of numeraire, $i_r^c = \rho - \hat{G}_r$,

⁴³ For the clarity of exposition, we omit time subscripts in subsequent analysis, when no ambiguity results.

⁴⁴ A hat over a variable denotes the log-derivative with respect to time, or the growth rate.

which leads to (5.2.3). This method allows us to dispense with introducing real interest rates explicitly.

2) The transversality condition:

$$\lim_{t \rightarrow \infty} h_{rt} A_{rt} = 0, \quad (5.2.4)$$

where h_{rt} is the dynamic Lagrange multiplier from the optimal control problem, interpreted as the present-value shadow price of income. This condition familiarly states that the value of the household's assets must approach 0 as time approaches the end of planning horizon.

5.2.1.2. Firms

Identical firms located in the region produce gross output by combining capital, effective amount of labour service, local goods, and a composite of tradable goods. These four inputs are denoted by K , \tilde{L} , \tilde{M} , and \tilde{E} , accordingly. Homogenous gross output serves a double purpose: first, it is one-to-one transformed into the local good (without a price mark-up), and secondly it is used as the only input in the production of a variety of tradable goods, the process characterized by increasing returns to scale. Different brands of tradables are sold in the monopolistically competitive market with free entry. These later stages of production process are the same as in the static version of the model and we will repeat the corresponding equilibrium conditions in the next subsection.

The regional gross output M is produced using the Cobb-Douglas technology:

$$M_r = \phi_r K_r^\chi \tilde{L}_r^\theta \tilde{M}_r^\beta \tilde{E}_r^\gamma, \quad (5.2.5)$$

where $\chi + \theta + \beta + \gamma = 1$, and ϕ_r is the fixed regional productivity parameter. The level of productivity may be different across regions, and no technological convergence is assumed. Firms pay the wage rate W_r for each unit of labour, and they buy intermediate inputs of local and tradable goods at respective prices P_r and Q_r . Note that P_r also denotes the price per unit of gross output. In addition to population growth, effective amount of labour input is assumed to grow at an exogenous rate of technological progress x , thus

$$\tilde{L}_{rt} = \bar{L}_r \cdot e^{(x+n)t}. \quad (5.2.6)$$

The evolution of the capital stock employed by the firms is given by

$$\dot{K}_r = I_r - \delta K_r, \quad (5.2.7)$$

where I_r denotes gross investment and $\delta > 0$ is the depreciation rate.

We now assume that investment is costly. Following Abel and Blanchard (1983), we assume that the cost in units of composite good (which is the same as composite consumption good) for each unit of gross investment is one plus an adjustment cost, which is an increasing function of investment-to-capital ratio. By introducing this assumption, we want to rule out an implausible outcome of the basic open-economy version of the Ramsey model, where the adjustment of capital stock is done through an instantaneous jump to the new location.⁴⁵ The total cost of investment, J_r , is thus written as

$$J_r = I_r \left(1 + \frac{\zeta}{2} \frac{I_r}{K_r} \right), \quad (5.2.8)$$

where $\zeta > 0$ is the parameter that expresses the sensitivity of the adjustment costs to the total amount invested.

The value of the firms' net cash flow is thus given by

$$F_r = P_r M_r - W_r L_r - G_r J_r - P_r \tilde{M}_r - Q_r \tilde{E}_r. \quad (5.2.9)$$

We assume that F_r is paid out as dividends to the shareowners (we have to allow for negative dividends to finance negative net cash flows, or, equivalently, to assume that in these cases firms borrow money at rate ρ). The firms make decisions to further the interests of shareholders and seek therefore to maximize the present value of the net cash flows between time points zero and infinity, discounted in accordance with the nominal interest rate. The rate of return to shareholders will then also be ρ at each date.

The firms' problem is thus to maximize the discounted sum $\int_0^{\infty} F_{rt} \cdot e^{-\rho t} dt$ subject to the capital accumulation rule in (5.2.7), and the initial stock of capital, \bar{K}_r . The present-value Hamiltonian for this problem is

$$H = e^{-\rho t} \left(P_r M_r - W_r L_r - G_r J_r - P_r \tilde{M}_r - Q_r \tilde{E}_r + R_r (I_r - \delta K_r) \right), \quad (5.2.10)$$

where R_r denotes the dynamic Lagrange multiplier, in this case interpreted as the current-value shadow price of installed capital. Hayashi (1982) showed that this shadow price equals the market value of a unit of capital stock as long as the production function exhibits constant returns to scale. The first order conditions can be expressed as:

⁴⁵ For the applications of this assumption in the dynamic CGE modelling see, for instance, Devarajan and Go (1998) or Goulder and Summers (1989).

1) The investment function:

$$Z_r := \frac{I_r}{K_r} = \frac{R_r / G_r - 1}{\zeta}. \quad (5.2.11)$$

R_r / G_r here is the ratio of the unit price of installed capital over the replacement (purchase) cost of a unit of capital good, and is known as ‘‘Tobin’s q’’ (Tobin, 1969). The bigger parameter ζ , the smaller is the investment rate, which has direct implications for the after-shock rate of convergence.

2) The equilibrium condition for the capital market:

$$\rho R_r = \frac{\chi P_r M_r}{K_r} + G_r Z_r^2 \frac{\zeta}{2} - \delta R_r + \dot{R}_r. \quad (5.2.12)$$

This equation has a no-arbitrage interpretation. The shareholders get the same rate of return from lending the amount R_r at rate ρ , or from financing an additional unit of capital for the firm. The right-hand side gives the total rate of return of a unit of capital: the marginal product, plus the marginal investment cost saving (when K_r rises for given I_r), less the depreciation at rate δ , plus the capital gain.

3) The standard marginal product pricing rules for the other factors:

$$W_r L_r = \theta M_r P_r \quad (5.2.13)$$

$$P_r \tilde{M}_r = \beta M_r P_r \quad (5.2.14)$$

$$Q_r \tilde{E}_r = \gamma M_r P_r \quad (5.2.15)$$

4) The transversality condition similar to the one from the consumer’s problem:

$$\lim_{t \rightarrow \infty} e^{-\rho t} R_{rt} K_{rt} = 0 \quad (5.2.16)$$

Thus, the value of the firms’ capital discounted to time 0 must approach zero. If this condition fails, then, loosely speaking, the firm is holding valuable capital forever, and thus it can increase the present value of its cash flows by reducing its capital stock.

5.2.1.3. Trade equilibrium

We repeat here the equilibrium conditions of the static model, commenting shortly on the necessary modifications.

Most importantly, we disaggregate the expenditure from the side of final demand, denoted by N_r in the static version, into the sum of consumption and investment demand. As al-

ready mentioned above, we assume investments to be composed of local and tradable goods just in the same way as consumption. The constant value shares of locals and tradables are given by ε and $(1-\varepsilon)$, respectively. The corresponding price index G_r , already used above, is then given by

$$G_r = P_r^\varepsilon Q_r^{1-\varepsilon}. \quad (5.2.17)$$

The value of tradables supply equals the value of gross output less the total value of demand for local goods (that is the local goods part of intermediate demand, investment demand, and consumption demand):

$$S_r = (1-\beta)P_r M_r - \varepsilon G_r (C_r + J_r). \quad (5.2.18)$$

The value of intermediate, investment, and consumption demand for tradables (valued inclusive of transport cost) is equal to:

$$D_r = \gamma P_r M_r + (1-\varepsilon)G_r (C_r + J_r). \quad (5.2.19)$$

The lower-level CES nest for tradables is the same as in the static version (see equation (4.3.17)), with the elasticity of substitution $\sigma > 1$:

$$Q_r = \left(\sum_s S_s P_s^{-\sigma} \tau_{sr}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}, \quad (5.2.20)$$

where τ_{sr} is the transport cost factor, meaning that transferring a good worth of \$1 from s to r requires a transport service worth of $(\tau_{sr}-1)$. We continue to apply the modified iceberg assumption of Chapter 4. The transport service is performed by using up composite tradables in the region of destination.

The value of trade from s to r at mill prices is given by

$$T_{sr} = \frac{S_s (P_s \tau_{sr})^{-\sigma}}{\sum_i S_i (P_i \tau_{ir})^{-\sigma}} \cdot D_r. \quad (5.2.21)$$

Finally, the equilibrium condition for the tradables market is

$$S_r = \sum_s T_{rs}. \quad (5.2.22)$$

We have now finished presenting the basic elements of the model. The next step is to put all elements together into a simultaneous system and to analyse its features. Before we do that, however, there is one point that we would like to stress, namely the interregional linkages on the capital market.

5.2.1.4. The open economy features

In the open-economy setting, the regional assets are not constrained by the regional capital stock. We assume that domestic and foreign assets are perfect substitutes as stores of value. Hence, each must pay the same rate of return. Since loans and shares are also assumed to be perfect substitutes as stores of value, ρ will be the single world nominal interest rate.

Combining the equilibrium conditions (5.2.11)-(5.2.13) and the definitions (5.2.18)-(5.2.19) with the budget constraint for the aggregate household in (5.2.2), we will get the following representation of the regional income balance equation (see Appendix C.1 for the derivation):

$$\dot{A}_r - \dot{K}_r R_r = S_r - D_r + \rho(A_r - R_r K_r) + K_r \dot{R}_r. \quad (5.2.23)$$

This expression has a familiar form of the macroeconomic accounting identity in value terms:

Savings – Investment = Exports – Imports + Factor income from abroad,
if viewed from a dynamic, continuous time perspective.

Capital mobility and international trade allow the value of domestic output to diverge from domestic expenditure. General equilibrium consistency requires, however, that the asset value held by all households in the economy equals the total market value of capital stock:

$$\sum_r A_r = \sum_r R_r K_r. \quad (5.2.24)$$

The equality between the value of assets and the value of installed capital thus holds for the whole world, but not for the individual regions.

5.2.2. The complete system

It is reasonable first to perform some cosmetic transformations in order to get rid of unnecessary variables. Using the first-order conditions in equations (5.2.13)-(5.2.15), the formula for regional output becomes

$$M_r = \mu_r K_r^\alpha \tilde{L}_r^{1-\alpha} \left(\frac{P_r}{Q_r} \right)^\pi, \quad (5.2.5')$$

where $\alpha = \frac{\chi}{\chi + \theta}$, $\pi = \frac{\gamma}{\chi + \theta}$, and $\mu_r = \left(\phi_r \beta^\beta \gamma^\gamma \right)^{\frac{1}{\chi + \theta}}$. This says that the output is a Cobb-

Douglas function of primary inputs, modified by a factor that is increasing in the region's terms of trade.

Introducing $\eta = \frac{\chi + \theta}{1 - \beta}$, the minimal cost corresponding to the production function for gross output is

$$P_r = \tilde{\phi}_r V_r^\eta Q_r^{1-\eta}, \tag{5.2.25}$$

where V_r stands for the unit cost of value-added of primary factors, and $\tilde{\phi}_r = \mu_r^{-\eta} (\chi + \theta)^{-\eta}$.

To link the dynamic equations with the steady state growth rates to be derived in the next section, we will rewrite equations (5.2.7) and (5.2.12). Using the definition of Z_r in (5.2.11), we get

$$\hat{K}_r = Z_r - \delta. \tag{5.2.7'}$$

After minor manipulations (5.2.12) becomes

$$\hat{R} = \delta + \rho - \frac{1}{R_r} \left(\frac{\chi P_r M_r}{K_r} + G_r Z_r^2 \frac{\zeta}{2} \right). \tag{5.2.12'}$$

At this point, we are ready to make a short break and summarize the model described so far. Table 5.2.1 recapitulates the model by listing the endogenous variables and the corresponding equations. In addition to these equations, the system includes the requirements about the initial stocks of regional assets (in nominal terms) and capital: $A_{r,0} = \bar{A}_r$ and $K_{r,0} = \bar{K}_r$. Finally, the terminal values of the variables are controlled by the transversality conditions in equations (5.2.4) and (5.2.16).

Table 5.2.1. Endogenous variables and equations of the dynamic model

Equation	2	3	5'	6	7'	8	11	12'	13	17	18	19	20	21	22	25
Variable	A	C	M	L	K	J	Z	R	W	G	S	D	Q	T	P	V
Type	V	Q	Q	Q	Q	Q	Q	P	P	P	V	V	P	V	P	P

A question we would like to address now is whether this dynamic system possesses a steady state, in which all underlying variables grow at constant rates. If that is the case, the next step would be to find this steady state.

5.2.3. The steady state growth rates and semi-endogenous growth

In the multiregional setup, the steady state should be a situation, in which all variables grow at constant rates that are homogeneous across regions. We can show that such a steady state for our model in fact exists by setting up a system of linear relations between the growth rates that have to hold in this equilibrium. Most of them are derived by taking

the log-derivatives of the model equations and evaluating them at the (hypothetical) steady state (see Appendix C.2 for details). The resulting system is then (the stars denote the steady-state values):

$$\left\{ \begin{array}{l} \hat{V}^* = (\pi + 1)\hat{P}^* - \pi\hat{Q}^*; \\ \hat{Q}^* = \frac{1}{1-\sigma}\hat{S}^* - \frac{\sigma}{1-\sigma}\hat{P}^*; \\ \hat{V}^* + \alpha\hat{K}^* + (1-\alpha)(n+x) = \hat{K}^* + \hat{G}^*; \\ \hat{R}^* = \hat{G}^*; \\ \hat{C}^* - \hat{K}^* = 0; \\ \hat{S}^* = \hat{C}^* + \hat{G}^*; \\ \hat{G}^* = \varepsilon\hat{P}^* + (1-\varepsilon)\hat{Q}^*; \\ \hat{C}^* = -\varphi\hat{G}^*; \end{array} \right. \quad (5.2.26)$$

This linear equations system can be uniquely solved for the growth rates of the eight variables involved, and we report the solution in Appendix C.2. The most important expression is the growth rate of consumption and capital stock:

$$\hat{C}^* = \hat{K}^* = (n+x) \frac{(\sigma - \varepsilon)\theta}{\sigma\theta + \chi\varepsilon + \beta - 1}. \quad (5.2.27)$$

Thus, by a computational argument, we could demonstrate that the steady state of our system exists and is unique in terms of growth rates. Note that it is only possible to solve for the homogenous steady state growth rates, if we assume all behavioural parameters with exception of μ_r to be identical for all regions.

