

**Links between the LIMOBEL Components:  
Summary of Discussion**

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# 1. Links between the three LIMOBEL components: summary of the discussion

This note summarizes the conclusions from the discussion between FPB, FUCaM and VITO on the links between the three model components of LIMOBEL.

Note: The text uses the following classification for zones in Belgium

NUTS0	Belgium
NUTS1	3 regions
NUTS2	Provinces
NUTS3	'Arrondissementen/arrondissements'
NUTS5	Municipalities
LAU2	Municipalities

NUTS = Nomenclature of Territorial Units for Statistics  
LAU = local administrative units

Both NUTS5 and LAU2 refer to municipalities. In what follows we will use LAU2 for the municipalities.

## 1.1. Economic Model

This part of LIMOBEL extends the PLANET model (referred to here as PLANET 1), by incorporating a new economic module that replaces the MACRO module of PLANET 1. The aim is to integrate the two-way interactions between the economy and transport. In what follows the new version of PLANET that will result is called PLANET 2. The following steps are modelled:

### 1.1.1. Economic projections

The economic projections use a computable general equilibrium model for Belgium, in which the three Belgian regions (NUTS1) are modelled. In each region the model considers several production sectors, different consumer groups and the government. The federal government level is also considered. A final economic agent is the rest of the world. The model looks at policies in the transport sector together with more general policies. The interaction between the transport sector and the economy in general is modelled explicitly.

### 1.1.2. Transport generation

Transport generation for freight and passenger transport is modelled on the basis of the economic projections, projections of transport costs and (exogenous) demographic projections by NUTS3 zone.

- Freight transport:
  - o By NST/R chapter
  - o Distinction between national transport, transport from Belgium to ROW, transport from ROW to Belgium and transit
- Passenger transport:
  - o commuting, school: production and attraction by NUTS3 zone in Belgium, ROW aggregated as 1 zone
  - o business, other: national and international

### 1.1.3. Trip distribution

Trip distribution is modelled both for freight and passenger transport. The modelling is the same as in PLANET 1, but uses in addition projections at the regional level from the economic module to introduce an additional reference point (in addition to the national reference point that was used in PLANET 1).

- Freight transport:
  - o By NST/R chapter
  - o Endogenous trip distribution at NUTS3 level for national transport, based on an estimated gravity model by NST/R chapter
  - o Exogenous trip distribution for international transport (NUTS3 for Belgium, NUTS0/NUTS1 for EU, aggregate for non-EU)
  - o In PLANET 1 the freight distribution model is based on an OD matrix for 2000. In PLANET 2 the exercise will be repeated with a more recent matrix when it becomes available.
  - o Note: in PLANET 1 we did not find data for the OD matrix of LDV, so we had to make an assumption about the distribution of these flows.
- Passenger transport:
  - o Commuting, school: endogenous trip distribution at NUTS3 level for Belgium and ROW as an aggregate, based on an estimated gravity model
  - o Business, other: data availability?
- The estimated gravity models for trip distribution use as explanatory variables characteristics of the origin and destination zones and the average generalised transport costs per zone pair, as derived in the modal and time choice module.
- Note: the level of detail and the type of explanatory variables are limited by the information that is available for future years in order to make projections. This is the main reason for limiting the exercise to the NUTS3 level, rather than a more detailed level of spatial disaggregation.

### 1.1.4. Modal and time choice

Modal and time choice is modelled per zone pair (as in PLANET 1 but with a somewhat different definition of modes):

- Freight transport:
  - o By NST/R and zone pair (with definition of zones as in PLANET 1)
  - o Modes: inland navigation, rail, road HDV, road LDV, SSS
    - Note: SSS was not yet modelled endogenously in PLANET 1
    - Note: DSS, air and pipelines remain exogenous
  - o For road freight: peak and off-peak
  
- Passenger:
  - o By trip purpose
  - o By zone pair (at least for commuting and school)(with definition of zones as in PLANET 1)
  - o Modes: company car solo, company car pool, private car solo, private car pool, motorcycle/moped, bus, tram/metro, rail, slow
    - Note: in PLANET 1 bus/tram/metro were considered as 1 category, here they are split into 2 categories
    - Note: in PLANET 1 no distinction was made between company cars and private cars – it is our aim to introduce this distinction here if the information is available
    - Note: air remains exogenous
  - o Distinction between peak and off-peak
  
- Note: the model considers both transport within and between the zones
  
- Modal choice is modelled using a nested CES function for each zone pair that is a function of the generalised costs of each mode for the zone pair. The generalised costs depend on
  - o the distance
  - o the monetary costs per vkm/transport/trip
  - o the various types of time costs per vkm/transport/trip.

### **Input from NODUS into PLANET 2**

An important input in the modal and time choice module of PLANET 2 consists of information on the different components of the generalised costs. Part of this information should be provided by the NODUS model. It concerns a transformation of the following NODUS outputs to the level of aggregation considered in PLANET 2:

- Average distance per NODUS zone pair per NODUS (sub)mode, NST/R chapter and trip purpose (in each year)
- Average transport time per NODUS zone pair per NODUS (sub) mode, NST/R chapter and trip purpose + components of transport time (in each year)

The transformation does not only entail an aggregation from the NODUS zones and modes to the PLANET 2 zones and modes, but we also need to complement this by these cost elements

for transport that stays within a given LAU2 zone.

Since PLANET 2 makes a distinction between peak and off-peak transport, a way should also be found to derive cost information for transport in these two periods from NODUS.

Moreover, NODUS should give an indication of how travel time changes over time as transport flows grow and infrastructure is changed.

The input from NODUS to PLANET 2 will probably be incorporated with a lag of 1 year, to avoid iterations between the two models in the same year.

#### **Coordination between the environmental model and PLANET 2**

The historical fleet of company cars and their use (based on DIV and on a number of projects: BIOSES, COCA and PROMOCO)

#### **1.1.5. Vehicle stock:**

The vehicle stock module determines the size and composition of the vehicle stock. It is most detailed for passenger cars. In each year the model determines the number of cars that are scrapped. The remaining total car stock is compared with the desired car stock. This results in the number of new purchases. Next, the choice of size, fuel type and car technology is modelled, dependent on the costs of each car type. The model therefore constructs the car stock in each year according to age, size, fuel type and technology.

For the other vehicle types, the size of the vehicle stock is derived from transport demand, while the composition of the vehicle stock is imposed exogenously. The exogenous assumptions should be coordinated with VITO.

In the vehicle stock module we also compute the average monetary costs of the different PLANET 2 modes: these will depend on the costs per vehicle type and age and the share of the different vehicle types and ages. The fuel efficiency will be based on the environmental model of VITO. A distinction is made according to road type. The evolution of the fuel efficiency will be the same for all road types, only the absolute figures differ.

In the vehicle stock module we also compute the average emission factors of the different PLANET 2 modes: these will depend on the emission factors and environmental costs per vehicle type and age and the share of the different vehicle types and ages. The emission factors will be based on the environmental model of VITO. A distinction is made according to road type.

### **Input from environmental model into PLANET 2**

- Emission factors of different vehicle types, by road type (when relevant) in each year
- Fuel efficiency of different vehicle types, by road type (when relevant) in each year –  
Note that the fuel efficiency is in fact linked to the emission factor for CO<sub>2</sub>, for a given fuel type

### **Coordination between environmental model and PLANET 2**

Exogenous evolution of vehicle stock for vehicles other than cars

Historical fleet

#### **1.1.6. Welfare**

PLANET 2 calculates the welfare impacts of various policies with respect to the reference scenario. The welfare impacts are calculated for different groups of consumers and for the producers. It takes into account the way in which additional revenue is raised or the way in which projects are financed.

The welfare module also calculates the change in the environmental damage of transport. In this part we use the results of the three models. Since the emission factors depend on the road type, the share of the different road types (by mode) should be taken from NODUS. NODUS will produce this information at the LAU2 level. This must be transformed to the NUTS3 level. Moreover, NODUS gives this information only for interzonal transport. A solution must be found for intrazonal transport.

For some pollutants the environmental damage depends on the place where the pollutants are emitted. VITO will investigate whether it is possible to compute the damage cost per tonne of emissions according to the NUTS3 zone where it is emitted. (Note that the patterns of population density are also likely to change over time – however, is it probably not possible to incorporate this in the model)

Note that the emission damage considered is the damage caused by pollutants emitted in Belgium (by Belgian and foreign transporters) and not the damage related to changes in the ambient concentrations in Belgium (which are also influenced by emissions abroad). It will be checked whether the damage of Belgian emissions can be split up in damage in Belgium and damage abroad.

### **Input from NODUS into PLANET 2**

- Share of the different road types for car, road HDV and road LDV transport per LAU2 zone (interzonal transport only)

### **Input from environmental model into PLANET 2**

- Damage per tonne of emissions for all relevant pollutants according to the NUTS3 zone where it is emitted – with a distinction according to urban, rural and highway

## **1.2. Network model**

The NODUS model starts from given OD matrices and is able to assign the flows to modes and routes. The current version of the model looks at freight flows only. In LIMOBEL it is extended to integrate passenger flows. The model considers the flows between zones, but not the flows within a given zone (except for the part of interzonal journeys that concerns the transport from the centroid to the point of connection with the major routes). Therefore, it is important to work at a more detailed level of spatial disaggregation, namely LAU2. Even with LAU2 zones some flows will however not be represented.

We use as a starting point for NODUS in LIMOBEL the transport flows by mode produced by PLANET, and to use NODUS in LIMOBEL mainly for the choice of the routes and the sub-modes for interzonal journeys. This requires the transformation of the OD matrices by mode produced by PLANET into OD matrices by mode at the level required by NODUS. This could be done by applying an upscaling/downscaling procedure based on the detailed matrices that are available for a given base year (freight matrix for 2005 and commuting and school matrix for 2001). This implies however that a change in transport costs for a zone pair that stays in a given NUTS3 zone will not affect trip distribution!

A problem remains for business and other passenger transport, for which the available information is limited, but which form an important part of passenger flows.

There is also a problem for road LDV if the new OD matrix for freight transport in 2005 does not contain data on LDV (to be checked by FUCaM). In that case the OD matrix for LDV should be derived in another way (i.e., loosely based on the OD matrix for trucks as in PLANET 1)

The submodes to be considered in NODUS would be:

- Freight transport:
  - o Road HDV: truck and articulated truck (the definition of these two types should be coordinated with VITO)



- Rail: diesel and electric
- Road LDV (if possible)
- IWW: different vessel types (to be coordinated with VITO)
- Passenger transport
  - Car
  - Rail: standard diesel, standard electric and high speed train (the share of high speed train will be set exogenously)

The slow modes are not considered because NODUS does not model the flows within LAU2 zones. Because of the same reason motorcycle/moped and tram/metro would be covered only to a partial extent. However, trams that cover larger distances will probably become more important in the future.

From the discussion of the NODUS model it also seemed that the shares of the different rail types (diesel/electric/HST) in the environmental model and PLANET 2 should not be taken from NODUS, but should be imposed exogenously instead.

Another input for NODUS is the monetary cost per vkm of the different modes.