The factor that multiplies $(n+x)$ in (5.2.27) is positive and bigger than 1, if the following stability requirement holds:

$$\sigma > 1 + \frac{\chi(1-\varepsilon) + \gamma}{\theta}. \quad (5.2.28)$$

We can interpret this restriction as a kind of “no-black-hole” condition known from the new economic geography literature. As a thought experiment, assume that we start with a high value of σ and reduce it gradually. Then, as we would approach the value of $1 + \frac{\chi(1-\varepsilon) + \gamma}{\theta}$, \hat{C}^* would approach infinity. This would mean explosive growth. In order to rule out such extreme outcome, we impose the stability requirement above⁴⁶.

⁴⁶ For the assumed values of other parameters in our calculations, this implies σ larger than 3.

Because of the complexity of the model, we lack a proof of uniqueness of the steady-state equilibrium in terms of levels of the underlying variables. However, by the analogy with the Ramsey model, we can expect that the steady state is at least locally unique. The results of the numerical experiments that we did with the model do not suggest that potential non-uniqueness influences the results in any important way. By the same analogy, we can assume that the long-run equilibrium is saddle-path stable. The latter assumption can be checked using the stability requirements to be derived in Section 5.3.

Returning to the solution for the growth rates, it is important to note that $\lim_{\sigma \rightarrow \infty} \hat{K}^* = n + x$, that is, if we drop the assumption of imperfect substitution between the tradable goods, we will get the familiar result of the classical Ramsey model. At the values of σ that are finite the growth rate is scaled up by a term that depends on the parameters of the model, which reflects the presence of an additional source of productivity growth on the dynamic equilibrium path – the expanding variety of tradables. This allows us to link our model to the literature on semi-endogenous growth pioneered by Jones (1995).

As Li (2000) puts it, semi-endogenous growth means that (i) technological change itself is endogenous, but (ii) long-run growth is pinned down by exogenous parameters, the consequence being that straightforward policies do not affect the long-run growth rate. In our case, endogenous technological change has the scale economies in the tradables sector as its source. This is basically the same mechanism as in the famous model by Romer (1990), an important difference being however the absence of an explicit R&D sector in our model. In contrast, the expansion of product diversity is here driven by the economies of variety on the consumer and producer side. The range of available goods is not an explicit variable in our model. However, if we recall expression (4.3.6), the growth rate of product variety can be written as

$$\hat{S}^* - \hat{P}^* = (n + x) \frac{(\sigma - 1)\theta}{\sigma\theta + \chi\varepsilon + \beta - 1}.$$

This expression is similar to the outcome of the models with “weak scale effects”, like Jones (1995), Kortum (1997), and Segerstrom (1998) in that the productivity growth is simply proportional to the growth of effective labour.

The dependence of the growth rate of real consumption and capital on the parameters of the model deserves further explanations. Under the stability condition (5.2.28), it is easy to show that the following relations hold:

- 1) $\frac{\partial \hat{C}^*}{\partial \sigma} < 0$, meaning that the multiplier on $(n+x)$ decreases with increasing σ ;
- 2) $\frac{\partial \hat{C}^*}{\partial \theta} < 0$, $\frac{\partial \hat{C}^*}{\partial \beta} < 0$: the growth rate is reduced if the shares of immobile inputs increase;
- 3) $\frac{\partial \hat{C}^*}{\partial \varepsilon} < 0$, $\frac{\partial \hat{C}^*}{\partial \gamma} > 0$: as a logical counterpart, additional growth is supported by

higher shares of tradables in production and consumption.

Summing up, the growth rate is higher the stronger the pro-variety elements of the model are (lower substitution elasticity, higher shares of tradables in consumption and production).

5.2.4. The transformed system

A standard step now is to switch to a set of variables that are constant in the steady state. We thus return to the model formulation and rewrite the whole model in new (small-letter) notation. We detrend all initial variables using the growth rates from Section 5.2.3 by performing the following transformation (here, for the case of consumption): $c_{rt} = C_{rt} \cdot e^{-\hat{C}^* \cdot t}$. As a result, all transformed variables will be constant in the steady state. In addition, a look at the equations listed in Table 5.2.1 suggests that many of them serve as auxiliary, and can be merged into the other equations, reducing the dimension of the system. In fact, the system boils down to six equations per region in the key variables $a_r, c_r, k_r, r_r, q_r, p_r$.⁴⁷

$$\left\{ \begin{array}{l} \dot{a}_r = \theta p_r \tilde{\mu}_r k_r^\alpha \left(\frac{p_r}{q_r} \right)^\pi - g_r c_r + (-\hat{A}^* + \rho) a_r; \end{array} \right. \quad (5.2.2'')$$

$$\hat{c}_r = -\varphi \hat{g}_r; \quad (5.2.3'')$$

$$\hat{k}_r = z_r - \delta - \hat{K}^*; \quad (5.2.7'')$$

$$\left\{ \begin{array}{l} \hat{r}_r = \delta + \rho - \frac{1}{r_r} \left[p_r \chi \tilde{\mu}_r k_r^{\alpha-1} \left(\frac{p_r}{q_r} \right)^\pi + g_r z_r^2 \frac{\zeta}{2} \right] - \hat{G}^*; \end{array} \right. \quad (5.2.12'')$$

$$q_r = \left(\sum_s s_s p_s^{-\sigma} \tau_{sr}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}; \quad (5.2.20'')$$

$$\left\{ \begin{array}{l} s_r = \sum_s t_{rs}. \end{array} \right. \quad (5.2.22'')$$

⁴⁷ In the following, we introduce $\tilde{\mu}_r = \mu_r \cdot \bar{L}_r^{1-\alpha}$.

The auxiliary variables $z_r, j_r, g_r, s_r, d_r, t_{rs}$ that are needed to construct the expressions above are related to the key variables through equations (5.2.8), (5.2.11), (5.2.17), (5.2.18), (5.2.19), and (5.2.21), transformed in a similar manner. Finally, the initial value conditions $a_{r0} = \bar{a}_r$ and $k_{r0} = \bar{k}_r$, as well as the transversality conditions, have to hold.

In the textbook discussion of the neoclassical growth model, after the dynamic system has been formulated using the variables that are constant in the steady state, the next step normally involves calculating the steady-state values of the transformed variables. Our setup is however different from the textbook models in that we have multiple optimizing agents (one per region) on the consumer side, whose decisions are interconnected. A consequence of this setup is that the steady-state distribution of assets and, consequently, the steady-state levels of consumption depend on the initial assets distribution, as well as on the entire time path of the economy. In other words, the steady state is not independent from the rest of the model. This becomes clearly visible if we evaluate the six equations above in the steady state. In the long-run equilibrium, both sides of the Euler equation (5.2.3") are equal to zero, and thus it is not possible to autonomously solve the system for the steady state values of endogenous variables. We can speak here of the "degrees of freedom" in the steady state that are as many, as there are regions in the model.

In order to handle this difficulty, we will make the dependence of the steady state on the complete time path of the economy explicit. Specifically, we are going to define an endogenous parameter vector that will close the remaining degrees of freedom in the steady state. This parameter vector will itself be determined from the overall stability conditions for the whole dynamic system.

As the Euler equation (5.2.3") cannot be used in the steady state, equation (5.2.2") suggests that either steady-state values of consumption or steady-state values of assets have to be determined from other constraints than the equations of the transformed system. Besides these equations, the model formulation contains the initial value conditions and the transversality conditions. In the next section, we will show how the transversality conditions can be replaced by a well-defined requirement of saddle-path stability of the system. This is the constraint that actually closes the aforementioned degrees of freedom.

We choose to treat the steady-state asset distribution (introduced below) as the parameter vector associated with these degrees of freedom. The results would not change if we used the steady-state levels of consumption in this role. We will now explain the final modifications to the equations of the model.

First, it is convenient to get rid of dynamic equation (5.2.3"), or, more precisely, to replace it by an algebraic constraint. We do this by integrating both sides of (5.2.3") in order to get

$$c_{rt} = \lambda_r g_{rt}^{-\varphi}. \quad (5.2.29)$$

By an analogy with a standard Cauchy problem, λ_r is an integrating constant (i.e., it is time-invariant) that has to be determined from the known values of other variables at some point in time.

It is natural now to try expressing λ_r as a function of steady-state levels of other variables (using values at $t=0$ is not an option, because these are known only for k_r and a_r). Insert (5.2.29) into (5.2.2") evaluated in the steady state (with corresponding values denoted by stars) to get

$$0 = \theta p_r^* \tilde{\mu}_r (k_r^*)^\alpha \left(\frac{p_r^*}{q_r^*} \right)^\pi - \lambda_r (g_r^*)^{1-\varphi} + (-\hat{A}^* + \rho) a_r^*. \quad (5.2.30)$$

Now, note that the following equilibrium relationship on the capital market holds:

$$\sum_r A_r = \sum_r R_r K_r, \text{ or, equivalently, } \sum_r a_r = \sum_r r_r k_r.$$

Introducing vector $\omega = \{\omega_r\}$, representing the steady-state distribution of assets (with $\sum_r \omega_r = 1$), we now write

$$a_r^* = \omega_r \cdot \sum_r r_r^* k_r^*, \quad (5.2.31)$$

which can be inserted into (5.2.30) above:

$$0 = \theta p_r^* \tilde{\mu}_r (k_r^*)^\alpha \left(\frac{p_r^*}{q_r^*} \right)^\pi - \lambda_r (g_r^*)^{1-\varphi} + (-\hat{A}^* + \rho) \cdot \omega_r \cdot \sum_r r_r^* k_r^*. \quad (5.2.30')$$

We can now use λ_r as an endogenous variable in the model, instead of c_{rt} . This variable only plays an auxiliary role, as its dependence on ω is explicit. The formulation is completed by replacing the dynamic equation (5.2.2") in the transformed system by

$$\dot{a}_r = \theta p_r \tilde{\mu}_r k_r^\alpha \left(\frac{p_r}{q_r} \right)^\pi - \lambda_r \cdot g_r^{1-\varphi} + (\rho - \hat{A}^*) \cdot a_r. \quad (5.2.2''')$$

In the steady state, this equation will take the form as in (5.2.30'). We now repeat the equations of the dynamic system again for clarity:

$$\begin{cases}
\dot{a}_r = \theta p_r \tilde{\mu}_r k_r^\alpha \left(\frac{p_r}{q_r} \right)^\pi - \lambda_r \cdot g_r^{1-\varphi} + (\rho - \hat{A}^*) \cdot a_r; \\
\dot{\hat{k}}_r = z_r - \delta - \hat{K}^*; \\
\dot{\hat{r}}_r = \delta + \rho - \frac{1}{r_r} \left[p_r \chi \tilde{\mu}_r k_r^{\alpha-1} \left(\frac{p_r}{q_r} \right)^\pi + g_r z_r^2 \frac{\zeta}{2} \right] - \hat{G}^*; \\
q_r = \left(\sum_s s_s p_s^{-\sigma} \tau_{sr}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}; \\
s_r = \sum_s t_{rs}.
\end{cases} \quad (5.2.32)$$

The result of these manipulations is that we have replaced a dynamic variable c_{rt} by a time-invariant variable λ_r , which reduces the dimension of the problem to be solved. The value of λ_r is determined from the steady-state system given the value of ω . The endogenous parameter vector ω itself is determined simultaneously with the time paths of endogenous variables when all boundary conditions are taken account of.

Finally, similar to the static setup, only relative goods prices are determined by the market clearing conditions (5.2.22"), and one of them is redundant due to Walras' law. Note that we are not free to simply set the absolute value of one price at each time point, because the price level was already determined by fixing the initial values of the household assets ($a_{r,0} = \bar{a}_r$), and by the choice of the intertemporal numeraire (nominal interest rate equal to ρ). Given the solution procedure described in the next section, we still have to fix the value of one price in the steady state. To do this in consistency with the previous assumptions, we define one steady-state price (the price of the local goods in the last region) as an additional endogenous parameter that will be determined from the boundary conditions.

With this, we finalize the formulation of the model and turn to the solution strategy. In the next section, we will determine the type of the mathematical problem we are facing, and will develop an algorithm to solve it.

5.3. Solution algorithm

5.3.1. Problem formulation

In general notation, solving our model means to look for a path $x(t) \in R^{n_x}$ and a vector $v \in R^m$ satisfying a differential-algebraic system of equations:

$$\begin{cases} \dot{x} = \tilde{f}(x, \nu) & (5.3.1) \\ 0 = \tilde{g}(x, \nu) & (5.3.2) \end{cases}$$

and constrained by a set of boundary conditions:

$$\begin{cases} b(x(0), \nu) = 0 & (5.3.3) \\ \lim_{t \rightarrow \infty} x(t) = x^*(\nu). & (5.3.4) \end{cases}$$

For the discussion below it will be convenient to stick to this general notation, which has the following interpretation in our case. Vector x contains the key variables a, k, r, q, p , where a and k are the predetermined state variables, and the rest the “jumpers”.⁴⁸ ν is the endogenous time-invariant vector having as its coordinates the steady-state asset distribution (actually, only its independent elements $\{\omega_2, \dots, \omega_n\}$) and a scalar fixing the price level in the steady state. $\tilde{f} : R^{n_x+m} \rightarrow R^{n_f}$ and $\tilde{g} : R^{n_x+m} \rightarrow R^{n_g}$ are known nonlinear functions, such that $n_f + n_g = n_x$. \tilde{f} contains the equations for capital accumulation (5.2.7"), asset accumulation rules of households (5.2.2"), and the no-arbitrage conditions (5.2.12"). The static equations in \tilde{g} are the contemporary market equilibrium conditions (5.2.20") and (5.2.22").

In addition to (5.3.1) and (5.3.2), two types of boundary conditions have to hold. The first type fixes historically inherited stocks that the agents are unable to change instantaneously. These are the capital stocks in each region and the asset values owned by each aggregate household. In general terms, these conditions can be written as a constraint $b(x(0), \nu) = 0$, with a function $b : R^{n_x} \rightarrow R^\ell$. Note that in total we should come up with $(n_x + m)$ boundary conditions, because we have $(n_x + m)$ endogenous variables at any time point. The remaining $n_x + m - \ell$ degrees of freedom are closed by the second type of boundary conditions, requiring that the system be on a stable path converging to a stationary state x^* . We have written this requirement in a very general form as $\lim_{t \rightarrow \infty} x(t) = x^*$. This is a reference to the transversality conditions in equations (5.2.4) and (5.2.16) that force the initial values of jumper variables to be on the stable path of the nonlinear system. We discuss this requirement more specifically in the next subsections. Note that x^* depends on ν , which we make explicit when necessary.

⁴⁸ Variables k and r enter vector x in logs (corresponding equations (5.2.7") and (5.2.12") describe their growth rates)

The mathematical problem in (5.3.1-5.3.4) is thus a two-point boundary value problem for a differential-algebraic system of equations (DAE), with the extra difficulty that one of the boundary points is at infinity.

We lack a solver for MATLAB, which is our programming environment, that would be able to solve a two-point boundary value problem for a DAE. That is why the problem has to be modified prior to solving it.

We proceed by taking the following steps:

- 1) We transform the DAE system into an ordinary differential equation (ODE) system by numerically solving the static equations (5.3.2) for prices and inserting the result into (5.3.1).
- 2) We transform the boundary condition at infinity into one at a finite horizon using the local stable manifold theorem.
- 3) We solve the resulting nonlinear two-point boundary value problem by a collocation method.

5.3.2. Transforming the DAE system

Looking more attentively at the static equations (5.2.20") and (5.2.22") comprising the \tilde{g} function in (5.3.2), one can realize that they implicitly define prices p and q as functions of dynamic variables a , k , and r . Moreover, there are no explicit dynamic equations describing the evolution of commodity prices p and q . Thus, our strategy is to rewrite the DEA system from the previous section as an ODE system in variables a , k , and r . The prices p and q will be solved for inside the ODE function using a nonlinear equation solver.

We divide the vector of endogenous variables x of length n into two components: vector x_f of length n_f , containing variables a , k , and r , and vector x_g of length n_g , containing only variables p and q .

Reinterpreting (5.3.2) as described above yields the system in the form

$$\begin{cases} \dot{x} = \tilde{f}(x_f, x_g, \nu) \\ x_g = g(x_f, \nu) \end{cases}, \quad (5.3.5)$$

or simply

$$\dot{x}_f = f(x_f, \nu), \quad (5.3.6)$$

where function $g : R^{n_g+m} \rightarrow R^{n_g}$ is analytically not solvable, and function

$f : R^{n_f+m} \rightarrow R^{n_f}$ contains the same equations as function \tilde{f} , and in addition numerically solves for x_g . The dependence of the function f on ν represents the fact that the auxiliary variable λ can only be determined from the system (5.2.32) evaluated at the steady state, and is thus dependent on the parameters in ν .⁴⁹

At $t = 0$, the same boundary conditions $b(x_f(0), \nu) = 0$ have to hold, and we want the system to converge to x_f^* for t tending to infinity. To solve our infinite-horizon problem on a computer, however, we would have to truncate the model at a certain time point. Thus, we have to find a finite-time alternative for the boundary condition (5.3.4).

Two broad approaches to determine such an alternative are compatible with the nonlinear solution strategy. The first is stemming from Auerbach and Kotlikoff (1987) and suggests fixing the terminal values of some of the variables at their steady-state values. As this requirement would have to bind after certain time, there is no assurance, however, that the system will thus converge to a point close to the steady state.

The second method is based on the use of the *local stable manifold theorem* of dynamic systems theory, presented, for example by Irwin (1980). The theorem says that, in general, what is true of the linearized system (in terms of determinacy and stability of equilibrium) is true of the original nonlinear system in some open neighbourhood of the steady state. The application of this theorem for the transformation of the boundary conditions at infinity is presented, for example, in Kehoe and Levine (1990) for the case of overlapping generations model. The useful corollary of this theorem is that the stable subspace of the linearized system is the best affine approximation to the stable manifold of the nonlinear system around the steady state.

The solution to our problem is thus to linearize the original system around the steady state, and then to fix a finite horizon T far enough in the future, such that the linearized version of the model can be used as a good approximation to the original system. From that time point on, we will require the system to move along the stable manifold of the linear approximation towards the steady state. Actually solving for the time path between time points 0 and T is a separate challenging task and we will discuss it in Section 5.3.4.

⁴⁹ In order to solve the steady-state system for the values of λ , one market clearing condition must be dropped, and one price fixed in the way described in Section 5.2.4.

5.3.3. Terminal conditions

Linearizing the system (5.3.6) in x_f at the stationary point x_f^* gives, for any given ν ,

$$\dot{x}_f = f_x(x_f^*, \nu)(x_f - x_f^*), \quad (5.3.7)$$

where $f_x(\cdot)$ is the $(n_f \times n_f)$ Jacobian of f with respect to x_f , evaluated at x_f^* .

The dynamic properties of the linearized system (5.3.7) are determined by the eigenvectors and eigenvalues of $f_x(\cdot)$. We can find an $(n_f \times n_f)$ -matrix $V(\nu)$ of eigenvectors and a corresponding diagonal $(n_f \times n_f)$ -matrix $L(\nu)$ of eigenvalues of $f_x(x_f^*, \nu)$. Let $L_u(\nu)$ denote the diagonal matrix of eigenvalues with positive real parts (unstable), and let $V_u(\nu)$ denote the matrix of the corresponding columns of $V(\nu)$. Let a matrix $V_c(\nu)$ be the complement of $V_u(\nu)$, such that $V(\nu) = (V_u(\nu), V_c(\nu))$. As $V(\nu)$ spans R^n , there is a vector of

constants $\xi = \begin{pmatrix} \xi_u \\ \xi_c \end{pmatrix} \in R^{n_f}$, such that for any time point T

$$x_f(T) - x_f^* = V(\nu)\xi = V_u(\nu)\xi_u + V_c(\nu)\xi_c. \quad (5.3.9)$$

If we want $x_f(T)$ to lie on the stable linearized manifold, we must have $\xi_u = 0$. Thus, one must have

$$V(\nu)_u^{-1}(x_f(T) - x_f^*) = 0, \quad (5.3.10)$$

where $V(\nu)_u^{-1}$ denotes the rows of $V(\nu)^{-1}$ corresponding to ξ_u . This is the transformation of the final boundary condition that we were looking for.

To summarize, we now have the two-point boundary value problem

$$\begin{cases} \dot{x}_f = f(x_f, \nu) \\ b(x_f(0), \nu) = 0 \\ V(\nu)_u^{-1}(x_f(T) - x_f^*) = 0. \end{cases} \quad (5.3.11)$$

With ℓ boundary conditions at the start point $x(0)$, we need exactly $n_f - \ell + m$ boundary conditions at the horizon T , in order to have $n_f + m$ boundary restrictions determining the n_f -vector $x_f(t)$ and the m -vector ν . Thus, if the number of rows in $V(\nu)_u^{-1}$ turned out to be more than $n_f - \ell + m$, the system would be globally unstable, and if it were less than $n_f - \ell + m$, the system would be underidentified, and thus its properties undetermined. In both cases, it would be of no interest to further try solving the model. We will have to rely

upon a computational argument here to demonstrate that the number of positive eigenvalues is exactly $n_f - \ell + m$.

5.3.4. Solving the ODE system

The final step is to solve the two-point boundary value problem. In theory, there exist quite a few techniques that could do this job. Many of them are treated in detail in Judd (1998) and Press et al. (2007). However, most of the widely cited methods are not suitable for the complex and high-dimensional problem of a kind we are facing here. Nevertheless, for the sake of completeness, we will now shortly describe the most popular techniques of shooting, relaxation, and projection methods.

In general, the *shooting method* is a method for solving a boundary value problem by reducing it to the solution of an initial value problem. The values for all dependent variables at one boundary are chosen. These values have to be consistent with boundary conditions for that boundary only, but otherwise are set to depend on arbitrary free parameters whose initial values are guessed. The differential equations are then numerically integrated towards the other boundary, where the discrepancies from the desired final values are determined. The strategy is then to find the adjustment of the free parameters at the starting point such that the discrepancies at the final point are minimized (Press et al., 2007).

Because single (forward) shooting, i.e. the numerical evaluation of a trajectory from a guessed initial value over the whole time interval $[0, T]$, yields arbitrarily large deviations from the desired solution, that are amplified exponentially with time, Lipton et al. (1982) propose *multiple shooting* for non-linear boundary value problems. Multiple forward shooting subdivides the evaluation on $[0, T]$ into several evaluations on subintervals. On each subinterval the initial deviation still grows exponentially but only on a small time scale so that the maximum error is kept small. The algorithm requires choosing a set of mesh points $t_0 < t_1 < t_2 < \dots < t_k$, where at each t_i an initial guess must be made. Particularly, $t_0 = 0$ and $t_k = T$. Starting with guessed values on each t_i the method applies a forward integration procedure for each interval $[t_i, t_{i+1}]$, where the deviations between the shot value and the guessed value are minimized using an update formula.

The next approach is to use the original idea of Shampine and Gordon (1975) to transform an inherently unstable boundary-value problem into a well-behaved initial value problem by the time reversal of the dynamic system. The methods of *reverse shooting* (Judd, 1998)

and *backward integration* (Brunner and Strulik, 2002) apply the time reversal to saddle-point dynamics, which means they exploit the numerical stability of an unstable but attractive manifold in a saddlepoint-stable system. If the state of the system at a future time point (the steady state) can be numerically approximated, the problem can be solved by recursively moving backwards in time to obtain any optimal state in the past up to the initial state at $t=0$. Brunner and Strulik (2002) show that in this way the initial error is reduced exponentially. The difference between the two methods is that backward integration can determine the optimal terminal time T endogenously, while reverse shooting only relies on an exogenous guess.

The use of the shooting methods is, however, not appropriate in our case, because of the following two features of the model. First, the steady state cannot be solved for independently. Thus, one cannot produce a good guess of the new steady state in the shock scenario. This will add to the instability of the forward shooting method, and will undermine the backward stability of the reverse shooting method. Second, the regional dimension of the model may become arbitrarily large. The problem to solve will then be of a very high dimension. The shooting methods simply lack instruments to ensure convergence and required accuracy under these circumstances (Judd, 1998).

Relaxation methods use a quite different approach. The differential equations are replaced by approximate finite difference equations (FDE) on a chosen mesh of points. For our example, writing $x_f^i := x_f(t_i)$, for short, a possible approximation is $x_f^{i+1} \approx x_f^i + f(x_f^i, \nu)(t_{i+1} - t_i)$. Such approximate FDEs are formulated on k points, and this whole set of equations is augmented by the boundary conditions. The relaxation method determines the solution in terms of the values of ν and the values of x_f^i at all $k+1$ mesh points by starting with a guess, and improving it iteratively by the multidimensional Newton's method. As the iterations improve the solution, the result is said to *relax* to the true solution (Press et al., 2007).

For every interval between the mesh points, the relaxation method thus produces a linear approximation of the time paths of the endogenous variables. It will thus always be inferior in terms of accuracy to the method of our choice, which is based on the polynomial approximation. We now turn to the discussion of this method.

Judd (1992) introduced *projection methods*, which are also known as *weighted residual methods*, to the economics profession. Whereas the previously mentioned methods focus

on computing values of a solution at specified values of t , projection methods take a functional analytic view of a problem. These methods are much more general and can be applied to a wide class of dynamic problems.

For our case, based on (5.3.6), we may define $\Lambda x_f \equiv \dot{x}_f - f(x_f, \nu)$. Λ is an operator, a function that maps functions to functions. The domain of Λ includes all C^1 (once continuously differentiable) functions. The task of solving the ODE system can now be viewed as a problem of finding a vector $x_f(t)$ of C^1 functions that satisfy the boundary conditions and are mapped by Λ to the zero function. The general approach, based on the Stone-Weierstrass theorem, is to use the approximation by a finite sequence of polynomials. Any time-dependent endogenous variable, such as variable k contained in vector x_f , could then

be represented, for example, as $k(t; e) \equiv \sum_{j=1}^{n_j} e_j h_j(t)$. The mappings h_j here contain simple

functions, frequently Chebyshev polynomials, and e is a vector of unknown decomposition coefficients. This approximation is substituted into some type of a residual function. Projection methods then choose values in e to minimize the residual function. Based on the criterion of good fit employed, Judd (1992) distinguishes between the least-squares approach, method of moments, collocation, Galerkin method, and subdomain method.

We use the *collocation method* provided by the MATLAB routine `bvp6c` described in Hale and Moore (2008). Collocation method finds a functional (piecewise cubic polynomial) approximation of the time path of our system, which exactly satisfies the differential equations at some chosen points in $[0, T]$ (so-called mesh points). The solver automatically chooses the mesh points, and extends or reduces its number, depending on the size of the residual. This method provides a uniform prescribed accuracy throughout the computational interval. Moreover, this method allows to solve for the endogenous time-invariant parameter vector ν , and to handle discontinuous changes in the values of exogenous parameters (as in the case of a time lag between policy announcement and realization).

Though our problem has a high dimension, the solution procedure is relatively fast and the precision is high. We feel however that performance could be improved if the first step in the solution algorithm is avoided and one directly solves a two-point boundary value problem for a DAE rather than an ODE.

5.4. Data sources and parameter calibration

5.4.1. Exogenous parameters

The share parameters $\chi = 0.19$, $\theta = 0.235$, $\gamma = 0.285$, $\varepsilon = 0.6$ are calculated from the aggregate GTAP data (Center for Global Trade Analysis, 2005). The depreciation rate δ is set at the value 0.05 per year. The elasticity of substitution among brands of tradables is set at the same level as in the static model, namely $\sigma = 12$. The elasticity of intertemporal substitution is commonly assumed to lie between 0 and 1. We choose the value of 0.8.

The default value of the parameter of the adjustment cost function $\zeta = 6$ is chosen after considering the implications for the value of the “Tobin’s q” and the convergence speed, following the lines of Barro and Sala-i-Martin (1995, p. 122-123). The econometric estimates of the “Tobin’s q” (e.g. Blanchard et al., 1993) usually do not exceed 1.5, while the plausible speed of convergence for the capital stock (calculated using the eigenvalues of the linearized system (5.3.7)) should not be higher than 0.05 per year. With chosen parameterization, both criteria are fulfilled for the test model described in Section 5.5.

Iceberg costs τ_{rs} have to come from the calibration of the static model (see Sections 4.5.3-4.5.4). Transport policy shocks are introduced also in the same way as in the static model (Section 4.5.6). For the test model runs the values of these parameters are freely assumed.

Two important parameters that remain to be specified are the rate of growth of efficient labour stock ($n + x$), and the rate of time preference ρ . Equation (5.2.27) suggests a link between the growth rate of the efficient labour and the real growth rate of consumption:

$$\hat{C}^* = (n + x) \frac{(\sigma - \varepsilon)\theta}{\sigma\theta + \chi\varepsilon + \beta - 1}$$

We choose to assume $\hat{C}^* = 0.02$ per year and calibrate $(n + x)$ accordingly.