- Monetary cost per vkm for the average car, LDV, HDV
- Monetary cost per pkm of rail, bus, tram/metro
- Monetary cost per tkm of rail and IWW
- Evolution of the wage cost
- Evolution of VOT

#### **Input from PLANET 2 into NODUS**

- OD matrices for freight transport at level of PLANET 2 zones – per NST/R category (in each year) – per mode (HDV, LDV, rail, IWW)
- OD matrices for commuting and school transport at level of PLANET 2 zones (in each year) – per mode (car, rail, bus, tram/metro(?))
- OD matrices for business and other transport at level of PLANET 2 zones (in each year) – conditional upon availability of information!
- Monetary cost per vkm of average car, LDV and HDV (taking into account fuel efficiency as determined in the environmental model)
- Evolution of the wage cost
- Evolution of VOT
- The link between PLANET 2 and NODUS will probably have to be integrated with a lag of 1 year

### Coordination between PLANET 2 and NODUS

Transformation of OD matrices to the level of spatial disaggregation of NODUS

Construction of OD matrix for LDV (dependent on available information)

VOT for different time components

### Coordination between PLANET 2, NODUS and environmental model

Monetary costs per pkm of rail, bus, tram/metro (taking into account fuel efficiency as determined in the environmental model)

Monetary cost per tkm of rail and IWW (taking into account fuel efficiency as determined in the environmental model)

Share of different road types for car, road HDV and road LDV transport per LAU2 zone

## 1.3. The environmental model

The environmental model determines the emission factors of the different vehicle types in the different years. In addition it provides information on the fuel efficiency. It also determines the damage costs per tonne of these emissions.

The level of detail for the vehicle types considered by VITO is much higher than for the two other models. This is summarized in the following table. The last column makes a proposal about the calculation of average values, given the vehicle types considered by VITO. This is also the place where there is a link between PLANET 2 and NODUS on the one hand and the environmental model on the other hand. Whenever the label “exogenous” is mentioned, the decision should be coordinated between the three teams.

**Table 1** Modes considered in LIMOBEL and links between the three models

	PLANET 2 modal and time choice module	NODUS	Environmental model	Determination of shares to calculate averages
Freight transport	Road HDV	Truck Articulated truck	Differentiation by age, size, fuel type and Euro class	Age, Euro class: vehicle stock module PLANET 2 Size: exogenous Fuel type: exogenous
	Road LDV	Road LDV	Differentiation by age, fuel type/	Age, Euro class: vehicle stock module

			technology, Euro class	PLANET 2 Fuel type/ technology: exogenous
	Inland waterways	Different vessel types (weight classes)	Ships/pontoons Weight classes?	NODUS?
	Rail	Electric Diesel	Differentiation by Euro class, type, fuel	Exogenous
	SSS	-	Differentiation by age, vessel type	Exogenous
<b>Passenger transport</b>	Private car Company car	Car	Differentiation by age, size, fuel type/ technology, Euro class	Vehicle stock module PLANET 2
	Motorcycle/moped	Motorcycle?	Differentiation by Euro class, fuel type and size	Exogenous
	Bus	Public transport?	Differentiation by age, size, fuel type/ technology	Age, Euro class: vehicle stock module PLANET 2 Size, fuel type/ technology: exogenous
	Tram/metro		Differentiation by age, type	Exogenous
	Rail	Electric Diesel HST	Differentiation by Euro class, type, fuel	Exogenous

In addition the three teams should coordinate when setting occupancy rates, load factors, and (for rail) the transformation of gross tkm to passengers transported (pkm) or tonnes transported (tkm).

**Input of PLANET 2 into the environmental model**

- Composition of the car stock and its evolution (for the simulation period)
- Age, Euro class of HDV, LDV, bus (note: Euro class of new vehicles will be linked to year of purchase)
- Evolution of damage cost per tonne over time (as a function of GDP per capita)

**Input of NODUS into the environmental model**

- Share of different weight classes for inland navigation

**Coordination between the three models**

All elements that are labelled “exogenous” in the previous tables

Load factors, occupancy rates, ...

## 2. General coordination issues

- Time horizon: 2030
- Time period historical data vs. simulated data:
  - Simulations start in 2005, except for vehicle fleet (simulations starting in 2007 or 2008)
- Common base year for real prices: 2005
- Policy instruments: to be decided later
- Historical fleet data: will be coordinated between FPB and VITO

## **Literature review for ISEEM and LIMOBEL**

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## List of abbreviations

CBA	Cost-benefit analysis
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
CH <sub>4</sub>	Methane
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
CRIA	Constant relative inequality aversion
CRS	Constant returns to scale
D-S	Dixit-Stiglitz
DSGE	Dynamic stochastic general equilibrium
EU	European Union
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GHG	Greenhouse gases
HCFC	Hydrochlorofluorocarbon
KLE	Capital-labour-energy
LES	Linear expenditure system
LUCC	Land-use/cover change
MES	Minimum efficient scale
NEG	New economic geography
NH <sub>3</sub>	Ammonia
PC	Perfect competition
PFC	Perfluorocarbon
PM <sub>10</sub>	Particulate matter with a diameter smaller than 10µm
R&D	Research and development
SO <sub>x</sub>	Sulphur dioxides
TFP	Total factor productivity
VAT	Value added tax
VOC	Volatile organic compounds

# I. Introduction

The aim of this report is to give an overview of the relevant literature for long-term economic modelling. The review was conducted in the framework of the ISEEM and LIMOBEL projects, two projects financed by the Belgian Federal Science Policy office. Since the aims of the two projects were similar at this stage, it was decided to join forces for this task. The literature review is the result of a close collaboration between the research team involved in the two projects. However, since the aims of LIMOBEL and ISEEM are different, the conclusions drawn from the literature review for the economic modelling differ in the two projects. These conclusions are described in separate notes.

The next two paragraphs give a short description of the two projects. Next, we turn to the literature review, which covers both applied and theoretical models.

## A. LIMOBEL: a short description

The aim of LIMOBEL is to develop a fully operational modelling tool to study the impact of transport policies on the economy and on emissions. The project will produce long-term projections (up to 2030) of passenger and freight transport demand in Belgium. A baseline scenario will be constructed which will be compared with alternative policy scenarios for more sustainable transport. In the alternative policy scenarios packages of instruments will be considered, including pricing instruments, regulation and infrastructure measures. Besides transport instruments the project may also consider more general instruments (such as labour taxes, transfers) in order to ensure budget neutrality. A cost-benefit analysis will be made of the policy packages.

The LIMOBEL modelling tool consists of three components: a model to determine long-term transport projections, a network model that assigns the transport flows to the network and an environmental model. The present paper provides an input in the first of these components. More specifically, the model for long-term transport projections incorporates a long-term economic model in which the interactions between transport and the economy are incorporated explicitly.

## B. ISEEM: a short description

The ISEEM project develops and implements for Belgium an integrated spatio-economic-ecological modeling approach, which can be used to assist policy makers in their choice of long-

term sustainability policies. The project aims to represent the state-of-the-art in different areas of economic, transportation, land-use and environmental modelling.

More specifically, the project builds a general equilibrium model of the New Economic Geography type (NEG). This refers to a class of economic models that looks not only into the equilibrium in the economy of a single country, but takes into account regional economic effects such as concentration and specialization of sectors, regional labour market effects, regional economic disparity, etc.

## II. The Applied Models

### A. The models under review

Before we plunge into a detailed description of the modelling practice, we first present an overview of the different models we have reviewed in this literature survey. The models we reviewed can be classified according to a few broad categories. Next to the more conventional CGE models<sup>2</sup>, we distinguish a group of applied models making use of New Economic Geography theory which we shall refer to as the “NEG CGE models”. Next to these two broad categories, we distinguish the land–use and transportation interaction models and models integrating economic systems with ecosystems. In a last category (‘macro–economic models’) we lump together two *sui generis* models, the macro–econometric model of NEMESIS and the neo–classical growth model of Mobilec. Table 1 gives an overview of the applied models considered here.

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<sup>2</sup> Computable General Equilibrium (CGE) models are simulations that combine the abstract general equilibrium structure formalised by Arrow and Debreu with realistic economic data to solve numerically for the levels of supply, demand and price that support equilibrium across a specified set of markets. They are a standard tool of empirical analysis, and widely used to analyze the aggregate welfare and distributional impacts of policies whose effects may be transmitted through multiple markets, or contain menus of different tax, subsidy, quota or transfer instruments.

**Table 1: Overview of Applied Models**

Model type	Models reviewed	Main source
Conventional CGE	GEM-E3	Capros et al. (1997) and
	GEM-E3 – regional version for Belgium	Saveyn and Van Regemorter (2007)
	EPPA	Paltsev et al. (2005)
	Greenmod II	Bayar (2006)
	Mayeres (1999)	Mayeres (1999)
	MMRF-Green	Adams et al. (2002)
	EDIP	Ivanova et al. (2007)
NEG CGE	CGEurope I and II	Bröcker et al. (2001, 2004)
	RAEM 2.0 and 3.0	Thissen (2004) and Ivanova (2007)
	REMI	REMI (2007)
Transport-land use interaction	RUBMRIO	Ruiz Juri and Kockelman (2003)
	RELU	Safirova et al. (2006)
Integrated economic-ecological models	GEEM-Alaska	Finoff and Tschirhart (2004)
Macro-economic	NEMESIS	Nemesis (1999)
	Mobilec	Van de Vooren (2002)

### 1. The conventional computable general equilibrium models

The **GEM-E3** model ('General Equilibrium Model for Energy-Environment-Economy interactions') aims at modelling the relationship between macro-economics, energy and the environment. Developed under the auspices of the European Commission, it focuses on the European level (as a whole or differentiated by country). In an environmental module, it considers policies with regard to energy related pollution. Some of the main applications are:

- The examination of the impact of creating a market of tradable pollution permits within the EU;
- The evaluation of macro-economic implications of the EU's targets for the Kyoto negotiations for greenhouse gas mitigation;
- The study of a possible "double dividend" for environment and employment.

Its multi-country and multi-sector design makes it possible to analyze distributional consequences of the aforementioned policies, within countries and among agents. The allocation of capital, trade and the impact on government finances and the current account can be analyzed. Its time horizon is 30 years. It comprises 18 sectors of production. The GEM-E3 model is extended to incorporate imperfect competition and increasing returns, making it particularly useful to analyze the above question with European integration at the background. A regional version of GEM-E3 has been applied for Belgium by Saveyn and Van Regemorter (2007), to evaluate the impact of different air pollutant abatement policies on the Belgian regions.

The **EPPA** model is the workhorse of the MIT Joint Program on the Science and Policy of Global Change. It is a recursive–dynamic multi–regional model of the world economy. It aims to develop long term (100 year) projections of economic growth and anthropogenic emissions of greenhouse gases and aerosols. EPPA is integrated as the ‘human activity’ module in a wider integrated global system model, but can also be used as a stand-alone model. Some of the policy questions that are addressed with the model include the economic implications of the diverse emissions mitigation policies. In this review, we made use of the 4<sup>th</sup> version of EPPA, as described in Paltsev et al. (2005).