Finally, the Keynes-Ramsey rule at any point in time is

$$\hat{C}_r = \varphi(i_r^c - \rho),$$

where $i_r^c = \rho - \hat{G}_r$ is the real interest rate in terms of consumables. Given that we have already fixed \hat{C}^* and \hat{G}^* , the choice is between assuming a value for i_r^c or for ρ . We choose to fix the real interest rate at the level of 0.05 per year and to calibrate ρ accordingly.

5.4.2. Initial steady state

It remains to specify region-specific parameters $\tilde{\mu}_r$ and initial values \bar{a}_r and \bar{k}_r . This is done by inserting data characterizing the base year (benchmark) into the model equations.

We make a commonly used assumption that at the time point $t=0$ (which may correspond to a past, current, or future year) the model is in its steady state. Hence, all variables in the equations to follow have to be thought of as evaluated at this initial steady state. We omit the notation with explicit time indices and stars, however, for the clarity of exposition.

In Section 5.2.4, we have introduced a parameter vector ω governing the steady-state distribution of assets among regions as endogenous – it is to be determined together with the time paths of the model variables. However, if we assume that in the base year the system is in the steady state, we can make use of the international trade data to calibrate the distribution of assets without solving for the dynamics.

Specifically, (5.2.18)-(5.2.19) suggest

$$d_r - s_r = g_r c_r + g_r j_r - (\theta + \chi) p_r m_r. \quad (5.4.1)$$

Next, the budget constraint (5.2.2"), taken in the steady state, suggests

$$\theta p_r m_r - g_r c_r + \rho a_r = \hat{A}^* a_r. \quad (5.4.2)$$

At the time point $t=0$, $(d_r - s_r)$ is nothing else as the benchmark regional trade deficit TD_r , the value of which we can compute for any needed base year from the trade statistics (e.g. by distributing the national trade deficit among regions, if better data is missing).

Combining (5.4.1) and (5.4.2), we get

$$a_r = \frac{1}{(\rho - \hat{A}^*)} (TD_r - g_r j_r + \chi \cdot p_r m_r). \quad (5.4.3)$$

The productivity parameter $\tilde{\mu}_r$ (time-invariant) is determined from the requirement that at $t=0$ the base-year regional GDP value is reproduced, which is equal to the primary factors' income. No technological convergence is assumed. Based on (5.2.5'), we have

$$\frac{GDP_r}{\theta + \chi} = p_r \tilde{\mu}_r k_r^\alpha \left(\frac{p_r}{q_r} \right)^\pi \quad (5.4.4)$$

Introducing (5.4.3) instead of (5.2.2"), and adding equation (5.4.4), we have our transformed system from Section 5.2.4 with equal number of equations and variables (after in-

serting expressions for auxiliary variables) and can solve for the values of $\tilde{\mu}_r$, a_r , k_r , r_r , q_r , and p_r . We formulate this steady-state system below for the sake of completeness:

$$\left\{ \begin{array}{l} (\rho - \hat{A}_r^*) a_r = TD_r - g_r j_r + \chi \cdot p_r m_r; \\ \frac{GDP_r}{\theta + \chi} = p_r \tilde{\mu}_r k_r^\alpha \left(\frac{p_r}{q_r} \right)^\pi; \\ \zeta \cdot (\hat{K}^* + \delta) + 1 = r_r / g_r; \\ 0 = \frac{1}{r_r} \left[p_r \chi \tilde{\mu}_r k_r^{\alpha-1} \left(\frac{p_r}{q_r} \right)^\pi + g_r z_r^2 \frac{\zeta}{2} \right] - \delta - \rho + \hat{G}^*; \\ q_r = \left(\sum_s s_s p_s^{-\sigma} \tau_{sr}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}; \\ s_r = \sum_s t_{rs}. \end{array} \right. \quad (5.4.5)$$

The solutions for a_r and k_r give the boundary values \bar{a}_r and \bar{k}_r . The values of endogenous variables r_r , q_r , and p_r can be used as initial values for the solver at the later solution steps. The values of ω_r that can now be computed from (5.2.31), can later also be used as initial values for the solver.

5.5. Numerical experiments

5.5.1. A test model

We first demonstrate the functioning of the model using a test setup with three symmetrical regions. We assume all regions to have initially equal values of GDP ($GDP_r = 1$), and zero trade deficits. The matrix of trade cost mark-ups is assumed to have the following symmetric form:

$$\tau_{rs} = \begin{pmatrix} 1.05 & 1.2 & 1.2 \\ 1.2 & 1.05 & 1.2 \\ 1.2 & 1.2 & 1.05 \end{pmatrix}.$$

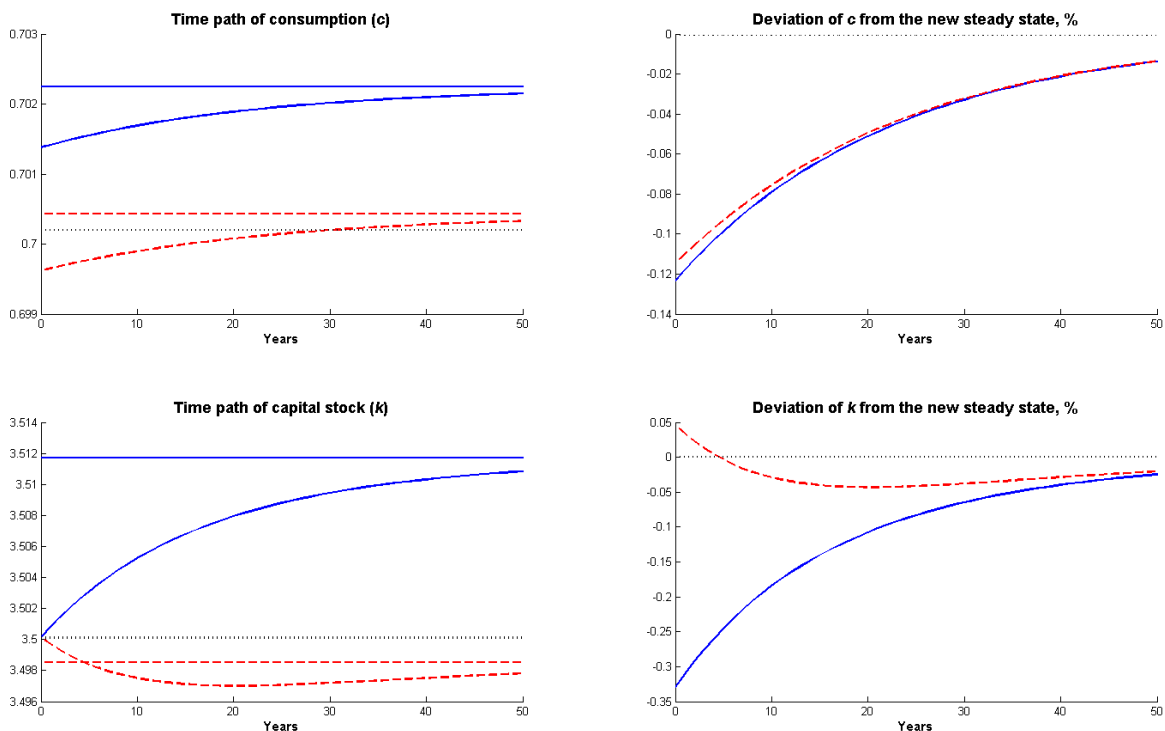
The experiment that we will perform is the simulation of an infrastructure improvement, leading to a 5% trade cost reduction between regions 1 and 2 in both directions (the corresponding values of τ_{rs} thus reducing to 1.19). As before, we will only look at the phenomena arising after the project completion, thus ignoring the effects during the construction

phase. In the first set of model runs, the infrastructure improvement is announced and realized at time $t = 0$ (we separately discuss the announcement effects later in this section). Due to this shock, the spatial symmetry will be destroyed. We can use the diagrams of the time paths of model variables to demonstrate the subsequent adjustment process predicted by our model. We will discuss the development of real quantities, such as consumption and capital stock, as well as of the “Tobin’s q ” and the trade flows.

In Figure 5.5.1, the results concerning consumption and capital stock are displayed.⁵⁰ The (equal) responses of the variables in the two directly affected regions are plotted using the solid lines, while the response of the indirectly affected third region is plotted using the dashed lines. Moreover, we display the post-shock steady state values of the respective variables using the solid and dashed straight lines. The pre-shock steady state values (common to all regions) are displayed using the dotted lines.

The adjustment process of consumption and capital stock is characterized by smooth convergence towards the steady state. As should be expected, the level of consumption jumps at $t=0$ (when the shock occurs), after which the convergence process begins. In contrast, the time path of capital stock starts at the predefined level of k_0 , which in our test setup is

Figure 5.5.1. Test model results: consumption and capital stock



⁵⁰ Note that we are looking at the transformed variables as defined in Subsection 5.2.4, because the original variables are growing at exponential rates and their graphs are hard to analyse.

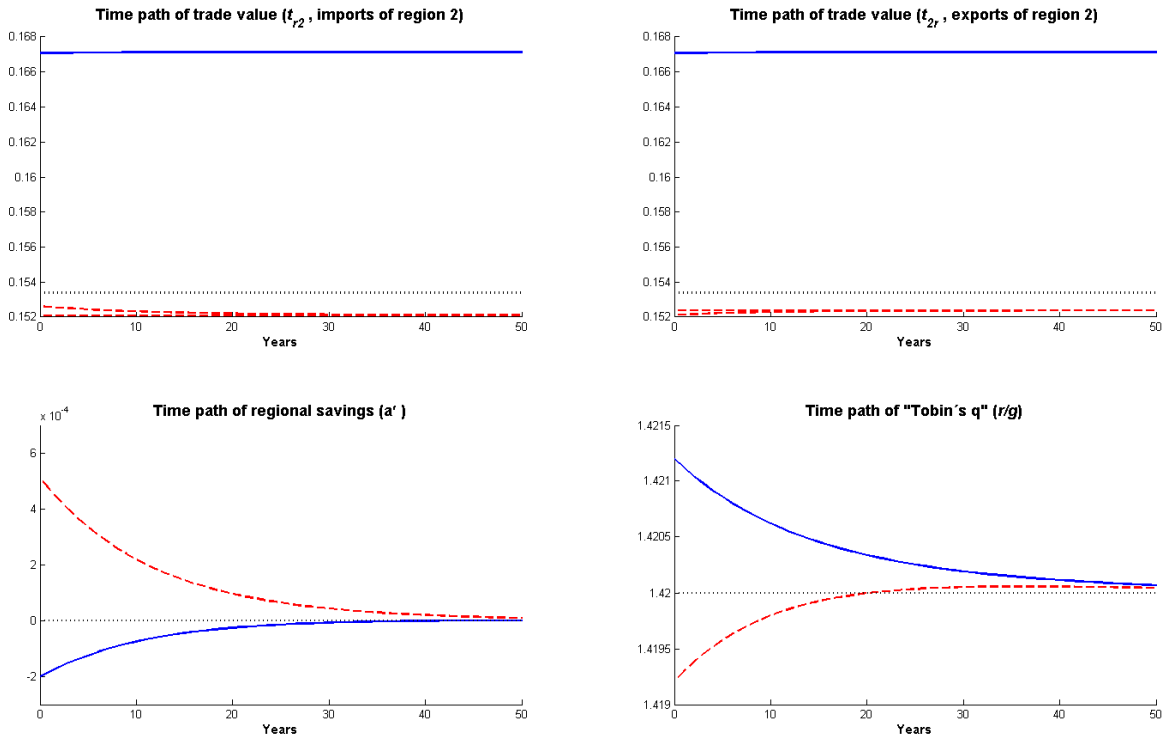
common to all regions. Under the chosen parameterization, it takes about 20 years for consumption and capital to cover half of the distance to the new steady state. Main parameters that control the speed of convergence are the elasticity of intertemporal substitution φ and the parameter of adjustment cost function ζ . The results of the sensitivity analysis that we performed with respect to the values of φ and ζ (not reported here) are straightforward. The speed of convergence is quite sensitive to large changes in these parameters, which suggests that a search for the most appropriate estimates for the study area under investigation (in the case of real policy analysis) is desirable.

The simulated reduction of trade costs allows all regions to increase consumption in the new steady state. However, immediately after the shock, the consumption in the directly and indirectly affected regions jumps in the opposite directions. In the case of directly affected regions 1 and 2, the biggest effect comes through the reduced prices of tradable goods. For region 3, the negative effect on consumption is due to the expectation of lower income flows in the future (as more demand shifts towards the other two regions and more output is produced there). Further effects, namely the income effect and the variety effect, acting as previously described in Section 4.7, with time lead to some gains for the indirectly affected region, and materialize in the higher long-run equilibrium level of consumption.

In regions 1 and 2, the expansion in consumer demand does not come at the cost of initially lower investment. In our case, the increased demand for the products of these regions leads to higher production activity and to additional capital accumulation, which is partly financed by region 3 (through an increase in foreign asset holdings). Own output in region 3, in contrast, shrinks slightly, and also its rate of investment goes down. In fact, the decrease in relative attractiveness of region 3 for investment is big enough to make the new steady-state level of capital stock go below its pre-shock level.

Further results are displayed in Figure 5.5.2. We see that the biggest part of adjustment of the trade flows between regions 1 and 2 is performed during the initial jump. The effect of the infrastructure improvement on trade between the two directly affected regions is substantial (the shock itself is also rather big), while the effect on the trade flows with the third region is quite small. We can notice that the directly affected regions will have a small trade surplus with respect to the third region in the new steady state.

Figure 5.5.2. Test model results: trade flows, assets, and Tobin's q



The two lower panels display the smooth adjustment of regional savings and the “Tobin’s q ”. By definition, \dot{a}_r is equal to zero in the steady state, and the equilibrium value of r_r is determined by the parameters of the model and is common to all regions, thus no separate representation of steady-state levels is needed there. The initial divergence in the regional values of the “Tobin’s q ” illustrates the change in the relative attractiveness of the regions for investment, with the region untouched by the infrastructure improvement being a clear loser.

An issue of separate interest is the measurement of welfare impact. We use two approaches. First, we compare the before- and after-shock steady states, using the indicators of real GDP and real consumption (equal to the consumption index c_{rt}), which is similar to doing comparative statics as in sections 4.6-4.7. Second, we would like to calculate a measure of dynamic impact of the policy on the consumers. For this, we calculate the Hicksian equivalent variation in consumption, EV_r^c , defined by

$$\int_{t=0}^{\infty} \frac{(C_{rt}^0 \cdot (1 + EV_r^c / 100))^{1-1/\varphi} - 1}{1-1/\varphi} e^{-\rho t} = \int_{t=0}^T \frac{(C_{rt}^1)^{1-1/\varphi} - 1}{1-1/\varphi} e^{-\rho t} + \int_{t=T}^{\infty} \frac{(C_{rt}^1)^{1-1/\varphi} - 1}{1-1/\varphi} e^{-\rho t} \quad (5.5.1)$$

Thus, this measure gives the percentage change in the time path of pre-shock consumption C_{rt}^0 , such that the discounted utility flows before and after the shock are equalized. As the

system is in the steady state before the shock, we have $C_{rt}^0 = C_{r0}^0 \cdot e^{\hat{C}^* \cdot t}$ at all times, and the integral on the left-hand side can be solved explicitly. Time $T=50$ is the time point, where we require the system to reach the stable manifold of the linearized system. Thus, after period T , values of C_{rt}^1 are determined from the solution of the linearized system (5.3.7). We summarize the welfare measures in Table 5.5.1.

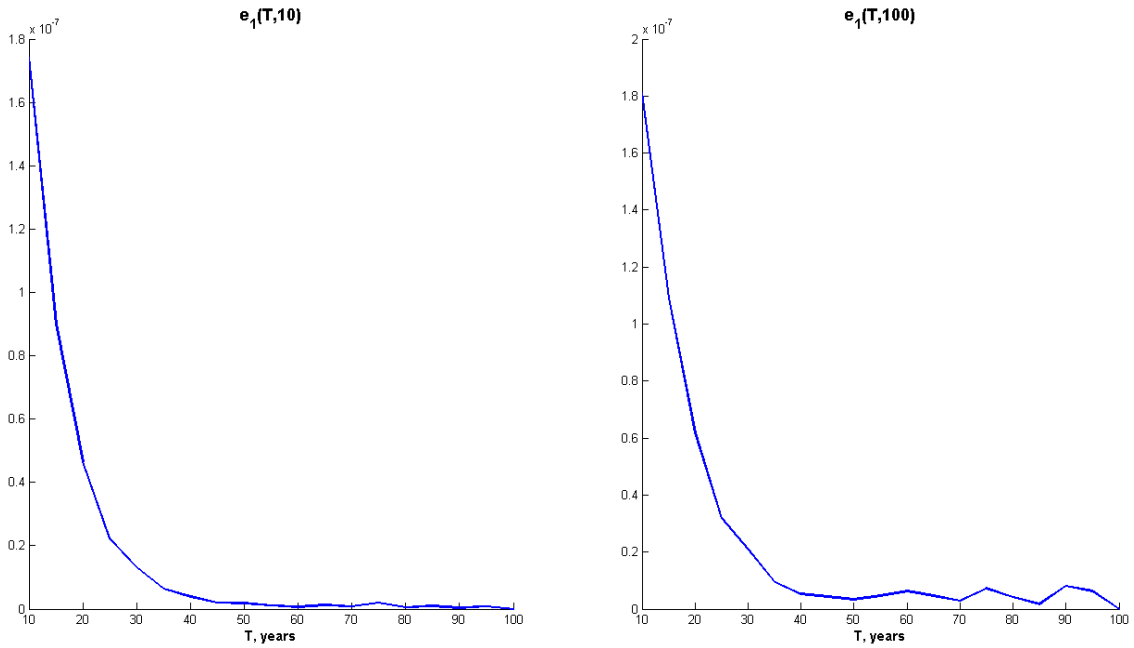
Table 5.5.1. Test model results: GDP and welfare

Indicators	Comparative steady state		Dynamics
	Real GDP change, %	Real consumption change, %	Equivalent variation in consumption, %
Regions 1 & 2	0.331	0.275	0.229
Region 3	-0.046	0.066	-0.028

The difference between the “static” and “dynamic” consumption-based welfare measures has a direct relation to the convergence process. The larger the adjustment of consumption during the initial jump, and the faster the convergence, the more close will the two measures be to each other. In our case, the convergence speed is quite moderate, and this leads to substantially different results from the two methods. The new steady state consumption levels for both regions lie above the old steady state. However, the initial jump in the directly and indirectly affected regions goes in different directions. The consumption in the indirectly affected region initially falls short of the old steady-state level. Because the future consumption is weighted less in the lifetime utility, the equivalent variation measure thus turns out to be slightly negative.

The difference between the real GDP and real consumption effects in the comparative steady state calculations can be clarified using the arguments similar to the ones that we used to explain the difference between the real GDP and real income effects of resource cost change for the static model in Section 4.6. This difference was due to capital in- or outflow in the static setup, and it is due to different rates of investment, and the changes in asset ownership in the dynamic setup. The transport cost reduction makes the third region relatively less attractive for investment, and it ends up having lower capital stock than in the pre-shock situation, which also reduces the output and thus the payments to the primary factors. In case of the households, the reduction of wage income is with time compensated by the additional income from the assets purchased in the other two regions.

Figure 5.5.3. Numerical errors due to finite horizon approximation



One interesting point we also want to look at is the dependence of the model solution on the choice of the terminal time point. We have approximated the solution of the infinite horizon problem with that of a finite horizon problem by imposing the boundary conditions at time T . This point has to be far enough in the future, so that the further adjustment process could be well represented by the linearization of the model around the new steady state. The results in Figures 5.5.1-5.5.2 are based on the calculations with T equal to 50 years. We can see that a relatively big part of adjustment of consumption and capital stock is still not finished after such a long time. We would like to know whether imposing the boundary conditions at an earlier or later point in time would have any important implications for the solution. We will only look at the time path of the detrended consumption c_{rt} .

The experiment setup stays unchanged. We now make a base run with T set to 100. In fact, the time path of consumption visually merges with the line representing the new steady-state level already at lower values of T . This base run will be considered as the “exact” solution. Then, model runs with shorter horizons T are performed. We denote the consumption paths produced by these model runs by c_{rt}^T (e.g. c_{rt}^{100} or c_{rt}^{25}). Then, we use the generalized Euclidean norm to construct the cumulative error indicator:

$$e_r(T, \tilde{t}) = \left(\int_{t=0}^{\tilde{t}} (c_{rt}^T - c_{rt}^{100})^2 dt \right)^{1/2}, \quad (5.5.2)$$

where \tilde{t} can be chosen to represent the most “sensitive” part of the time path (e.g. the first

10 years). Figure 5.5.3 displays the results for the consumption paths of region 1. These results suggest that $T=50$ is a rather optimal cut-off point, as no significant gain in precision is achieved by further increasing the length of the non-linear solution. In fact, the figures tell even more. Because the absolute value of $e_r(\cdot)$ is low even with low T , it means that the linearized version of the model is a good approximation for the nonlinear solution already after very short time.

Quite often, the announcement of the policy can be viewed as an additional policy instrument, when the timing of the announcement by itself affects the economic outcomes.⁵¹ The dynamic, perfect-foresight formulation of the model allows to identify the implications of the different timing of the announcement and the realisation of the policy measure. In the next experiment, we assume that the infrastructure improvement is announced at $t=0$, and it is implemented at $t=10$. Figure 5.5.4 displays the results.

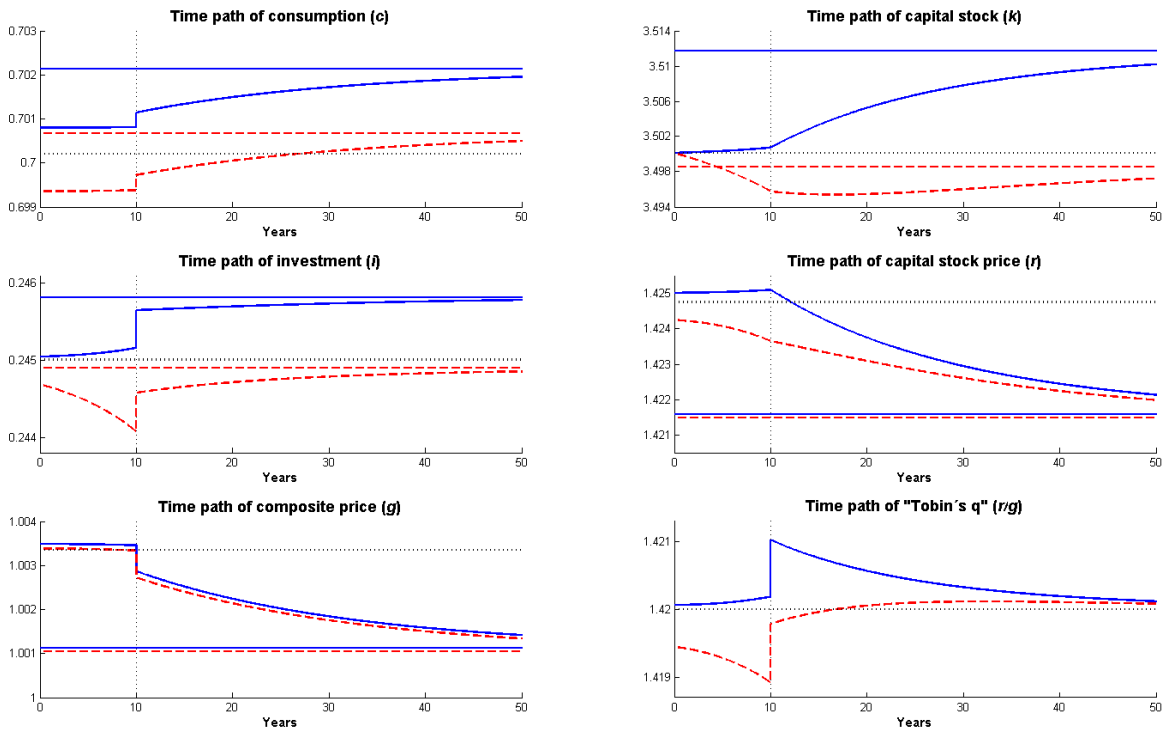
The graphical convention is as in the earlier figures. In addition, we introduce a thin vertical dotted line to represent the time point of policy realization. However, also without an explicit representation, this point is easily identified on all six panels in the figure. In the graphs of consumption, trade flows, consumer price index, and the “Tobin’s q ”, the realization point is characterized by an explicit jump of these variables. The graphs of the time paths of capital stock and its market price, in turn, display the change of curvature at the realization point. The time paths of all variables after the realization point are very similar to the time paths displayed in Figures 5.5.1-5.5.2. In the following, we would thus focus on the adjustment processes that take place before the policy realization.

The largest effect from the transport cost reduction is on the trade flows. However, prior to the actual project completion, the pattern of trade cannot change a lot, as the cost reduction is not modelled as accumulating gradually, but it rather comes all at once. Thus, in the phase between the announcement and the realization of the policy measure, the adjustment is mainly done by other processes. After the realization, however, the trade flows almost completely adjust through the instantaneous jump (see Figure 5.5.2).

One immediate effect of the announcement of the future infrastructure improvements is the change in the investment pattern and in the valuation of the existing capital stock. The forward-looking agents realize that the transport cost reduction will lead to the establishment of tighter economic links between the two directly affected regions, whereby the lower

⁵¹ See e.g. Obstfeld and Rogoff (1996) for a comprehensive discussion of macroeconomic effects of policy announcement in an open economy

Figure 5.5.4. Test model results: announcement effects



prices of tradable goods will decrease the costs of investment and consumption. Thus, the expectation of the realization of the policy will create incentives for new investment, but it will also motivate the purchase of the existing assets in the directly affected regions. This raises the market price of the existing capital stock in these regions after the announcement, and reduces the market price of the capital stock in the third region. The adjustment in all regions is realized through an initial jump in the price r_r (as well as in the investment amount), which is followed by a monotone trend until the realization. After the realization point, the above-mentioned decrease in the cost of investment makes the market price of capital stock go down in all regions.

Quite importantly, no additional jump of the capital stock price occurs at time $t=10$. Technically, the evolution of the stock price is controlled by the no-arbitrage condition in (5.2.12"), which suggests that a discontinuous parameter change (such as a change of transport costs at the realization point) induces a jump of the rate of growth of the stock price (the slope of the time path). However, such a change does not induce a jump in the level of the stock price (which would mean a break in the time path itself). Intuitively, because the instantaneous reallocation of capital is ruled out by the presence of adjustment costs, a sudden jump in the stock price would create spatial arbitrage possibilities, which would not be consistent with the optimality conditions.

The second important effect concerns the households revising their lifetime consumption plans. The individuals in the directly affected regions perceive the future increase of demand for the products of their region, they expect a higher amount of output to be produced, and thus they also expect to get a higher wage income. This expectation of higher wealth in the future makes households increase consumption demand already prior to policy realization. Consumption thus jumps up right after the announcement. Because the cost decrease has not yet materialized, the increased consumption demand initially creates slight upward pressure on the goods prices in the directly affected regions. For the third region, the opposite of what has been described above holds true: an expectation of lower wealth in the future drives consumption down. At the realization time point, however, the goods prices drop in all regions and then continue converging to a new, lower steady-state level. The time path of consumption, given by Eq. (5.2.29), follows the movement of the composite price and is roughly inversely proportional to it.

The inclusion of the announcement phase also has consequences for the measurement of the welfare effect. Because the movement towards the new, higher steady-state level of consumption for all regions is largely postponed until the realization point, the lower levels of consumption in the starting phase drive the equivalent variation indicator down. The value of EV_r^c constitutes +0.214% for the directly affected regions and -0.044% for the indirectly affected region.

5.5.2. A Fehmarn Belt simulation

Our final numerical experiment is the simulation of the Fehmarn Belt project implementation (occurring in the year 2020) in a simplified setup with 10 regions.⁵² The calibration is done as described in Section 5.4. The matrix of trade cost mark-ups is the aggregated version (with regional GDPs used as weights) of the matrix used for the static model runs discussed in Section 4.7. Similarly, the cost change matrix is the aggregated version of the matrix used for the experiments with the static model. Further, the two pieces of information that are needed to identify the initial steady state are the 2020 values of regional GDP and trade deficit. These are also aggregated from the data used for the static model runs.