The **Greenmod II** model is a multiregional model for Belgium similar to EPPA, aimed at being the first multi–regional, multi–sectoral CGE model of the Belgian economy that can be used to evaluate the regional effects of different environmental and energy policies. It aims to take into account the complex interdependencies between Belgian regions, and also includes a representation of different income categories to analyze interpersonal distributional issues.

The model of **Mayeres** (1999) seeks to shed light on improved transport pricing in the light of various externalities, given the need of policymakers to raise revenue through distortionary taxation and the need for an equitable distribution of the tax burden and feedback effects. Policy instruments include peak road pricing, higher fuel taxes, public transport subsidies, which are weighed against lump sum transfers and labour income taxes. In this respect, the study is closely related to the double dividend literature. To this end a static CGE model for Belgium is developed. There is no regional breakdown.

The **Monash Multi–Regional Forecasting (MMRF)–Green** model is a multi–regional, dynamic, computable general equilibrium model. It distinguishes up to eight Australian regions and, depending on the application, up to 144 commodities/industries. The model contains a module able to capture energy usage and greenhouse gas emissions by fuel, user and region. It fits in the tradition of Johansen/ORANI models, using a system of linearised equations. Policy questions that are answered through the model are the effects of regional infrastructure projects and the effects of different policies to reduce Australian emissions of CO<sub>2</sub> in line with Kyoto commitments.

Finally, **EDIP** is designed to evaluate income distribution and inequality effects of economic and environmental policies. Its relative strength comes from the detailed way in which different household types and transport sector are represented.

## 2. [New economic geography computable general equilibrium models](#)

A distinct class of CGE models is the so–called “NEG CGE models”, explicitly incorporating elements from the New Economic Geography literature. The principal aim of the models

considered is to analyze the (spatial) economic impact of new transport infrastructure. Economic impacts have to be understood as indirect effects (for example: migration, improved market access and access to varieties, possibly leading to agglomeration). Other policies with a possible regional impact (e.g. capital income taxation) may be analyzed as well. Models in this tradition are CGEurope, RAEM and REMI.

The **CGEurope** models have been designed mainly to analyze the static impacts on regional welfare of different EU transportation policies. These projects comprise of new network links: high speed railways, conventional railways, roads (either in the EU-15 or EU-27), pricing scenarios such as the introduction of social marginal cost pricing and the development of a dedicated rail network scenario. The impact on some 1372 European regions (in the EU-27 and non-aligned European nations) is studied. The CGEurope models examine indirect effects on welfare through improved accessibility, but model only limited agglomeration effects. The CGEurope I model is able to provide simulations at the greatest level of regional detail but is limited in sectoral detail, whereas the CGEurope II model provides more sectoral detail (8 sectors), but uses a lower level of regional disaggregation (288 regions).

The different versions of the RAEM models are developed for the Netherlands. They distinguish 40 regions. The **RAEM 2.0** version allows for agglomeration effects through migration. It has, for example, been applied to examine the spatial effects, such as job reallocation, of a new railway link from the Dutch Randstad (Amsterdam) to the province of Groningen. **RAEM 3.0** extends its predecessor by incorporating dynamics, extending the government sector, introducing a foreign sector, making unemployment endogenous and introducing passenger trips in a more detailed way.

**REMI** Policy insight is a structural forecasting and policy analysis model. It integrates methods from several other model types to help its user understand the total macro-economic effects of policy decisions. It has the inter-industry detail available from input-output models. It allows for behavioural reactions to housing and consumer prices, wages and production costs, as in computable general equilibrium models. Dynamic responses and other parameters are estimated using econometric methods. It represents various agglomeration effects using new economic geography theory. The model incorporates some agglomeration effects not found in other models, such as the 'labour access' effect. The model has been used to evaluate the effects of various EU investments (transport and non-transport related) on the regional economies of Southern Italy and Andalusia (Spain). It has been recently applied for Belgium and used by DG REGIO for the analysis of the use of its cohesion funds.

### 3. Land use and transportation interaction models

A distinct kind of models tries to capture in more detail the interaction between transportation and land use. RUBMRIO and RELU are two examples of this kind.

**RUBMRIO** is a transportation economic model that simulates the flow of goods, labour, and vehicles across a multi zonal area (e.g. across the 254 counties in the state of Texas, as well as domestic export shipments to 49 U.S. States and foreign export shipments to 18 ports). RUBMRIO simulates trade flows across zones in a region, as motivated by foreign and export demands, and computes this trade across numerous economic sectors. Input–output relationships/tables are used to anticipate consumption needs of commodity producers, and multinomial logit models distribute commodity flows across origin zones and shipment modes. The model incorporates two factor markets, namely labour and floorspace. It has been used to predict the spatial redistribution of economic activities, population, rent and wages following the implementation of a large transport infrastructure project in Texas.

**RELU** is a spatially disaggregated CGE of a regional economy that is grounded in micro–economic theory and can be used for comprehensive welfare analysis. In order to shed light on the nature of interaction between land use, transportation and other forces in the regional economy, RELU is supposed to be integrated with a detailed transportation model. It has been applied to evaluate the land use effects of road pricing policies.

It should be noted that RELU and RUBMRIO are not situated in the New Economic Geography tradition. They do not exhibit the NEG’s distinguishing features such as increasing returns and the preference for variety, and so do not capture the circular causality of NEG models.

### 4. Integrated economic–ecological models

Next to the classical CGE models, we consider an integrated **Economic–Ecosystem model, applied to Alaska**. The basic philosophy behind that model is the following: ecosystems and economies are jointly determined, and both systems are general equilibrium in nature. The particular model considered links the Alaskan economy to an 8 species marine ecosystem, including an endangered species (the Steller sea lion), through the fisheries and tourism sector. The impact of some fishing restrictions is then analyzed. In our review we will only discuss this model in the section on modelling the environmental impacts (Section II.H).

### 5. Macro–economic models

**NEMESIS** is a large macrosectoral econometric model of the European economy (with the US and Japan being included), aiming to give short and medium term forecasts, and to treat policy issues related to the environment and R&D. It builds upon the E3ME model, with more user



friendly software, a new version of the energy / environment module and with the incorporation of recent economic theory developments on R&D and innovation spillovers.

**Mobilec** is a modified neoclassical growth model. It describes the relationship between the economy, mobility, infrastructure and other regional features in an interregional dynamic way. A main characteristic of the model is the representation of the two-way interaction between economy and mobility. In the traditional transport models transport is estimated as a derived demand of the economical development scenarios. The Mobilec model also determines the contribution of infrastructure to economic development, by including transport (productive mobility) in the production function. Outputs are time paths on macroeconomic aggregates, freight transport by modes within and between regions and passenger transport by modes, commuting, business and other purposes.

## **B. Firm behaviour**

When reviewing the modelling of firm behaviour, one has to answer following questions:

- Which arguments enter the production function?
- What is the functional form of the production function?
- Does the production process exhibit economies of scale?
- How does competition take place, i.e. what is the market structure?
- Does the model incorporate any elements of new economic geography, and if so, which ones?

Table 2 summarises the discussion.

**Table 2: The representation of producer behaviour**

	No. of industries	Capital in production function ?	Vintage capital?	Labour by skill group?	Functional form	Regional capital mobility?	Sectoral capital mobility?	Scale economies?	Market Form	'Love of variety' inputs?	Labour access effect?
GEM-E3	18	Y	N (Y in extension)	N (Y in extension)	CES	N (Y in extension)	Y/N (optional)	N (Y in extension)	PC (Cournot / Bertrand in extension)	N (Y in extension)	N
Greenmod II	62	Y	Y	N	Leontief/ CES	N	N (even for malleable part)	Y	Cournot and Monopolistic competition	N	N
EPPA	5	Y	Y	N	Leontief/ CES	N	Y (malleable part)	N	PC	N	N
Mayeres	12	Y	N	N	Leontief/ CES	n.a.	Y	N	PC	N	N
EDIP	59	Y	N	N	Leontief/ CES	N	N	Y	D-S	N	N
CGEurope I	6	K and L Lumped together	N	N	Cobb-Douglas	N	N	N / Y	PC / D-S	Y	N
CGEurope II	3		N	N	CES	N	N	Y	PC / D-S	Y	N
Raem 2.0	14	N	n.a.	N	Cobb-Douglas /CES	n.a.	n.a.	Y	D-S	Y	N

	No. of industries	Capital in production function ?	Vintage capital?	Labour by skill group?	Functional form	Regional capital mobility?	Sectoral capital mobility?	Scale economies?	Market Form	'Love of variety' inputs?	Labour access effect?
Raem 3.0	14	Y	N	N	Cobb–Douglas /Leontief /CES	N	N	Y	D–S	Y	N
REMI	26 - 30	Y	N	Y	Cobb–Douglas /CES	N	N	Y	D–S	Y	Y
MMRF - Green	13	Y	N	Y	Leontief/ CES	Y	N	N	PC	N	N
RUBMRIO	21	N	N	Y	Cobb–Douglas implied	N	N	N	PC	N	N
RELU		Y	N.	Y	Cobb–Douglas /CES	Y	N	N	PC	N	N
GEEM Alaska	3	Y	N	N	CES	Y (between Alaska and RoW for 1 sector)	Y	N	PC	N	N
Mobilec	1	Y	n.a.	N	Cobb–Douglas	Y	n.a.	N	PC implied	N	N
NEMESIS	30	Y	(capital quasi fixed factor)	N	McFadden Cost function	N	N	Y	Monopolistic Competition	N	N

PC: Perfect competition; D–S: Dixit–Stiglitz monopolistic competition; n.a. : not applicable

## 1. The production function and production factors

It is obvious that the choice of which production factors to include, depends greatly on the purpose of the model. The most extensive production functions, with several nests reflecting the choice between several detailed inputs, are found in the environmental models. These models must of course capture the most complex substitution mechanisms between different kinds of polluting inputs. Usually models such as these will provide different production functions for different sectors.

The GEM-E3, Greenmod II and EPPA models are three models concerned with the economic effects of the abatement of greenhouse gases. The production functions in these models capture a wide range of inputs. Next to capital and labour, electricity, fuels and a wide range of intermediates are usually included. The level of detail ranges from 3 fuels (coal, oil, gas) in the GEM-E3 model to 9 in the Greenmod II model. The GEM-E3 model only allows for one nested production function for its 18 sectors.<sup>3</sup> The production function consists entirely of CES nests. The Greenmod II model distinguishes three groups of sectors ('conventional' energy producers, agriculture and 'other industry and services') and 2 sectors producing backstop energy (Coal gasification and carbon-free electricity generation). The EPPA model considers 5 groups of sector (Refined Oil, Primary energy, Electricity, Agriculture and 'Energy Intensive, Transportation and Other industries and services'). Different substitution elasticities for different sectors within the latter group are allowed for. Next to these 5 sectors, 4 backstop energy sectors are modelled (Shale oil, Wind and Solar, Coal gasification and Advanced Fossil electricity). A noteworthy feature of the EPPA electricity production sector is that it allows various substitution possibilities between different generating technologies. Conventional suppliers are supposed to be perfect substitutes with each other and most backstop technologies. Solar and wind energies are modelled as imperfect substitutes for all other sources, due to their erratic supply.

The use of vintage capital specifications is sometimes used in the environmental models. New capital installed at the beginning of each period is malleable, i.e. highly substitutable. At the end of a period, a part of this malleable capital becomes rigid, and frozen into the prevailing techniques of production. The remaining malleable portion can have its input proportions adjusted to new inputs prices or can be reallocated to other sectors. Each of the capital vintages is tracked through time as a separate capital stock. Production that uses a vintage of rigid capital is subject to a fixed coefficient transformation process in which the shares of capital, labour and energy are identical as in the first year of the vintage. None of the stocks of rigid capital are subject to improvements in energy efficiency. The vintage capital structure is thus one way of slowing down the effects of environmental policies or energy price movements.

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<sup>3</sup> Though different parameters for different sectors can be calibrated, of course.

Mayeres (1999), which focuses heavily on transportation, uses nested CES functions considering 12 main sectors. These 12 sectors are divided into 4 groups using different production functions. Inputs include among others business transport and freight transport. A distinction is made between different transport modes, and between peak and off-peak transport (for road transport). The transport labour costs depend on the level of congestion.

The NEG models we reviewed in general use less sectoral detail and less elaborate production functions. Their focus lies less on describing the production process in detail to unravel the different substitution mechanisms between value-added factors and different kinds of energy, than on capturing spatial effects.

The RAEM 2.0 Model for example, just uses a two tier production function. The first tier uses a Cobb-Douglas function with labour and intermediate inputs. Note that capital is not included. Labour is the only value added factor, and is assumed to be mobile across sectors. This choice is certainly driven by the need to keep the model simple, since its focus is on agglomeration through the interaction between labour mobility and firm location decisions (as in the standard core-periphery model of New Economic Geography). In any NEG model the choice of which inputs to include, and of the degree of mobility of these inputs, is crucial to the nature of spatial effects. The RAEM 2.0 model thus rules out agglomeration through capital mobility. The second tier in the production function distributes the amount of intermediates demanded among the different suppliers according to a CES function. This way of modelling relates closely to the classic NEG 'love of variety' concept that will be described in the section on consumer behaviour. (section 1.3.) Due to the CES specification, the production function exhibits internal economies of variety. An increased diversity of inputs allows producers to use a more roundabout production process and lower unit costs at given input prices. In a spatial framework, this implies that producers will want to locate in a region with better access to the greatest variety of inputs, thus inducing an agglomeration effect. The strength of this effect depends on the elasticity of substitution. The lower this elasticity, the higher is the productivity gain from input diversification. The strength of this effect will depend on the industry. For example, electrical equipment industries, machinery and cars are dependent on specialised inputs which cannot easily be substituted, so input variety effects will be stronger for these industries. The substitution elasticity should thus be estimated / calibrated for each industry. In general, this is not done because of the lack of reliable sectoral time series data.

The production functions in the CGEurope I and II models seem to be modelled in a similar way. They consist of nested CES functions, the lower nest being a CES aggregate over different intermediate inputs. (In CGEurope I the first level of the production function is Cobb Douglas.) It should be noted that the production function consists of one value added factor, which is assumed to be immobile across regional borders. The model thus rules out a self reinforcing

process of agglomeration due to factor mobility (usually dubbed 'circular or cumulative causation', according to Myrdal (1957)) that is so typical for many of the New Economic Geography models. In the absence of factor mobility, the spatial effects of infrastructure improvement on the different European regions from this model should thus be considered as short term effects. CGEurope I makes a distinction between a local goods and a tradable goods sector. CGEurope II does not make such a distinction.

We find many elements of the above in the REMI model. Its Cobb–Douglas production function consists of labour, capital, fuels and intermediates. A novel element in the REMI model is that different kinds of labour – according to occupational group – are allowed. Labour is mobile across borders. The model contains an equation measuring the productivity of intermediate inputs depending on the effective distance of the input supplier and a sector specific productivity advantage parameter, which is just the substitution elasticity between intermediates in the lower nest of the production function.

The REMI model introduces a novel spatial effect relating to the access to specialised labour. Labour productivity is made dependent on the access to specialised labour in a region. For each occupation, a labour productivity equation is calculated. Occupational productivity is dependent on the *number* of all potential workers and their commuting cost to that region. The number of potential workers is the main determinant of productivity, since it is assumed that even within occupational categories each single worker brings a set of unique skill to the firm. The greater the pool of workers, the higher is the chance that the best man for the job can be chosen. Again, the strength of this effect is determined by an elasticity parameter, by occupation.

The growth model of Mobilec uses the classic Cobb–Douglas production function, with the novelty that the arguments of the production function now include – next to capital and labour – productive mobility by mode between regions as inputs. This essentially captures the link from 'mobility to economy' as envisaged by the model.

In order to derive factor demand equations, NEMESIS describes the production process by a cost function, rather a production function. An average variable symmetric general McFadden cost function is used, which is improved to account for the presence of quasi–fixed factors of production such as R&D capital and physical capital. Variable inputs are labour, energy and materials. Using Shephard's Lemma, expressions for the factor intensities of variable inputs are derived. From an intertemporal cost minimisation program, dynamic quasi–fixed factor demands are derived. The cost function exhibits increasing returns. We note that the same dual form is used in GEM–E3.

In RUBMRIO (applied to Texas), producers face choices about input and labour origin over about 254 zones and a multitude of transportation modes. In RELU, producers decide on the location of

labour hired, input and buildings. To capture the decision process of producers, discrete choice models are used. In RUBMRIO, trade disutility is measured by distance (as a proxy for transport costs) and input prices. The parameters are calibrated from a nested logit model on commodity flow data and Census data on county-to-county work flows.

## 2. Market Structure

The use of imperfect competition sectors is most prevalent, and indeed a necessity, in the NEG models. Imperfect competition is also found in GEM-E3 and Greenmod II. The land use and transportation models RELU and RUBMRIO assume perfect competition.

Firms in sectors facing imperfect competition are usually modelled as having economies of scale due to a fixed cost element in the cost function, usually consisting of fixed amount of labour, capital and/or fuel services. It is not always clear how models calibrate this crucial parameter. The GEM-E3 model estimates the fixed cost component using extraneous information at the industry level on the minimum efficient scale (MES) and cost gradients (the % increase in average cost when scale is reduced from MES to one third). If zero profits are assumed (in order to isolate marginal costs) fixed costs can be numerically calibrated. The MES information is also used to determine which sectors are designated as being imperfectly competitive. The modellers use the fact that under imperfectly competitive conditions the scale of production falls below the MES.

One encounters two main forms of imperfect competition in the models, oligopolistic competition and (Dixit-Stiglitz) monopolistic competition. The distinguishing feature between both kinds of competition lies in firm behaviour.

In the monopolistic competition case, the firm views itself as an atomistic part among a large number of firms, and does not engage in strategic behaviour. In this case the price-cost mark-up does not depend on the size of the market, and in combination with the usual Dixit-Stiglitz demand specification (explained in Section II.C.4), leads to a constant mark-up of prices over costs. Together with the assumption of multiplicative transport costs (made in all NEG models), this implies so-called mill pricing, leading to the same production price for goods sold in every region. This result explains the huge popularity of Dixit-Stiglitz monopolistic competition in economic geography models, since the assumptions provide for analytically tractable results and a controllable amount of equations when the number of regions gets fairly large. Another implication of this specification is that firm scale only depends on the cost parameters and the elasticity of demand, and is thus invariant to market size. Market size only influences the number of varieties. Note that not all models introducing monopolistic competition will use the Dixit-Stiglitz kind, which is a special case due to its CES demand specification.

The oligopolistic competition case assumes strategic interaction by producers, so that firms recognise their own market power. Price–cost margins will be higher, will depend on the number of firms and will thus react to the size of the market. (Note that the assumption of mill pricing will therefore not hold, so that in extremis one will have to calculate one price for each region. Most models limit the degree of regional price discrimination, though.) Increasing market size leads to more competition due to entry of firms, which will reduce price–cost margins and causes suppliers to operate at larger scale. In new economic geography terms, this is a pro–competitive effect through which regional market size lowers regional prices which complements the usual effect of increasing variety on the region’s ‘perfect’ price index, as well as a cost of living effect which, in the case of agglomeration, reinforces demand linked circular causality (Fujita et al., 1999). Both GEM–E3–IM (the extension with imperfect competition) and Greenmod II (which are no NEG models) allow for such market form. The Greenmod II model imposes a zero profit condition, which allows one to compute the equilibrium number of firms thanks to the fixed cost component per sector. GEM–E3–IM allows for two mechanisms in which the equilibrium number of firms is computed. The first uses the zero profit condition to ensure instantaneous adjustment of firms in each period, the second takes the number of firms in one period to be fixed, and lets the number of firms adjust in the next period according to an ad hoc equation.

The GEM–E3–IM model lets each producer calculate 3 prices, one for the domestic market, one for the EU market, and one for the rest of the world. The way the mark–ups react to market conditions, depends on the type of competitive regime chosen, either through Nash–Bertrand or Nash–Cournot. In setting prices, the firm will have to conjecture on changes in the competitive environment, either from a change in the number of firms or the opening of markets, and the change in the shares of domestic and imported goods in final demand. In setting prices for the rest of Europe, firms are assumed to take into account a weighted average of perceived demand elasticities. Since computational resources for such a calculation may be unrealistically demanding, bounded rationality of the firm is assumed. We note that, contrary to GEM–E3–IM, the Greenmod II model does not allow for any price discrimination between the home region and the other Belgian regions. The same assumption is made for the regional GEM–E3 model of Saveyn and Van Regemorter (2007).

It may be worth noting that CGEurope II uses a modified version of the standard Dixit–Stiglitz monopolistic competition. They allow for a ‘degree of monopolistic competition’, so that every sector is situated between perfect competition and pure monopolistic competition. In this case some degree of market crowding may be allowed for in partially monopolistically competitive industries. With full market crowding, an increase in market supply then has its full impact on supply prices. Agriculture is seen as perfectly competitive, services as close to Dixit–Stiglitz, industry as lying in between.



From the review, it should be clear that the distinction between Dixit–Stiglitz monopolistic competition and Cournot oligopolistic competition is an important one. The former is routinely used by the NEG models; the latter seems prevalent in the environmentally related models.

Dixit–Stiglitz competition has proven to be important in the theoretical NEG literature due to its tractability. There is no reason to assume, however, that other market forms cannot generate the same economic geography results, as long as increasing returns to scale and the love of variety in consumer preferences are included. Increasing returns to scale are necessary to derive an endogenous number of firms (and thus of varieties) which can be done both in the Dixit–Stiglitz framework, as well as in the Cournot framework. The CES consumer preferences over a number of varieties can also be retained in both cases, as is done in the GEM–E3 imperfect competition extensions. But even CES preferences are not an absolute necessity. It is well known that quasi linear quadratic preferences can yield the love of variety too, as is shown in Baldwin et al. (2003). A number of theorists have worked on developing NEG models without the restrictive features of Dixit–Stiglitz monopolistic competition (See e.g. Ottaviano et al., 2002).