We did not give special treatment to revenue-generating charges in the dynamic setup, so only the resource cost change is simulated. For the ten-region aggregation of the model, we

⁵² The project, described in more detail in Section 4.7, includes the construction of a fixed link across the Fehmarn Belt, as well as the update of access routes on the Danish and German side.

can actually display the benchmark distance cost mark-ups f_{sr} and the values in the parameter matrix $\Delta_{sr} = \Delta r_{sr} + \Delta j_{sr}$ (see Eq. (4.5.5)) that characterize the Fehmarn Belt project implementation (the regional composition is in Table 5.5.2 below):

$$f_{sr} = \begin{pmatrix} 1.02 & 1.04 & 1.04 & 1.06 & 1.11 & 1.05 & 1.07 & 1.08 & 1.16 & 1.98 \\ 1.04 & 1.02 & 1.04 & 1.04 & 1.10 & 1.07 & 1.08 & 1.08 & 1.17 & 1.98 \\ 1.04 & 1.04 & 1.03 & 1.05 & 1.11 & 1.06 & 1.08 & 1.07 & 1.16 & 1.98 \\ 1.06 & 1.04 & 1.05 & 1.02 & 1.09 & 1.08 & 1.10 & 1.09 & 1.18 & 1.98 \\ 1.11 & 1.10 & 1.11 & 1.09 & 1.08 & 1.12 & 1.14 & 1.14 & 1.21 & 1.98 \\ 1.05 & 1.07 & 1.06 & 1.08 & 1.12 & 1.03 & 1.04 & 1.07 & 1.14 & 1.99 \\ 1.07 & 1.08 & 1.08 & 1.10 & 1.14 & 1.04 & 1.02 & 1.07 & 1.13 & 1.99 \\ 1.08 & 1.08 & 1.07 & 1.09 & 1.14 & 1.07 & 1.07 & 1.05 & 1.14 & 1.99 \\ 1.16 & 1.17 & 1.16 & 1.18 & 1.21 & 1.14 & 1.13 & 1.14 & 1.10 & 2.00 \\ 1.98 & 1.98 & 1.98 & 1.98 & 1.98 & 1.99 & 1.99 & 1.99 & 2.00 & 2.18 \end{pmatrix},$$

$$\Delta_{sr} = \begin{pmatrix} -0.00 & -0.01 & -0.00 & -0.02 & -0.00 & -0.32 & -0.24 & -0.01 & -0.05 & -0.00 \\ -0.01 & -0.00 & -0.00 & -0.02 & -0.00 & -0.23 & -0.19 & -0.00 & -0.05 & -0.00 \\ -0.00 & -0.00 & -0.00 & -0.01 & -0.00 & -0.23 & -0.18 & -0.00 & -0.01 & -0.00 \\ -0.01 & -0.02 & -0.01 & -0.00 & -0.00 & -0.15 & -0.13 & -0.00 & -0.05 & -0.00 \\ -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.07 & -0.06 & -0.00 & -0.00 & -0.00 \\ -0.32 & -0.23 & -0.23 & -0.15 & -0.07 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 \\ -0.23 & -0.19 & -0.18 & -0.13 & -0.06 & -0.01 & -0.00 & -0.00 & -0.00 & -0.00 \\ -0.01 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 \\ -0.05 & -0.05 & -0.01 & -0.05 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 \\ -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 & -0.00 \end{pmatrix}.$$

The values in Δ_{sr} indicate that the simulated infrastructure update is expected to bring considerable resource and time saving for the transport crossing the Fehmarn Belt, but also for the local transport between Schleswig-Holstein, Hamburg, and Bremen (due to the upgrade of access railways).

In order to make comparison with the static model version, we will use the results produced by the model with capital mobility (*Model 2* of Section 4.7), where only the resource cost component was shocked. This is the relevant benchmark for comparison, because capital is mobile in the dynamic model, and we did not introduce labour market imperfections there. The results are reported in Table 5.5.2.

Table 5.5.2. Fehmarn Belt simulation results

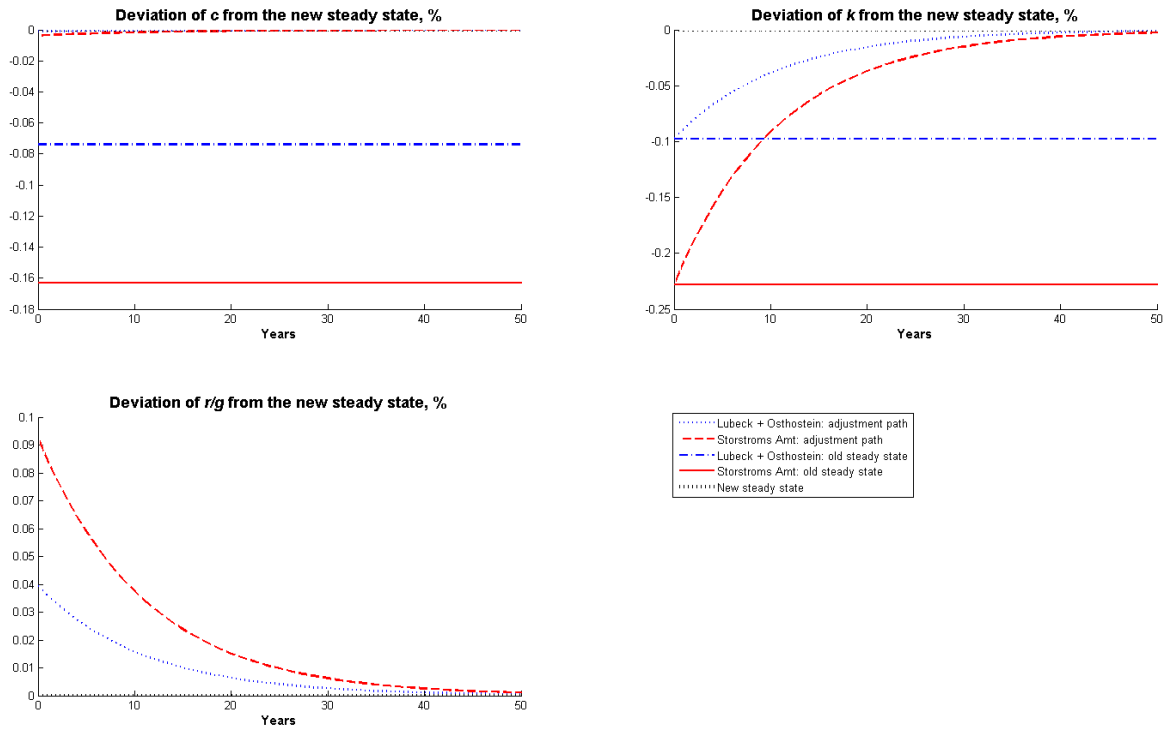
Region	Composition	Comparative statics		Comparative steady state		Dynamics
		Real GDP change, %	Real consumption change, %	Real GDP change, %	Real consumption change, %	Equivalent variation in consumption, %
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	Lübeck + Ostholstein	0.074	0.057	0.097	0.074	0.074
2	Hamburg	0.071	0.054	0.094	0.072	0.071
3	Rest of Schleswig-Holstein	0.025	0.019	0.033	0.025	0.025
4	Bremen + Bremerhaven	0.059	0.045	0.080	0.061	0.060
5	Rest of Germany	0.004	0.003	0.007	0.005	0.005
6	Storstrøms Amt	0.149	0.122	0.228	0.163	0.162
7	Rest of Eastern Denmark	0.107	0.087	0.161	0.115	0.114
8	Western Denmark	-0.019	-0.014	-0.024	-0.016	-0.017
9	Sweden	0.005	0.004	0.009	0.007	0.007
10	Rest of the world	0.000	0.000	0.000	0.000	0.000

Intuitively, one may expect that the static gains from trade cost reduction would be easily dwarfed by the accumulated growth effects through increased investment in capital stock, and expanding product variety. Indeed, the GDP and welfare effects of comparative steady state calculations are roughly 30-35% stronger than the corresponding effects from the comparative statics calculations. The spatial pattern, however, remains essentially unchanged, the correlation coefficients are close to 100%.

Note that the results in columns 3 and 4 in the above table do not exactly match the results of the comparative static Fehmarn Belt experiment in Table 4.7.1 (columns 7 and 4, respectively). The reason is that in the current section we recalibrated the static model using the parameters of technology and preferences that are homogenous across regions (for a better correspondence between the static and the dynamic model). The differences in the results are however very slight.

One can easily note that the values for the German regions in columns 3, 6, and 7 are almost identical. Whereas the similarity of the last two columns can be explained by the fast convergence of the dynamic system to the new equilibrium (to be illustrated below), the coincidence of the values of the GDP effects from the comparative static experiment and the welfare effects from the comparative dynamic experiment can only be attributed to chance. In order to check the robustness of this result, we ran several test scenarios with different cost shocks, and were not able to produce a similar picture in any of those cases.

Figure 5.5.5. Fehmarn Belt simulation results



The dynamic impact adds to other indirect effects caused by the infrastructure improvement. The total benefit multiplier calculated from the static model equals 1.30, and the dynamic model increases it to 1.75. The main source of this additional impact is the induced capital formation, whereby regional output and welfare increase more than static effects alone would predict. The exact magnitude of this effect depends on the parameters of the model, which control the capital share in production, the strength of the variety effects, and the cost of investment. We consider the uncovering of the underlying links and of the general conditions under which these dynamic gains exist as an independent task open for future research.⁵³

Figure 5.5.4 shows smooth adjustment of consumption, capital stock, and the “Tobin’s q ”, of the kind already indicated by the output of the test model. Note that the before- and after-shock steady state values of the “Tobin’s q ” coincide, as the equilibrium market price of capital stock measured in units of investment good is common to all regions and is entirely determined by the model parameters.

The values of the two consumption-based welfare measures for the dynamic model in Table 5.5.2 almost coincide. This indicates that the main part of adjustment is done during the

⁵³ As shown by Baldwin (1992) in the analysis of the dynamic gains from trade liberalization, the existence of scale economies is definitely one of such conditions.

initial jump of consumption. In fact, this could be expected, as the size of the shock is very small in comparison to the size of the economies involved. Figure 5.5.4 confirms this presumption. The adjustment paths of consumption lie very close to the zero-line, and can hardly be distinguished from it visually. The presence of adjustment costs, however, makes capital stock and its market price only gradually approach the new equilibrium levels.

5.6. Summary

In this chapter, we have presented an operational dynamic SCGE model and used it to analyse the regional economic effects of the transport cost changes.

The basic formulation is the open-economy version of the Ramsey model with investment costs. We are able to combine this framework with the structure of the static SCGE model described in Chapter 4. Under the assumption of homogeneity of preference and technology parameters across regions, the model is shown to possess a steady state. It is characterized by saddle-path stability and semi-endogenous growth. The formulation is rather non-standard and needs a specially designed solution procedure that we present in due detail. We are able to solve for the time paths of the model variables by employing a collocation method.

The functioning of the model is first demonstrated using an experimental three-regions setting. We show that the predictions of the model are plausible and that it can be used to uncover the complex patterns of dynamic adjustment of the economy, including the policy announcement effects. Finally, we simulated the Fehmarn Belt railway axis implementation and discovered important differences to the predictions of the static model.

Chapter 6. Conclusions

6.1. Main findings

This thesis concerns both static and dynamic modelling in the spatial computable general equilibrium framework, with the focus on its application for transport policy analysis. We will now shortly summarize our main findings.

The SCGE modelling is an appropriate method to study the economy-wide effects of the large-scale transport infrastructure improvements and the pricing policies in transport, as suggested by several reviewers (Williams et al., 2002; Gunn, 2004; Laird et al., 2005; DfT, 2006). The use of these models allows to take account of the indirect effects of policies and of the related spatial spillover effects in a consistent way. Decisive for the ability of the SCGE models to bring forward new insights about the policy effects is the incorporation of the fundamental principles of regional and spatial economics: factor mobility, economies of scale, and the presence of trade-linked transport costs. The models used in this thesis incorporate all these features in a certain way.

An important part of work underlying this thesis concerns the connection of the SCGE model covering the whole Europe on a fine regional scale with the external transport network model. A desirable feature for the purposes of transport policy analysis would be the consistent integration of the two models, which means making the transportation coefficients endogenously determined. This task however is to this day not realised on the European scale because of the technical and data-related difficulties that we described in Chapter 3. The search for a compromise between the desire of having a realistic representation of transport as a resource-using activity linked to the actual trade flows and the technical difficulty of implementing a fully integrated CGE-transport network model leads to the choice of the “iceberg” assumption to model the transport costs of the firms. This method is also not easy to put into operation, but we were able to employ it and documented the encountered problems and their solutions in due detail.

The purpose of the modelling effort in this thesis was the improvement of the methodology applied for transport projects evaluation in the light of growing demand for a corresponding general-purpose tool from the side of the policymakers. In particular, an up-to-date methodology used for transport policy assessment should be able to take account of the various economy-wide effects thereof.

The modifications of the existing methodology suggested in Chapter 4 allow to incorporate the following indirect effects of transport policies:

- regional employment effects,
- public revenue redistribution effects,
- spatial spillover effects due to capital mobility.

These add to the agglomeration effects and spillover effects due to product mobility (trade) that are present in the basic model of Bröcker (1998b).

The incorporation of wage rigidity and capital mobility into the SCGE modelling framework in Chapter 4 was motivated by the omission of these factors in the previous analyses of the economic effects of infrastructure improvements, and by the potentially important role of these assumptions for the magnitude of the predicted indirect effects. The functioning of the model including these assumptions was first checked using a set of sensitivity tests for the aggregate indicators.

The order of magnitude and the sign of the economy-wide GDP, welfare, and employment effects of transport cost changes can be correctly predicted using the rough back-of-envelope calculations. The exact model predictions, however, reflect the interdependencies between the variables in the model (in particular, the existence of the indirect effects) and depend a lot on the specific parameter values used in the model.

Both the introduction of an internationally mobile factor of production and the introduction of a certain degree of wage rigidity into the model have the same direction of effect on the output indicators of GDP and welfare in our test scenarios simulating the changes of the transport costs. The two assumptions reinforce each other in combination, so that the impact of the two modifications together on the produced indicators is larger than the sum of the additional impacts they cause individually.