As for the importance of market structure for environmental modelling, there is a large literature on how optimal environmental policy should be set in the face of different market structures. One example can be found in Requate (2005). He describes how optimal Pigouvian taxation differs when applied to an industry characterised by Dixit–Stiglitz monopolistic competition or Cournot competition with free entry.

### 3. Land and housing markets

In NEG models, the housing/land market may play a crucial role in determining the nature of agglomeration in the model. In many of the first theoretical models agglomeration was said to be irreversible once transport costs are lowered beneath a certain threshold. Further economic integration would only sustain the agglomeration pattern, since in those first models both the dispersion and agglomeration forces decline in strength with falling trade costs, but the dispersion force does so at a higher rate than the agglomeration force. This results in the familiar pattern of agglomeration at ‘low’ costs, and dispersion at ‘high’ costs. Including a dispersion force which does not depend on trade costs but only on regional density, would alter this pattern and create an opportunity for re–dispersion if trade costs fall any further (because agglomeration forces diminish in strength relative to the stable dispersion force) and would generate more realistic degrees of clustering, apart from the ‘100% or nothing’ that is found in the theoretical models. The housing market is a first candidate to play this role (see also Helpman, 1998).

Most models do not include a separate housing market. In the RAEM 2.0 model, housing does enter the overall consumer utility function and plays a crucial role as an additional dispersion force. The housing stock is kept at an exogenous fixed level, even though the scenario where

housing becomes important is described as the 'long run' case. Additional migration to a region will lower the amount of housing per capita, which in turn lowers utility from living in a region.

The RELU model includes equations describing a floor space market with consumer and landlord behaviour. The amount of floor space is determined by the amount of buildings, which is in turn determined by the behaviour of real estate developers. Landlords decide to rent out a unit of floor space, depending on costs common to all landlords, and a random i.i.d Gumbel cost component. From this the probability that a landlord rents out floor space is derived, which determines the overall supply. Consumers' demand of floor space, by type, is determined by a Cobb–Douglas utility function. The total stock of buildings is determined by the decision of developers to construct or demolish. The value of buildings will depend, among others on rents, which are weighed against maintenance costs.

RUBMRIO also models the housing market, but keeps floor space supply (in the short run as well as in the long run) fixed, so that all changes in rents are demand driven.

### **C. Household behaviour**

Models aiming at capturing the relationship between policy, the economy and the environment, need to capture the relevant choices made by economic agents, of which households are among the most important. Responses in demand, driven by policy-induced price changes are of the highest importance to final outcomes. In this paragraph, we will review how consumer demand has been modelled in the various models under consideration. Table 3 gives a summary of the discussion.

**Table 3: The representation of household behaviour**

	No. of commodities	Labour Supply (Leisure in utility function)	Time in utility function ?	Externalities in utility function?	Functional Form	Linkage Durable / Non-durable ?	'Love of variety'	Armington preferences	Different household groups? Per country / region?
GEM-E3	11 nondurable 2 nondurable	Y	N	Y (separable)	LES (lower CES nests in extension)	Y	N (Y in extension)	Y	N
GreenMod II	67 other 2 energy	Y	N	N	LES	N	N	Y	Y
EPPA	12	N (Y in extension)	N	N	CES	N	N	Y	N
Mayeres (1999)	36 transport 4 energy 1 other	Y	Y	Y (separable + non-separable)	LES/CES	Y	N	Y	Y
EDIP	59	Y	Y	Y	LES/CES	N	N	Y	Y
CGEurope I	7	N	Y	N	CES	N	Y	N	N
CGEurope II	7	N	Y	N	CES	N	Y	Y	N
RAEM 2.0	14	N	N	N	LES/CES	N	Y	N	N
RAEM 3.0	14	N	N	Y	LES/CES	Y	Y	Y	N
REMI	13	n.a.	n.a.	n.a.	n.a.	N	Y	Y	Y
MMRF-Green	13	N	N	N	LES/CES	N	N	Y	N
RUBMRIO		N	N	N	n.a.	N	N	N	N
RELU		Y	N	N	Cobb-Douglas/CES	N	N	Y	Y

	<b>No. of commodities</b>	<b>Labour Supply (Leisure in utility function)</b>	<b>Time in utility function ?</b>	<b>Externalities in utility function?</b>	<b>Functional Form</b>	<b>Linkage Durable / Non-durable ?</b>	<b>'Love of variety'</b>	<b>Armington preferences</b>	<b>Different household groups? Per country / region?</b>
Mobilec	Aggregate output + consumptive travel	n.a.	n.a.	n.a.	Fixed proportion of output	n.a.	n.a.	n.a.	n.a.
NEMESIS	27	n.a.	n.a.	n.a.	Econometric demand system (CBS version)	N	N	n.a.	N

n.a.: not applicable

## 1. The components of the utility function

First, a decision has to be made on the arguments that enter the household utility function. The most general functional form of utility (in a static framework<sup>4</sup>) is the following.

$$U = U(C, L, T, G, E)$$

Utility consists of utility out of consuming commodities (C) (transport and non -transport related), leisure (L), time spent on various activities, including transport (T), public goods (G) and disutility out of negative environmental externalities (E). All the models we consider use a variant of this general utility function, with arguments chosen in function of the purpose of the model. Variations on the above function can choose to include arguments for time, public goods and externalities in a separable way or not, which matters greatly for the amount of substitution between different arguments and related feedback mechanisms (see also Section III.E).

In most models leisure enters the utility function, which implies that labour supply is determined endogenously. Modelling labour supply may be quite important when analyzing the labour supply effects of different forms of environmental and transportation reform packages. The distortionary effects of labour taxes are, for example, frequently used by the so-called double dividend literature, which investigates whether the introduction of a revenue neutral externality tax leads to an increase in welfare, even when not taking into account the impact on the externality. An example of such a study can be found in Mayeres (1999). The more NEG oriented models like RAEM 2.0 and CGEurope do not include leisure in the utility function. RELU models the choice to be unemployed as a discrete choice problem. In this case, there is no income effect which rules out a backward bending labour supply curve.

Few models explicitly include the time spent on transportation in the utility function. The CGEurope models take a negatively additive separable function of travel time in the utility function, since its main goal is to analyze the changes in welfare due to improvements of transport infrastructure, i.e. lower travel time between European regions. The model of Mayeres also takes into account travel time (for each transport commodity considered), but in a different way. Here time enters the utility function in a non-separable way. This is done to capture the feedback effect of congestion abatement. In this case, non-separability would lead the consumer to consume more transport services if the level of congestion goes down, thus dampening the effect of policies to reduce congestion. The (dis)utility from travel time is made endogenous in the model. The RAEM 3.0 model accounts for the changes in time costs of passenger trips. An

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<sup>4</sup> The savings decisions of households are discussed in Section II.J.1.

increase in the time costs of passenger trips reduces the available regional labour endowment and, hence the amount of labour, which can be used for production.

In a simple growth model such as Mobilec the focus is on production, so consumption plays only a minor role. Aggregate consumption is exogenously determined by the regional product by a constant saving rate, just like consumptive mobility, which is a fraction of regional product and a function of prices. Travel time shows up in real prices, and is the result of aggregate capacity utilisation.

## 2. The budget constraint

Most models, with the exception of Mobilec, define an explicit consumer utility maximisation problem under a budget constraint. The extensiveness of this budget constraint varies across the different applications. In some instances, additional constraints, next to the classic budget constraint, are specified. Mayeres (1999), for example, makes use of time allocation constraints by transport activity, which specifies a minimum time requirement by activity. If these constraints are binding, the value of time spent in that activity is positive, so transport time used on transport is not considered to be part of leisure.

## 3. Durable non–durable linkage

Some models, such as the GEM–E3 model and the CGE model of Mayeres use a more sophisticated way of modelling the ownership and use of durables. They make use of the general demand system described by Conrad and Schröder (1991), where non–durable consumption is being divided in a part that is implied by the ownership of durable goods, and a part that is not. The latter part is called substitutable; the former part can be called ‘committed’. Total utility is defined over the stock of durables, and the substitutable part of the non–durable goods. The cost of durables in the budget constraint does not only include the cost of purchase of the durable (including taxes), but also the operating cost in terms of committed non–durable goods. (This has been described by Conrad en Schröder as follows: if someone buys a durable only taking into account its own price and not the additional expenditure on non–durables associated with the use of the durable, he will violate his budget constraint later on). The result of such a specification is that a more detailed analysis of the effects of environmental policies can be performed. For example, a reduction in the committed expenditure of fuel in a car (for example due to increased economies in fuel consumption) may result in a higher demand for cars, and thus higher fuel consumption. Raising the fuel costs through taxes will not only result in less ‘substitutable’ fuel consumption, but also in a lower car stock.

In Conrad en Schröder’s model the level of committed expenditure of non–durables is being modelled as ‘technically determined’ (i.e. exogenous). A different interpretation of the committed

expenditure comes from Koopman (1995). The model assumes people only buy a car when they know they will drive a certain minimum amount of mileage with it. This is called committed mileage. All miles driven above this minimum mileage are termed supplementary mileage. The cost of the former includes besides the vehicle also the operational costs, while the costs of the latter include only the operational costs. The consumer chooses the level of committed and supplementary mileage. Deciding on committed mileage is equivalent to deciding upon the size of the car fleet.

The NEMESIS econometric demand model distinguishes non durables, durables and related non durable consumption. The model does not capture the durable / non-durable linkage, however.

#### 4. The functional form of the utility function

After the decision on what to include in the utility function, one has to decide on the functional form. The most common specifications found in the literature are the CES and LES specification, usually combined in some sort of nesting structure. Sometimes the CES function appears in its Leontief version or the Cobb–Douglas version. Since the CES function is homogenous of degree one, it will produce unit income elasticities. This means a doubling of expenditure (or income) will leave the relative expenditures between categories unchanged. Of course this is highly unrealistic. The EPPA modelling team, which uses the CES specification throughout, acknowledges this feature may be a problem in their 100 year prediction horizon. Over 100 year (which – at a growth rate of 2% - implies an increase in income by factor 7.25) aggregate expenditure shares are bound to change, thus changing the composition of industrial production and ultimately the environmental impact of the economy. The EPPA model uses CES functions because they simplify the solution of the model. The problem of fixed shares is undercut by making elasticity and share parameters an explicit function of income. Most models, however, use the LES specification to attribute total expenditure to different goods. Of course, when saving is directly included in the utility function, using CES type functions will lead to a constant saving rate.

NEG Models, such as the RAEM 2.0 and the CGEurope models, usually rely heavily on Dixit–Stiglitz type monopolistic competition. The consumer in this market form is assumed to have CES type preferences defined over different varieties of the same good. The most important feature of this type of preferences is the so-called love of variety, which can be understood in different ways. One way of understanding it, is that a consumer will gain in welfare when the number of varieties at his disposal grows. Or, put in different terms, the price index associated with this preference structure will be lower, the more varieties there are. This ‘love of variety’ is an indispensable tool in analyzing the spatial distribution of consumers’ utility, since it implies that consumers living in a region with access to a lot of varieties will need less expenditure to reach the same level of utility. The crucial parameter governing the strength of the love of variety is the

elasticity of substitution of the CES function, with a higher substitutability reducing the strength of the preference for more varieties.

Another implication of CES preferences is that people would gain more utility from spreading a given amount of expenditure maximally on a given number of varieties. This observation leads to the so-called Armington assumption of preferences over product varieties from different countries. In practice this entails a lower CES nest allocating expenditure of a good over different import regions. The consumer will then want to spread his expenditure of goods over the different regions, leading to cross-hauling in international trade. Of course, models that use the Dixit–Stiglitz market structure implicitly use the Armington assumption. Virtually every model that incorporates a foreign sector and does not use Dixit–Stiglitz competition will explicitly introduce the Armington assumption.

In CGEurope II and RAEM 3.0 the decision tree involves an upper CES nest choosing from different supplying regions and a lower CES nest choosing from varieties within each region. The model thus incorporates two different substitution elasticities. The same combination of Armington preferences and preferences over regional varieties is found in GEM–E3. RAEM 2.0 and CGEurope I subsume both specifications.

The NEMESIS model makes use of an econometric demand system, relating log quantities to log consumption and log prices. Some restrictions on estimated parameters are imposed, ensuring consistency with rational consumer behaviour. The CBS version of the standard econometric demand system is used in the final estimation. It is assumed that demand will adjust slowly to its new equilibrium as a response to shocks, so an error correction mechanism is also estimated using the Engel–Granger two–step estimation procedure.

## 5. Household types

Most models consider one representative consumer. Therefore, they do not allow for an analysis of distributional issues. Exceptions to this are REMI, Mayeres (1999), Greenmod II, EDIP and RELU. The REMI model makes a distinction according to income group and age class. However, the behaviour of these consumer groups is not modelled explicitly. It is derived from an aggregate consumption function using correction factors for age and income levels. In Mayeres (1999), Greenmod II, EDIP and RELU different consumer groups are considered. Each of these groups is assumed to maximize its utility. Mayeres (1999) and Greenmod II use income to define the different groups. In EDIP consumers are differentiated according to income, education level and type of profession. RELU makes a distinction between 4 skill levels.



## 6. Some calibration issues

Given the crucial importance of the substitution elasticity in the 'love of variety' and Armington specifications, we will pay some more attention to the way this parameter is estimated in various models. In the imperfect competition part of the GEM-E3 model, the elasticity of substitution is calibrated given the formula:

$$N = Y / (\sigma * FIX)$$

N is the number of firms, calculated by the inverse of the sectoral Hirschman–Herfindahl Index and FIX is the estimated fixed cost of firms, calculated using minimum efficient scale and cost gradient estimates according to the method of Pratten (1988). Y is sectoral production. The elasticity of substitution  $\sigma$  follows from this formula given estimated values.

The CGEurope models use an estimation procedure based on the fact that the Armington substitution elasticity shows up in the distance function of the gravity equation of interregional trade. From this function, one can obtain the parameter estimate of a regression of the value of interregional trade and generalised distance between regions. Using this parameter and an independent estimate of the transport cost intensity (namely the average ratio of transport costs over the value of trade) the substitution elasticity can be inferred. Ideally, one would need interregional trade flow data for this exercise, but due to a lack of data availability the CGEurope team had to make use of international trade flow data.

### D. The labour market

In our review of the way the labour market is represented in the different models, we paid particular attention to the following issues. Is the labour market modelled as the classical interplay between supply and demand with adjustment of the wage rate as the equilibrating factor? In such a setting, unemployment is taken to be voluntary. In this context we also find a number of models assuming a perfectly inelastic labour supply. Or is there some kind of labour market imperfection due to union wage bargaining? For dynamic models, the issue may arise whether some kind of nominal inertia will be used. MMRF–Green allows for a specification that holds wages sticky in the short run (employment effects of shocks disappear after 10 years). Likewise, the NEMESIS model uses an error correction mechanism to describe the adjustment of wages to their new equilibrium. Some models also pay particular attention to the search and matching process, for various reasons. For the models with a spatial touch, it is also interesting to check whether wage differentials between regions and migration or commuting are allowed. Table 4 summarises the discussion.

**Table 4: The representation of the labour market**

	Perfectly inelastic labour supply?	Wage bargaining?	Nominal inertia? (For dynamic models)	Search and match model?	Commuting between geographical entities?	Migration?	Uniform wage across geographical entities? ('regional' vs. 'national' market)	Skill/occupation groups?
GEM-E3	N	N (Y in extension)	N	N (Y in extension)	N	N	N	N (Y in extension)
GEM-E3 (Belgium)	N	N	N	N	Y (From the national labour market equilibrium condition)	N	N (only due to commuting costs)	N
Greenmod II	N	Y	N	Y	Y (exogenous)	N	N	N
EPPA	Y	N	N	N	N	N	N	N
Mayeres (1999)	N	N	n.a.	N	n.a.	n.a.	n.a.	N
EDIP	N	N					N	N
CGEurope (I,II)	Y	N	N	N	N	N	N	N
Raem 2.0	Y	N	n.a.	Y	Y (From the matching function)	Y	N	N
Raem 3.0	N	N	N	Y	Y (discrete choice)	Y	N	N

	Perfectly inelastic labour supply?	Wage bargaining?	Nominal inertia? (For dynamic models)	Search and match model?	Commuting between geographical entities?	Migration?	Uniform wage across geographical entities? ('regional' vs. 'national' market)	Skill/occupation groups?
REMI	N	N	N	N	Y	Y	N	Y
MMRF-Green	Optional	N	Y	N	N	N	N (exogenous or endogenous)	Y
RUBMRIO	Y*	N	N	N	Y (discrete choice)	Y (discrete choice)	N	Y
RELU	N	N	N	N	Y (discrete choice)	Y (discrete choice)	N (due to commuting costs)	Y
Mobilec	Y	N (wage exogenous)	N	N	N	N	N	N
NEMESIS	N	Y	Y	N	N	N	N	N

n.a.: not applicable

\* Total labour force is a constant fraction of population, although labour will divide itself across regions according to wage differences.

GEM-E3 (in its core model), EPPA, EDIP and Mayeres (1999) model labour supply as the result of a decision of the households on the amount of leisure to consume. Unemployment is thus taken to be entirely voluntary. As has been said before, the decision to include the labour supply decision may be driven by the need to capture the distortionary effect of labour income taxation in order to be able to address the double dividend issue in these environmentally oriented models. The GEM-E3 model assumes a high elasticity of labour supply to capture the fact that in many European countries a fair amount of additional labour force is available to enter the labour market. Equilibrium in the labour market is given by the wage rate that equates supply and demand. Some New Economic Geography inspired models also make use of this Walrasian modelling of the labour market, but on top of this assume a fixed labour supply. The CGE Europe models for example assume an immobile, fixed labour in every region, which is quite compatible with their short term horizon. The RAEM 2.0 model also assumes an exogenous labour supply, and models unemployment as the equilibrium result of a search and matching process. The REMI model is the only NEG model with an elastic labour supply curve. Labour force participation is made dependent on the wage and employment opportunities, the strength of which is allowed to vary across the different socio-economic groups considered.

The land use model RELU models the decision to work as a discrete choice, where the explaining variables are the wage and the outside option. Since leisure does not enter the utility function there are no income effects and so there is no backward bending labour supply curve. The elasticity of labour supply is determined by the relative weight of the idiosyncratic component and the wage related portion of the indirect utility function that derives from the discrete choice problem. RUBMRIO takes total labour supply as a fixed proportion of the population, and only concerns itself with the spatial distribution of labour supply, either through commuting or migration.

Only in some models, namely Greenmod II, NEMESIS and an extension of GEM-E3, is the assumption of competitive markets dropped and is the competitive labour supply curve replaced by a wage bargaining curve (determined according to Nickell's right-to-manage model.) NEMESIS uses an econometrically estimated wage equation, by industry and region, where wages depend on inside factors such as productivity and outside factors such as unemployment. Wages in GreenMod II are determined at the regional level, and by sector. From the GEM-E3 reference manual, it is not clear whether such sectoral disaggregation is made. Most NEG models assume a competitive labour market and ignore wage bargaining. In RAEM 3.0 however, a wage curve (relating unemployment negatively to the level of wages) is included in the labour market model. As is well known, the wage curve, which is an empirical phenomenon, can be interpreted both as an inverse labour supply curve, thus arising from the functioning of a competitive labour market, or as the result of union bargaining.

Some models find it useful to use elements from the search and matching model of the labour market (RAEM 2.0 and 3.0 and Greenmod II, albeit for different reasons). The usual specification is the model according to Pissarides (2000). This model views the co-existence of vacancies and unemployment as equilibria, rather than disequilibrium phenomena. Workers and firms engage in costly search to find each other. Firms spend resources posting vacancies and screening employees while workers spend time searching and applying. Workers and firms are assumed to be randomly matched. The model is formalised by a matching function (usually of the Cobb–Douglas type) relating the matches on the labour market to the number of vacancies and unemployed. From this and from information on the flow into unemployment a Beveridge curve can be derived, relating vacancies to unemployment.

The Pissarides search and match model is used in Greenmod II to calculate the probability that someone who becomes unemployed finds a job again. This probability shows up in the outside option of the employees, which is in turn a parameter of the utility function of the union in the bargaining problem. RAEM 2.0 uses the Pissarides model for a different reason. It is used as a gravity equation to describe commuter behaviour across regions, which is assumed to be the result of the unemployed searching for new jobs across all regions. Note that this specification thus rules out the possibility of ‘on the job’ search. The number of matches produced by the process determines a commuting matrix across regions. It should be noted that the matching function in RAEM 2.0 includes a term capturing the sensitivity of the labour market to the cost of travelling between regions. Estimating this sub–model entails the estimation of the Pissarides regional Beveridge curve, by minimising the relative quadratic distance between the estimated and the actual commuting matrix.

In RAEM 3.0, a different commuting generating function is used. The arguments in the pair wise gravity equation are no longer unemployment and vacancies (as in RAEM 2.0), but labour supply in a region *minus* unemployment and labour demand in the other region. The equation is scaled by an exponential function comprising the time and monetary costs of commuting, as was done in RAEM 2.0.

Commuting shows up in Greenmod II too, but is taken to be an exogenous share of total labour supply in each region.

Next to commuting, migration is another important aspect of spatial models, especially the ones which are situated in the NEG tradition. Indeed, the seminal core–periphery model of Krugman (1991) uses (labour) migration as one of the driving forces behind its most celebrated result. Most (non-NEG) models with a regional dimension do not model any migration between countries, which may be defensible given the geographic scope of the models (world regions in the EPPA model) or plainly the reality of limited international migration between EU countries (e.g., GEM–E3). As has been said before, CGEurope is the only NEG model not allowing for migration, most

likely due to its European wide scope. A salient feature of the Belgian regional models, regional GEM-E3 and Greenmod II, is the absence of interregional migration, reflecting the limited migration from unemployment ridden Wallonia and Brussels to Flanders.

The REMI, RAEM 2.0 and 3.0 models do address interregional migration. The REMI model has been developed in the U.S., where interstate migration is prevalent, and applied to Italy and Spain, nations with fairly homogenous populations. The scope of the RAEM models is the Netherlands, which is also a very homogenous country.