The main effect of transport cost changes is the adjustment of relative prices of local and tradable goods inside and across the regions. This leads to an increased demand for tradable varieties stemming from the regions, the products of which become relatively cheaper, thus making the firms there more competitive. Either of the new assumptions then opens an additional source of inputs for production that can be used by the more competitive firms in order to meet larger demand. Capital flows to these regions because the increased demand for their products creates a tendency for the regional factor returns to rise. Furthermore, the real wages go up in these regions, stimulating the entry of additional labour force out of unemployment. This, in turn, increases the overall economic effect. The size of

this effect is then positively correlated with the assumed share of mobile capital in the factor income and the benchmark level of the unemployment rate.

Assuming flexible wages, the model predicts indirect effects in the order of 20% of the direct effects, which resembles the results of the previous studies using a similar model (Bröcker and Schneider, 2002). These arise from the monopolistic competition on the tradables market, “love for variety”, and the resulting “agglomeration” effects on the consumers and the firms. Setting the elasticity of the wage curve in the range predicted by the empirical studies increases the magnitude of the indirect effects drastically. These additional effects coming from the changes in employment levels are much stronger than the effects brought about by the agglomeration forces only, and are in the order of 50% of the direct effects for the default value of the elasticity. Such large values of indirect effects mean that the conventional CBA analysis would significantly underestimate the benefits from transport projects, and would thus introduce a bias into the decision-making process.

The presence of a mobile factor of production can be viewed as an additional channel through which the spatial spillover effects may arise. The spatially connected markets in our model are initially characterized by market imperfection in the form of monopolistic competition. Capital mobility means that the resulting agglomeration effects can now be distributed in space more easily, not only through trade, but also through the reallocation of resources. This additional effect from capital mobility is reinforced when all markets are characterized by even more market imperfection, including the labour market response.

In our simulation of the implementation of the *Fehmarn Belt railway axis* (including the fixed link between Puttgarten and Rødby), relatively large positive welfare effects are predicted only for a few regions, mostly those directly touched by the updated infrastructure. The effects accruing to Germany, Denmark, and other Nordic countries (Norway and Sweden) amount to 52%, 23%, and 25%, correspondingly. We can thus confirm the finding of previous studies that this project induces moderate spillover effects for the Nordic countries that are not involved in the financing of the construction works. We can however illustrate the spatial distribution of the effects in much more detail. In particular, we are able to demonstrate that the difference in the degrees of the wage rigidity for Germany and Denmark is a substantial factor determining the relative magnitude of the regional effects of the trade cost reductions.

SACTRA (1999) recommendations for transport policy appraisal emphasize the need for incorporating endogenous dynamic mechanisms into the existing CGE models. The under-

lying idea is that in practice, many effects need time to fully materialize, and the explicit time paths of these effects may be of interest to the policymakers. A particular point of interest here concerns the policy announcement effects.

Chapter 5 has set up a consistent dynamic spatial CGE model applicable for the study of the effects of transport policy measures on a fine regional scale. We have described the model structure and the solution technique. The model is characterized by saddle-path stability and boils down to the open-economy version of the optimal savings (Ramsey) model if the imperfect substitution between the brands of tradable goods is abolished. The steady state growth rates as well as the transition paths have plausible properties.

The difficulty for solving the perfect foresight model system is usually that a subset of endogenous variables (the “jumpers”, such as the start levels of consumption and stock prices of installed capital) is not predetermined, but only fixed through the requirement of saddle path stability of the system. Our solution is to transform the system into a two-point boundary value problem in finite time and then to apply a collocation method to solve it.

An additional difficulty in solving our model is the presence of a large number of optimizing agents (one per region) on the consumption side. The consequence of this multi-agent setup under the assumption of perfect foresight is that the steady-state levels of household assets and consumption depend on the entire time path of the economy. As the steady-state values of endogenous variables are needed for the formulation of terminal conditions, the only option is to apply a simultaneous solution technique. We do this by specifying an additional endogenous parameter vector (representing the steady-state assets distribution) that closes the degrees of freedom in the steady state.

The functioning of the model has been described by means of numerical experiments. We find that the regional effects of big infrastructure projects (including the announcement effects) can be successfully analysed using the suggested framework. The welfare effects evaluated using a dynamic model turn out to be substantially larger than the effects predicted by the similar static model setup. An important caveat is however that the speed of convergence, and thus the welfare results, depend on the parameters of the model, which thus have to be carefully chosen in order to represent the features of the study area under investigation.

6.2. An outlook

The use of the iceberg assumption alone, as is done in this thesis, precludes the integration of the private demand for transportation into the model. We decided not to focus on private passenger transport in this thesis because the effects in this sector have been studied previously by many authors and in much detail. In contrast, the effects related to trade in goods did not receive so much attention. Nevertheless, for the purpose of full-scale transport policy analysis, one would like to integrate demand for private passenger trips into households' decisions, and demand for freight and business passenger travel into firms' decisions within the general equilibrium framework. This exercise is, of course, only sensible if the regional scale is fine enough to allow for direct influence of transport policy measures on the choices of firms and households. Obviously, if one starts reducing the size of the interacting economies in the model, very soon data availability problems come up, and one has to make choices about the affordable level of detail. For this reason, we are so far unaware of the full integration of all trip types in an SCGE framework. This issue thus remains on the research agenda.

We mentioned on several occasions that the quantitative predictions of the models employed in this thesis are characterized by considerable dependence on the parametric assumptions. The qualitative predictions of our model (the direction of change of the indicators), however, remain stable for the plausible range of values of the key parameters. The values of the key parameters are thus of importance for the results of eventual project evaluation and must be chosen using a transparent method and reliable data sources. This is often not the case in the reviewed studies, especially those published in non-academic editions.

All simulations performed in this thesis and in the reviewed studies employing the SCGE methodology are looking at the cases, where the envisioned infrastructure improvement or another policy measure has not yet been implemented. Thus, no test of the plausibility of model predictions can be provided under these conditions. A much more challenging task for this modelling framework would be its application to the ex-post analysis of some policy measure already in place. The study doing this in a consistent way is still to be written.

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Appendix A: Supplement for Chapter 4

A.1. Details on consumer behaviour

The following derivations are based on Fujita et al. (2000, Ch. 4).

In every region r representative consumers share the same Cobb-Douglas tastes for the local goods and the composite of tradable goods:

$$U_r = \bar{M}_r^\varepsilon \bar{T}_r^{1-\varepsilon}, \quad (\text{A.1.1})$$

where quantity index \bar{T} is assumed to be a symmetric CES function, combining all \bar{l} available varieties of tradables, and ε is a constant representing the expenditure share of local goods. The expression for \bar{T} is

$$\bar{T}_r = \left(\sum_{i=1}^{\bar{l}} t_{i,r}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \quad (\text{A.1.2})$$

where $t_{i,r}$ denotes the consumption in r of each available variety i , and $\sigma > 1$ represents the elasticity of substitution between any two varieties.

Denoting the price of a tradable variety by $c_{i,r}$, a standard optimization procedure in the lower nest leads to the following expression for the price index for tradable goods:

$$q_r = \left(\sum_{i=1}^{\bar{l}} c_{i,r}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}. \quad (\text{A.1.3})$$

Note that if we assume that all products are available at the same price c , the price index simply becomes

$$q_r = c \cdot \bar{l}^{1/1-\sigma}. \quad (\text{A.1.4})$$

Thus, increasing the range of varieties reduces the price index and hence the cost of attaining a given level of utility. In other words, consumers share “love for variety”.

The demand function for the i^{th} variety of tradable good is

$$t_{i,r} = \left(\frac{c_{i,r}}{q_r} \right)^{-\sigma} \bar{T}_r, \quad (\text{A.1.5})$$

which after inserting the result of upper-level optimization becomes

$$t_{i,r} = (1 - \varepsilon) \bar{N}_r \frac{c_{i,r}^{-\sigma}}{q_r^{1-\sigma}}, \quad (\text{A.1.6})$$

where \bar{N}_r is household's income.

Holding price index q_r constant, the price elasticity of demand for every available variety is thus constant and equal to $-\sigma$. Fujita et al. (2000, Ch. 4) further show that in the case of multiple locations and iceberg-type transportation costs, the aggregate demand for each variety with respect to its mill price is also $-\sigma$, regardless of spatial distribution of consumers.

A.2. Details on producer behaviour

The tradable varieties are produced on the market characterized by monopolistic competition, with the only input given by the local goods. Consider a particular firm producing a specific variety at location r and facing a given price, p_r , for local goods there. We assume firms' technology to involve economies of scale (decreasing average cost) that arise at the level of the variety. This technology is the same for all varieties and in all locations and can be described by the input requirement function $I(x)$, where x is the firm's output. The simplest example would be a linear function $I(x) = F + c \cdot x$.

Firms choose optimal output level by maximizing their profit, but being aware of the finite price elasticity of demand for the variety, $-\sigma$. Let the inverse demand function be given by $\tilde{p}(x)$. The profit is then equal to

$$\pi = \tilde{p}_r(x) \cdot x - p_r \cdot I(x). \quad (\text{A.2.1})$$

The first-order condition suggests optimal pricing according to the Amoroso-Robinson relation:

$$\left(1 - \frac{1}{\sigma}\right) \tilde{p}_r(x^*) = p_r \frac{dI(x^*)}{dx^*}. \quad (\text{A.2.2})$$

Another equilibrium condition is implied by the free entry and exit requirement, which means all firms earn zero profit in the equilibrium. Then the price equals average costs:

$$\tilde{p}_r(x^*) = \frac{p_r I(x^*)}{x^*}. \quad (\text{A.2.3})$$

Combining these two conditions, we get an expression for x^* as an implicit function of the constant price elasticity of demand. Thus, x^* and $I(x^*)$ are constants common to every active firm in the economy. The pricing rule can be formulated as

$$\tilde{p}_r = p_r \cdot \mu, \quad (\text{A.2.4})$$

where

$$\mu = \frac{\sigma}{\sigma - 1} \cdot \frac{dI(x^*)}{dx^*} = \text{const}, \quad \mu > 1.$$

A.3. Derivation of the welfare measure

The indirect utility function corresponding to the Cobb-Douglas direct utility function of the households has the following form:

$$u_r(p_r, q_r, N_r) = \frac{N_r}{p_r^\varepsilon q_r^{1-\varepsilon}}, \quad (\text{A.3.1})$$

where N_r is nominal income, p_r is price of local goods, q_r is composite price of tradables. u_r is unique up an arbitrary monotonically increasing transformation.

Let N_r^b, p_r^b, q_r^b and N_r^a, p_r^a, q_r^a denote the income and prices before and after the policy shock, respectively. The Hicksian equivalent variation EV_r is defined as an absolute increase in before-shock disposable income that under the before-shock prices would render the after-shock level of utility:

$$u_r(p_r^b, q_r^b, N_r^b + EV_r) = u_r(p_r^a, q_r^a, N_r^a). \quad (\text{A.3.2})$$

Relative equivalent variation is then:

$$REV_r = \frac{EV_r}{N_r^b}. \quad (\text{A.3.3})$$

The Hicksian compensating variation CV_r is defined as an absolute decrease in after-shock income that under the after-shock prices would render the before-shock level of utility:

$$u_r(p_r^b, q_r^b, N_r^b) = u_r(p_r^a, q_r^a, N_r^a - CV_r). \quad (\text{A.3.4})$$

Relative compensating variation is then:

$$RCV_r = \frac{CV_r}{N_r^a}. \quad (\text{A.3.5})$$

Substituting the definition (A.3.1) into (A.3.2) and (A.3.4) and using $G_r = p_r^\varepsilon q_r^{1-\varepsilon}$ yields

$$\frac{N_r^b + EV_r}{G_r^b} = \frac{N_r^a}{G_r^a},$$

$$REV_r = \frac{N_r^a / N_r^b}{G_r^a / G_r^b} - 1 \quad (\text{A.3.6})$$

and

$$\frac{N_r^b}{G_r^b} = \frac{N_r^a - CV_r}{G_r^a},$$

$$RCV_r = 1 - \frac{N_r^b / N_r^a}{G_r^b / G_r^a}. \quad (\text{A.3.7})$$

If the fractions in the expressions (A.3.6) and (A.3.7) are sufficiently close to one, both, REV_r and RCV_r , can be approximated as logarithmic changes

$$REV_r \approx RCV_r \approx \log(N_r^a / N_r^b) - \log(G_r^a / G_r^b). \quad (\text{A.3.8})$$

A.4. Additional Fehmarn Belt experiment results

Table A.1. GDP and welfare effects in selected regions in year 2020 (scenario including the change in charges)

Region	Country	Welfare effects			Real GDP effects		
		<i>Model1</i>	<i>Model2</i>	<i>Model3</i>	<i>Model1</i>	<i>Model2</i>	<i>Model3</i>
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Bremen, Kreisfreie Stadt	Germany	0.045	0.045	0.077	0.042	0.058	0.102
Hamburg	Germany	0.041	0.041	0.063	0.038	0.053	0.082
Stade	Germany	0.031	0.031	0.046	0.028	0.039	0.059
Lübeck, Kreisfreie Stadt	Germany	0.055	0.055	0.083	0.052	0.072	0.110
Ostholstein	Germany	0.031	0.031	0.046	0.028	0.039	0.059
Københavns Amt	Denmark	0.027	0.027	0.026	-0.002	-0.003	-0.005
Frederiksborg Amt	Denmark	0.028	0.028	0.027	-0.001	-0.002	-0.003
Roskilde Amt	Denmark	0.041	0.041	0.052	0.012	0.015	0.029
Vestsjællands Amt	Denmark	0.035	0.035	0.040	0.006	0.007	0.014
Storstrøms Amt	Denmark	0.037	0.037	0.045	0.008	0.010	0.020
Skåne Län	Sweden	0.047	0.047	0.085	0.048	0.061	0.109
Västra Götalands Län	Sweden	0.024	0.024	0.051	0.024	0.031	0.065

Appendix B: List of countries and regions

The 27 EU and 4 EFTA countries (Norway, Switzerland, Iceland, Liechtenstein) are divided according to the official NUTS3 classification (http://ec.europa.eu/eurostat/ramon/nuts/home_regions_en.html).