In the RAEM 2.0 model, migration is allowed in the 'long run' version. In the short run version, with exogenous unemployment rates and commuting, utility differences between regions are allowed. The long run condition is that (relative) utility should be equalised across regions, so that the (exogenous) national population is being distributed across regions to satisfy this condition. Utility consists not only of the utility of consumption (heavily dependent on the regional access to varieties, see supra), but also on the utility of living in a region. This latter component depends solely on the stock of regional housing per person. Housing is assumed to be a normal good. The stock of housing is taken to be exogenous. There is thus no explicit housing market sub-model included. No other regional amenities – e.g. environmental congestion – are considered. The only additional dispersion effect is due to diminishing housing capacity per person.

In RAEM 3.0 migration is modelled by a two stage discrete choice decision process. In a first stage the decision to migrate is dependent on the difference between average utility across regions and regional utility. In a second stage, the total of migrating households is distributed among the regions according to region specific utility. Housing does not show up in household utility in the preliminary version of RAEM 3.0. Other models using discrete choice in migration (and commuting) behaviour are RELU and RUBMRIO.

The REMI model tackles the migration issue in a more detailed way. Migration for economic reasons and migration for non-economic reasons (e.g., military migration and retiree migration) are considered. We will focus on their treatment of economic migration. The driving forces behind the migration equation are wages and employment opportunities and the access to variety. People will also value some places more than other (e.g. sunny Florida). These non-economic amenities are captured by compensating differentials measured by looking at migration patterns over the last 20 years. (e.g. people would like to live in Florida even for 85% of the national average wage rate). The REMI model does not seem to take any congestion effects into account. Housing prices are a consequence of migration decision but not a cause for it, since they do not show up in the migration equation. There are no environmental congestion effects. For a theoretical model including spatially distributed environmental quality in a NEG model, see Friedl et al. (2006)

A last question for regional models, the answer to which may have quite profound implications, is whether wages are formed (or set) at a regional level or at a supra-regional ('national') level. Most models using competitive labour markets and no migration assume wages to be determined by market forces at the regional level. We mention one exception here: the GEM-E3 application for Belgium by Saveyn and Van Regemorter (2007). They apply GEM-E3 to the three Belgian regions, and thus find the labour immobility assumption of the GEM-E3 model to be insufficient in a Belgian context. Moreover, the inclusion of commuting behaviour in an environmental model of a federal state is important for the overall impact of a regionally diverse implementation of environmental policy instruments (see Saveyn and Van Regemorter, 2007). They therefore consider a national labour market, with the Walrasian condition that the sum of labour demand across regions has to equal the sum of labour supply, from which commuter flows follow. Regional wages are allowed to vary only due to commuting costs.

Nothing in the RAEM and REMI models would cause wages to equalise across regions. The models which assume imperfect competitive conditions on the labour market assume wage setting at the regional level too. However, this approach may not be a good representation of reality. In the Netherlands for example, the country which the RAEM 2.0 model is assumed to represent, wages are bargained at the sectoral level (i.e. nationally) with a strong influence of national macro-economic coordination. The same is true in Belgium (although the influence of national coordination is not that strong, sectoral bargaining is prevalent).

We note that an early predecessor of the RAEM 2.0 and RAEM 3.0 models (RAEM 1.0) recognised the facts of Dutch wage setting, thus only allowing for one wage rate in all regions. This is said to limit the incentives for regional labour mobility. It is not clear how this uniform wage is to come about. Note also that unions do not negotiate the real wage rate, or certainly not the wage divided by a perfect CES price index, which is bound to differ across regions. So there will still be source for migration.

The MMRF-Green model lets the user choose whether to keep labour supply fixed or flexible. More precisely, the modeller can choose whether to keep one of these three variables: regional labour supply, the regional unemployment rate or the regional wage differential (defined as the difference between the regional wage and the average national wage).

## **E. International trade**

In most models, trade between the regions of the model economy is implied by the equations of the model itself. Usually demand will be distributed over the regions according to Armington preferences (*see above*). When trade between the model economy and the rest of the world is

included, additional foreign demand and supply equations must be specified. This section will deal with the modelling of trade with a 'rest of the world' entity, rather than 'interregional' trade between sub-entities of the model economy. Only RAEM 2.0 and RELU are closed economies. The discussion is summarised in Table 5.

**Table 5: The representation of the 'rest of the world'**

	Foreign sector?	Flexible current account?	Exogenous RoW?
GEM-E3	Y	Y / N	Y (N in extension)
Greenmod II	Y	N	Y
EPPA	n.a. (model captures whole world)	n.a.	n.a.
EDIP	Y	N	Y
Mayeres	Y	N	Y
CGEurope I	Y	n.a.	n.a.
CGEurope II	Y	n.a.	n.a.
RAEM 2.0	N	n.a.	n.a.
RAEM 3.0	Y	N	Y
REMI	Y	N	Y
MMRF-Green	Y	N	N
RUBMRIO	Y		Y
RELU	N	n.a.	n.a.
Mobilec	N	n.a.	n.a.
NEMESIS	Y	Y	Y

n.a.: not applicable

In many models the behaviour of the rest of the world is very important to the final outcome of the model. To give an example from the environmentally oriented models: the enactment of climate policy in one country may induce a shift in demand from the expensive domestic goods to the more competitive foreign sector, thus dampening the overall positive effect on the environment, and worsening the position of the home country. The strength of this effect will typically depend on the elasticity of foreign export supply, and the substitutability of domestic goods for imports. In RUBMRIO, a spatial model, the demands from the foreign sector have an important influence on the distribution of economic activity in the economy, which does not change a lot precisely since foreign demand is assumed to remain fixed throughout the simulation.



It may be worth mentioning that next to the representation of export and import interaction, Mayeres (1999) also models the use of transit transport by the Rest of the World in the economy. This form of transport demand will depend on the relative price of transport abroad and at home. The price abroad is assumed to be fixed; the price at home will depend, among others, on externality taxation and the level of congestion.

To model the foreign sector one must consider in turn foreign demand, foreign supply, domestic import demand and domestic export supply.

In this respect, the assumption of a small open economy is very important, since it assumes the economy in question to be a price taker on the world market. This could be understood as the domestic sector facing perfectly elastic import supply and export demand from the rest of the world. Most models however assume some kind of imperfect substitutability between domestic goods and foreign goods

In the case of foreign demand for domestic goods models frequently make the *share* of the home country in RoW export demand dependent on the relative price at home and abroad, where the price abroad is taken to be exogenous, and on the total (exogenous) *volume* of demand for exports. These assumptions on the exogeneity of RoW prices respect the small open economy assumption. The foreign demand function contains an elasticity parameter. This specification is found in Mayeres (1999) and GEM-E3. Foreign export demand can also be made dependent on foreign income. The GEM-E3 model for example contains an extension where the increase of imports from RoW triggers a feedback effect, increasing RoW income and thus in turn raising exports, which is more in line with the modelling of the EU as a large economy. The MMRF-GREEN model uses finitely elastic foreign demand curves, with the novelty that these demand curves are distinct for each Australian region. In RUBMRIO, final demands from 'the rest of the world' outside Texas are exogenous just as final demand from inside Texas.

Regarding the foreign supply of imports many models take RoW prices as completely exogenous, thus assuming an infinitely elastic supply curve. This assumption is relaxed in an extension of the GEM-E3 model, where foreign supply is also taken to be finitely elastic. This would resemble reality more closely, given the size of the EU economy.

Domestic import demand usually also depends on relative prices and income. The strength of the effects depends on the Armington elasticity, which in virtually all models governs demand for foreign goods.

As regards domestic export supply, in some models domestic producers must explicitly decide on the allocation of production to the domestic market and foreign markets. This is modelled by including a constant elasticity of transformation production function over the domestic regions

and foreign regions. In this way, the supply of exports to RoW by domestic producers will also depend on the elasticity of transformation, as well as on relative prices, so that domestic export supply will react more slowly to changes in the latter. This kind of modelling is found in Greenmod II and RAEM 3.0. Greenmod II only allows for this specification in the perfectly competitive sectors, however.

One further issue concerns the closure of international trade via the current account. Usually the current account is assumed either to balance, or to exhibit some predefined exogenous deficit/surplus (possibly over time). The exchange rate is then allowed to vary to satisfy the current account condition. The GEM–E3 model however allows for a flexible current account, the exchange rate being fixed.

## **F. Government, policy and welfare**

### **1. The government sector**

As far as the representation of the government sector is concerned, several choices must be made. How many government instruments should be represented? How many layers of government (and their interactions) must be included? How to treat the deficit?. It should also be noted that none of the reviewed models represents the government as an independent actor with its own utility function (e.g. revenue or welfare) to be maximised. This rules out the modelling of any strategic interaction between either different geographical entities or different layers of government. Government behaviour is thus completely exogenous. The closest to independent government maximising behaviour is the inclusion in GreenMod, Mayeres (1999) or RAEM 3.0 of a Cobb–Douglas utility function dividing exogenous government consumption over different expenditure categories. Table 6 summarises the discussion.

**Table 6: The representation of the government**

	Receipts	Spending	Multi-Layered?	Deficit possible?	'Manna from the sky'?
GEM-E3 and Regional GEM-E3	Value Added Taxes Indirect Taxes Direct Taxes Environmental Taxes Production subsidies Social Security Contributions Import Duties Foreign Transfers Government Firms	Government consumption by product (By Fixed coefficients) Government investment by branch Transfers at exogenous rate per head	N Y in regional version (Federal to regional transfers endogenous)	Y (Fixed / flexible closure)	N
EPPA	Employers' social contribution Employees' social contribution Personal income tax Corporate income tax Subsidies on production Taxes on production Subsidies on products VAT	Government consumption of public services, education, health, social work Unemployment benefits Other transfers Subsidies	N	N	N

	Receipts	Spending	Multi-Layered?	Deficit possible?	'Manna from the sky'?
Greenmod II	Value Added Taxes Indirect Taxes Direct Taxes (personal / corporate) Environmental Taxes Taxes on investment goods Social Security Contributions Import Duties Foreign Transfers	Government consumption of public services, education, health, social work Unemployment benefits Other transfers Subsidies	Y	Y (assumed fixed)	N
Mayeres (1999)	Labour income / capital income tax Excises, VAT Externality tax	Poll transfer Subsidies Transfers to ROW Government consumption Capital services	N	Y (assumed fixed)	N
CGEurope	CGEurope does not include a government sector				Y
RAEM 2.0	Labour income tax	Unemployment benefits	N	N	Y
RAEM 3.0	Social security contributions, corporate income taxes, Excise, VAT and other consumption taxes, production taxes, income taxes	Consumption and production subsidies, commodity demands, transfers to EU, transfers to households, unemployment benefits	N	Y	<i>(no policy applications yet)</i>

	<b>Receipts</b>	<b>Spending</b>	<b>Multi-Layered?</b>	<b>Deficit possible?</b>	<b>'Manna from the sky'?</b>
REMI	Social Security contributions Taxes (aggregated)	Government consumption (aggregated) Transfer payments (aggregated)	Y		Y
MMRF-Green	Commodity taxation by 5 expenditure categories Direct taxation (labour income, non-labour income, others) Agricultural production tax Land tax, rental property tax, stamp duties on property transactions Tariffs Interests received	Subsidies Interest payments Current and investment expenditure Personal benefits (disaggregated?)	Y (Commonwealth to state transfers endogenous)	Y (Fixed / flexible closure)	N
RELU	Income tax	Unemployment benefit, other transfers to households	N		N
Mobilec	Mobilec does not include a government sector				
NEMESIS	Income Taxes Social Security Contributions VAT, Indirect taxes on consumers and industries	Intermediate consumption Social Security benefits	N	Y	N

When debt is included, GEM-E3, GreenMod II and MMRF-Green allow different closure options for the government budget: either the deficit is kept flexible, or the deficit is kept fixed, and some tax shifter is made endogenous. The model of Mayeres only allows for fixed deficits / surpluses.