In addition, the following regions are used:

Code	Country	Region name
AL1	Albania	North Albania
AL2	Albania	Tirana
AL3	Albania	South Albania
BA1	Bosnia	Brosanska Krupka
BA2	Bosnia	Brosanska Krupka
BA3	Bosnia	North Srpska
BA4	Bosnia	Drvar
BA5	Bosnia	Central Bosnia
BA6	Bosnia	Mostar
BA7	Bosnia	Sarajevo
BY1	Belarus	Homyel'skaya Voblasts'
BY2	Belarus	Brestskaya Voblasts'
BY3	Belarus	Minsk
BY4	Belarus	Mogilev
BY5	Belarus	Hrodzyenskaya Voblasts'
BY6	Belarus	Vitsyebskaya Voblasts'
MK1	Macedonia	West Marcedonia
MK2	Macedonia	Skopje
MK3	Macedonia	East Marcedonia
HR011	Croatia	Krapinsko-zagorska zupanija
HR012	Croatia	Varazdinska zupanija
HR013	Croatia	Medjimurska zupanija
HR014	Croatia	Koprivnicko-krizevacka zupanija
HR015	Croatia	Bjelovarsko-bilogorska zupanija
HR016	Croatia	Sisacko-moslavacka zupanija
HR017	Croatia	Karlovacka zupanija
HR021	Croatia	Grad Zagreb
HR022	Croatia	Zagrebacka zupanija
HR031	Croatia	Istarska zupanija
HR032	Croatia	Primorsko-goranska zupanija
HR033	Croatia	Licko-senjska zupanija
HR034	Croatia	Zadarska zupanija
HR035	Croatia	Sibensko-kninska zupanija
HR036	Croatia	Splitsko-dalmatinska zupanija
HR037	Croatia	Dubrovacko-neretvanska zupanija
HR041	Croatia	Viroviticko-podravaska zupanija
HR042	Croatia	Osjecko-baranjska zupanija
HR043	Croatia	Vukovarsko-srijemska zupanija
HR044	Croatia	Brodsko-posavska zupanija
HR045	Croatia	Pozesko-slavonska zupanija
IS000	Iceland	Island
LI000	Liechtenstein	Liechtenstein
MD	Moldavia	Moldova
RU100	Russia	Arkhangel'skaya Oblast'
RU102	Russia	Vologodskaja Oblast
RU103	Russia	Murmanskaja Oblast

RU104	Russia	Karelijal, Republika
RU200	Russia	Sankt-Peterburg
RU203	Russia	Novgorodskaja Oblast
RU204	Russia	Pskovskaja Oblast
RU301	Russia	Brjanskaja Oblast
RU302	Russia	Vladimirskaja Oblast
RU303	Russia	Ivanovskaja Oblast
RU304	Russia	Kaluzskaja Oblast
RU305	Russia	Kostromskaja Oblast
RU306	Russia	Moskva Oblast
RU308	Russia	Orlovskaja Oblast
RU309	Russia	Rjasan Oblast
RU310	Russia	Smolenskaja Oblast
RU311	Russia	Tverskaja Oblast
RU312	Russia	Tulskaja Oblast
RU313	Russia	Jaroslavskaja Oblast
RU501	Russia	Belgorodskaja Oblast
RU502	Russia	Kurskaja Oblast
RU503	Russia	Lipeckaja Oblast
RU600	Russia	Stavropol'skiy Kray
RU700	Russia	Tatarstan
RU800	Russia	East Russia
RUA	Russia	Kaliningrad
TR01	Turkey	Istanbul
TR02	Turkey	Edirne
TR03	Turkey	Izmir
TR04	Turkey	Bursa
TR05	Turkey	Ankara
TR06	Turkey	Antalya
TR07	Turkey	Kirsehir
TR08	Turkey	Karabuk
TR09	Turkey	Ordu
TR10	Turkey	Erzurum
TR11	Turkey	Malatya
TR12	Turkey	Kilis
UA1	Ukraine	Cherkas'ka Oblast'
UA10	Ukraine	Kirovohrads'ka Oblast'
UA11	Ukraine	Krym, Respublika
UA12	Ukraine	Kyyivs'ka Oblast'
UA13	Ukraine	Luhans'ka Oblast'
UA14	Ukraine	L'vivs'ka Oblast'
UA15	Ukraine	Mykolayivs'ka Oblast'
UA16	Ukraine	Odes'ka Oblast'
UA17	Ukraine	Poltavs'ka Oblast'
UA18	Ukraine	Rivnens'ka Oblast'
UA19	Ukraine	Sums'ka Oblast'
UA2	Ukraine	Chernihivs'ka Oblast'
UA20	Ukraine	Ternopil's'ka Oblast'
UA21	Ukraine	Vinnys'ka Oblast'
UA22	Ukraine	Volyns'ka Oblast'
UA23	Ukraine	Zakarpats'ka Oblast'
UA24	Ukraine	Zaporiz'ka Oblast'
UA25	Ukraine	Zhytomyrs'ka Oblast'
UA3	Ukraine	Chernivets'ka Oblast'
UA4	Ukraine	Dnipropetrovs'ka Oblast'
UA5	Ukraine	Donets'ka Oblast'

UA6	Ukraine	Ivano-Frankivs'ka Oblast'
UA7	Ukraine	Kharkivs'ka Oblast'
UA8	Ukraine	Khersons'ka Oblast'
UA9	Ukraine	Khmel'nyts'ka Oblast'
ME	Montenegro	Montenegro
RS1	Serbia	Novi Sad
RS10	Serbia	Kosovo
RS2	Serbia	Subotica
RS3	Serbia	Belgrad
RS4	Serbia	Sabac
RS5	Serbia	Uzice
RS6	Serbia	Kragujevac
RS7	Serbia	Novi Pazar
RS8	Serbia	Bor
RS9	Serbia	Nis

Appendix C: Supplement for Chapter 5

C.1. The regional budget constraint

As a starting point, use equations (5.2.18)-(5.2.19) to get

$$D_r - S_r = G_r C_r + G_r J_r - (\theta + \chi) P_r M_r. \quad (\text{C.1.1})$$

Now, express the value of consumption expenditure from (C.1.1) and insert it into the budget constraint (5.2.2):

$$\dot{A}_r = W_r L_r + \rho A_r - (D_r - S_r) + G_r J_r - (\theta + \chi) P_r M_r,$$

which, using equation (5.2.13), and rearranging terms, becomes

$$\chi P_r M_r = \rho A_r - \dot{A}_r - (D_r - S_r) + G_r J_r. \quad (\text{C.1.2})$$

This can now be inserted into the market clearing condition for the capital market (5.2.12):

$$\rho R_r K_r = \rho A_r - \dot{A}_r - (D_r - S_r) + G_r J_r + G_r K_r Z_r^2 \frac{\zeta}{2} - \delta K_r R_r + K_r \dot{R}_r. \quad (\text{C.1.3})$$

In order to simplify this expression, we employ the investment function (5.2.11), and equations (5.2.7)-(5.2.8):

$$\rho(R_r K_r - A_r) + \dot{A}_r - K_r \dot{R}_r + (D_r - S_r) = G_r J_r + G_r K_r Z_r^2 \frac{\zeta}{2} - \delta K_r R_r;$$

$$\rho(R_r K_r - A_r) + \dot{A}_r - K_r \dot{R}_r + (D_r - S_r) = G_r I_r + G_r K_r Z_r^2 \zeta - (I_r - \dot{K}_r) R_r;$$

$$\rho(R_r K_r - A_r) + \dot{A}_r - K_r \dot{R}_r + (D_r - S_r) = G_r I_r + G_r K_r Z_r^2 \zeta - I_r (\zeta Z_r + 1) G_r + \dot{K}_r R_r;$$

$$\rho(R_r K_r - A_r) + \dot{A}_r - K_r \dot{R}_r - \dot{K}_r R_r + (D_r - S_r) = G_r I_r + G_r K_r Z_r^2 \zeta - G_r K_r Z_r^2 \zeta - G_r I_r;$$

$$\rho(R_r K_r - A_r) + \dot{A}_r - K_r \dot{R}_r - \dot{K}_r R_r + (D_r - S_r) = 0.$$

Finally, rearrange the terms to get

$$\dot{A}_r - \dot{K}_r R_r = (S_r - D_r) + K_r \dot{R}_r + \rho(A_r - R_r K_r). \quad (\text{C.1.4})$$

C.2. The steady state growth rates

In the following, the steady-state values will be denoted by a star. All indices are dropped in this section.

We start by taking Eq. (5.2.7'), substituting the expression for Z from Eq. (5.2.11), and rearranging to get $\zeta \cdot (\hat{K} + \delta) + 1 = R/G$. Taking now log-derivatives, and evaluating the resulting expressions at the steady state (where all growth rates are constant by assumption) leads to

$$\hat{R}^* = \hat{G}^*. \quad (\text{C.2.1})$$

Thus, "Tobin's q" is constant in the steady state. Note that the investment-to-capital ratio

$$Z = \frac{R/G - 1}{\zeta}$$

is then also constant in the steady state.

Taking log-derivatives in equation (5.2.23), we get the following relationship:

$$\hat{P}^* = \eta \hat{V}^* + (1 - \eta) \hat{Q}^*,$$

or, equivalently,

$$\hat{V}^* = (\pi + 1) \hat{P}^* - \pi \hat{Q}^*. \quad (\text{C.2.2})$$

Next, we use (5.2.12') to derive the following expression:

$$\hat{P}^* - \hat{G}^* + (\alpha - 1) \hat{K}^* - (\alpha - 1) \hat{L}^* + \pi \hat{P}^* - \pi \hat{Q}^* = 0,$$

or, using the definition of regional output M in (5.2.5'),

$$\hat{P}^* - \hat{G}^* + \hat{M}^* - \hat{K}^* = 0.$$

These, using (C.2.1)-(C.2.2) and (5.2.6), simplify to

$$\hat{V}^* + \alpha \hat{K}^* + (1 - \alpha)(n + x) = \hat{K}^* + \hat{G}^* \quad (\text{C.2.3})$$

and

$$\hat{P}^* + \hat{M}^* = \hat{K}^* + \hat{G}^*. \quad (\text{C.2.4})$$

We continue by substituting (5.2.11) into (5.2.8), which produces

$$\frac{J}{K} = Z \left(1 + \frac{\zeta}{2} Z \right).$$

As Z is constant in the steady state, so is also the ratio $\frac{J}{K}$, meaning

$$\hat{J}^* = \hat{K}^*. \quad (\text{C.2.5})$$

Note also that by our construction of investment and consumption composite,

$$\hat{J}^* = \hat{C}^*, \quad (\text{C.2.6})$$

implying

$$\hat{K}^* = \hat{C}^*. \quad (\text{C.2.7})$$

Now, take time derivatives of equation (5.2.18), and switch to the notation in terms of growth rates to get:

$$S \cdot \hat{S} = (1 - \beta) \cdot P \cdot M \cdot (\hat{P} + \hat{M}) - \varepsilon \cdot C \cdot G \cdot (\hat{C} + \hat{G}) - \varepsilon \cdot G \cdot J \cdot (\hat{J} + \hat{G}).$$

Evaluating this expression at the steady state, and using (C.2.4)-(C.2.6), we arrive at the following relationships:

$$\hat{S}^* = \hat{P}^* + \hat{M}^* = \hat{K}^* + \hat{G}^* = \hat{C}^* + \hat{G}^*. \quad (\text{C.2.8})$$

In a similar fashion, (5.2.19) leads to

$$\hat{S}^* = \hat{D}^*. \quad (\text{C.2.9})$$

The definitions of composite prices Q and G imply the following expressions for their steady-state growth rates (note that by the definition of the steady state, the same rates of growth should prevail in all regions):

$$\hat{Q}^* = \frac{1}{1 - \sigma} \hat{S}^* - \frac{\sigma}{1 - \sigma} \hat{P}^* \quad (\text{C.2.10})$$

and

$$\hat{G}^* = \varepsilon \hat{P}^* + (1 - \varepsilon) \hat{Q}^*. \quad (\text{C.2.11})$$

One more equation is given by the Ramsey rule in (5.2.3):

$$\hat{C}^* = -\varphi \hat{G}^*. \quad (\text{C.2.12})$$

The final linear relationship is derived from (5.2.2) and is just

$$\hat{A}^* = \hat{G}^* + \hat{C}^*. \quad (\text{C.2.13})$$

Summarizing (C.2.1)-(C.2.13), we have the following system of linear equations in the steady-state growth rates:

$$\left\{ \begin{array}{l} \hat{V}^* = (\pi + 1) \hat{P}^* - \pi \hat{Q}^*; \\ \hat{Q}^* = \frac{1}{1 - \sigma} \hat{S}^* - \frac{\sigma}{1 - \sigma} \hat{P}^*; \\ \hat{V}^* + \alpha \hat{K}^* + (1 - \alpha)(n + x) = \hat{K}^* + \hat{G}^*; \\ \hat{C}^* - \hat{K}^* = 0; \\ \hat{S}^* = \hat{C}^* + \hat{G}^*; \\ \hat{G}^* = \varepsilon \hat{P}^* + (1 - \varepsilon) \hat{Q}^*; \\ \hat{C}^* = -\varphi \hat{G}^*; \\ \hat{A}^* = \hat{S}^*. \end{array} \right.$$

This linear equations system can be solved for the growth rates of the eight variables involved, and below we present the solution:

$$\left\{ \begin{array}{l} \hat{C}^* = \hat{K}^* = (n+x) \frac{(\sigma - \varepsilon)\theta}{\sigma\theta + \chi\varepsilon + \beta - 1}; \\ \hat{G}^* = \hat{R}^* = -(n+x) \frac{(\sigma - \varepsilon)\theta}{\varphi(\sigma\theta + \chi\varepsilon + \beta - 1)}; \\ \hat{P}^* = -(n+x) \frac{(\sigma - \varepsilon - \varphi + \varphi\varepsilon)\theta}{\varphi(\sigma\theta + \chi\varepsilon + \beta - 1)}; \\ \hat{Q}^* = -(n+x) \frac{(\sigma - \varepsilon + \varphi\varepsilon)\theta}{\varphi(\sigma\theta + \chi\varepsilon + \beta - 1)}; \\ \hat{A}^* = \hat{S}^* = (n+x) \frac{(\varphi - 1)(\sigma - \varepsilon)\theta}{\varphi(\sigma\theta + \chi\varepsilon + \beta - 1)}. \end{array} \right.$$

Note also that (C.2.1), (C.2.7), and (C.2.12) imply that (C.1.4) in the steady state simplifies to

$$(D_r^* - S_r^*) = (\rho - \hat{A}^*)(A_r^* - R_r^* K_r^*).$$

Eidesstattliche Erklärung

Ich erkläre hiermit, an Eides Statt, dass ich meine Doktorarbeit selbständig und ohne fremde Hilfe angefertigt habe und dass ich alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehenden Ausführungen meiner Arbeit, besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert habe.

Kiel, 5. November 2009

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