Concerning the range of the government instruments that are included, we give an elaborate overview in Table 6. We confine ourselves here to noting that the degree of detail ranges from none (there is no government sector in CGEurope) over sparse (just one income tax, unemployment benefit in the RAEM 2.0 model) to very detailed (MMRF-Green). A common feature seems to be that the NEG models pay less attention to the modelling of the government sector compared to the conventional environment and transportation oriented models (with the notable exception of the REMI model).

We will spend more time considering the representation of the vertical structure of government, given the importance of the regions and communities in our country. We consider GreenMod II and the regional extension of GEM-E3 to Belgium by Saveyn and Van Regemorter (2007), since they both model the Belgian case. We pay particular attention to the division of competences and instruments between the regions and the federal government and the transfers between governments. These distinctions are made to capture the so-called vertical externalities between different government levels, where the policies of one layer (e.g. a unilateral move of one region) affect tax revenues of the federal state, and vice-versa. The regional GEM-E3 model has been used to explicitly calculate the vertical effects of different climate policies. The analyses done with Greenmod II do not yet explicitly consider such externalities, but the model is also able to do so.

In GreenMod II the federal government levies the VAT, excises, other consumption taxes, personal income taxes, corporate taxes, social security contributions, taxes on production and taxes on investment goods. Transfers in GreenMod II are 'other transfers' (including pensions) and unemployment benefits. The federal government consumes public services, education, health and social work: these goods are produced by the production sector. Regional governments collect taxes on private consumption, capital use and production (The inheritance taxes thus are not included). They also levy an additional percentage on the personal income taxes. The regional governments give transfers to households and consume education services and public services. We note that the French community is modelled as an autonomous entity, whereas the Flemish community is lumped together with the Flemish region.

Saveyn and van Regemorter (2007) use the following distribution of tax revenue between federal and regional (including municipal) governments, when constructing the social accounting matrix.

**Table 7: Breakdown of tax revenue accruing to different government levels in Belgium (before redistribution) according to the regional GEM–E3 model**

	Federal Government	Regional Government
Direct taxes	79 %	21 %
Indirect taxes	64 %	36 %
Subsidies	0 %	100 %
Duties	100 %	0 %
VAT	100 %	0 %
Government Firms	50 %	50 %
Social Security	80 %	20 %

Source: Saveyn and Regemorter (2007)

Also important is the constitutional transfer from the federal level to the regional level. A large part of the regional budget is provided by transfers of part of the fiscal revenue from the federal government, notably part of the personal income tax and the VAT. This transfer is indexed with the regional consumer price index (CPI) in GreenMod II. The regional GEM–E3 model lets the *size* of the transfer vary according to real GDP growth (91% of GDP growth with a minimum growth rate of 2%) and the number of students in each region (proxied by the number of inhabitants), the *distribution* between communities varies according to the share of revenue from each region, the share of each region in total student numbers and other parameters.

We close this discussion by noting that the Belgian federal model is until now a so-called expenditure federalism, with few competences for regions on the taxation side, but important competences on the expenditure side. These expenditure competences may be important for transportation purposes. In 2000 the federal government spent about 4577 million euro on transportation. The lower governments' transportation expenditure amounted in the same year to some 4907 million euros (Nautet and Vuidar, 2006).

## 2. Policy

After describing how the government sector enters the model, we will go into more detail about how government instruments are actually used by the modellers for policy simulations.

In this respect one quite important remark is appropriate. Some models use policy simulations, which enter the model as 'manna from the sky' (or 'leak to nowhere' if the instrument in question is tax). For example, CGEurope simulates European investments in transportation, as well as social marginal cost pricing scenarios. In both cases it is unclear where the money for these investments comes from, or where the revenues of the pricing policies are reallocated in the economy. RAEM 2.0 and RUBMRIO also simulate infrastructure projects, without specifying where the funds for these investments are raised. These policies thus take place outside the

budget of the government, which is subject to some closure rules. This essentially violates the general equilibrium requirement that all money flows should end up in and originate from within the economy.

The policy issues considered in the applications of the NEG models of CGEurope, RAEM 2.0 and RUBMRIO are improvements in transport possibilities. In RAEM 2.0 these are measured as reductions in the (monetary) cost of transporting goods and the search cost of finding goods. Next to these the cost of commuting is also considered. Any improvement in transportation will result in changes in the transportation cost matrix. An explicit distinction between time costs and monetary costs is not made. The CGEurope model also considers the lowering of transport costs, including both the cost of freight and the cost of business travel. (CGEurope II also considers long distance passenger travel)

The transport model of Mayeres conducts simulations whereby an exogenous increase in government consumption is accompanied by an increase in taxation, either through peak load pricing, fuel taxation, labour taxation or a lump sum tax. A decrease in public subsidies to transport is also considered. The aim is to compare the marginal social costs of the different tax instruments, from which possibilities for welfare improving tax reforms can be derived. RELU is used to estimate the land use and general economic effects of a cordon toll, in combination with a more detailed transport model.

The GEM-E3 model allows for the flexible introduction of environmental taxes, permits and technical standards. Standards of energy use can be imposed on countries, sectors and on individual goods. Taxes (on emissions, energy content, depositions and damage) can be set as a fixed rate, or as an endogenously varying amount, given a certain quantity restriction. Markets in permits can be specified, in which permits are allocated on the basis of grandfathered rights. Auctioning of permits is not modelled since it is equivalent to a tax. Various kinds of permits can be introduced, ranging from undifferentiated emission permits to regionally differentiated immission permits.

The same amount of flexibility characterises the EPPA model, which allows for constraints on different regions, sectors or greenhouse gases. This flexibility allows for the calculation of several sector / greenhouse gas specific prices.

In describing the emission permit markets, different departures from the Walrasian case can be considered. In the perfectly competitive market profit maximisation by firms (including the value of permits that are not consumed) will lead to a permit price equal to the marginal product of the polluting input. However, different imperfections can be modelled. First, firms selling on the permit market may have market power, so unless firms exactly consume their permits, the market will be inefficient, since price and marginal cost will not be the same anymore. A second



departure from the Walrasian market is the introduction of market makers, who cause a bid and ask spread. Again, inefficiencies arise since prices of suppliers and demanders are not equal. The same inefficiencies arise when transaction costs are introduced. The EPPA model, used to analyze the European Trading Scheme, does not include any transaction costs due to setting up registries or due to market makers, but this is not considered to be a problem, since the changes to the overall conclusions of introducing such costs are not expected to be large. (Reilly and Paltsev, 2005). The GEM-E3 model has been extended to allow for market power. (Pratlong et al., 2004)

In case of multiple pollutants, it may be possible to model trade among the different pollutants. In this case a trading rate must be specified to express all the pollutants in terms of a reference. The EPPA model allows for such a unified market, by expressing all gases in carbon-equivalent. Markets can also be organised in terms of each pollutant. In this case, marginal productivities of pollutants are not equalised, as in the case of a unified market.

In an intertemporal framework, one can consider the possibility of permit banking. In this case, firms can store their permits in one period to be used later. Banking will take place if the amount of permits allocated at the outset is sufficiently high. The Greenmod team has considered introducing banking in the model.

One other possible extension may be the introduction of uncertainty in the permit market. In such a case, firms may benefit from the purchase of derivatives such as futures, forwards and options. It is not sure whether any of the models considered have specified derivatives markets in their model.

## **G. Modelling transport decisions**

### **1. Modelling of transport/supply production**

The transport sector is somewhat special, when treated in economic modelling. First of all, it is quite heterogeneous. For example, there are both consumers and firms that use inputs of the transport sector, but with different purposes. Consumers will be the major users of passenger transport, which can be private transport, supplied by their own vehicles and fuels. Or they can buy access to a specific transport mode, ranging from different transport modes and supplied by different firms, including public enterprises. Firms will be preferential users of freight, influencing the transport costs and the economic structure of the country. They also use passenger transport as an input (business transport).

Table 8 summarises the discussion.

**Table 8: Modelling transport decisions**

Model	Freight& passenger transport?	Own/purchased transport?	Transport sector?	Market structure	Iceberg assumption?	Transport modes	Trips purposes/goods types?	External Model?
GEM-E3	Y	Y	Y	User choice	N	N	N	N (externalities by ExternE)
EPPA	N Household/Firm consumption of transport separately	Y	Y	PC	N	Water, air, other	N	N
NEMESIS	Y	Y	Y	MC	N	Private car, Rail, air, public road, other	N	N
Green-ModII	N	N	Y	OC	N	Land, water, air	N	N
MMRF-Green	Freight transport services are sold indirectly as margins on flows of goods and services.	N	Y	PC	N	Road and other Substitution effect road & rail	N	N
CG-Europel	N	N	N	N	Y	Trans European Transport Networks	N	SCENES
CG-EuropelII	N	N	Y	PC	Y	see CG-Europel	N	SCENES
Mayeres (1999)	Y	Y	Y	PC	N	Road, rail, inland navigation	N	Y for externalities
EDIP	Y	Y	Y	PC	N	4 modes	Y (3 distance classes)	TRE-MOVE TRANS-TOOLS

Model	Freight& passenger transport?	Own/purchased transport?	Transport sector?	Market structure	Iceberg assumption?	Transport modes	Trips purposes/goods types?	External Model?
RAEM	Y	Y	Y	PC	N	Road	Shopping, education, commuting & other	SMART
REMI	-	-	N	-	-	-	-	-
RELU	Y	N	N	N	-	Road	Cost disaggregated by trip purpose, OD pair and skill level	-
RUBMRIO	N	N	N	N	-	Road		-
Mobilec	Y	N	N	N	-	Road	Consumptive mobility (shopping, education, leisure,...) and commuting	-

Note: PC = perfect competition, MC = monopolistic competition, OC = oligopolistic competition

The first choice to make is whether the model will incorporate a separate transport sector or not. Models that focus more on trade flows and spatial economics, such as RUBMBRIO, RELU and Mobilec, do not have a separate transport sector and only incorporate an exogenously given transport cost. CGEuropeI only models transport costs and does not consider a separate transport sector, while CGEuropeII uses a representation of a transport sector, but still considers transport costs in a simplified way.

When models use a distinct representation of the transport sector, it can be further disaggregated by transport mode. GEM-E3 only considers one aggregate transport sector. Other models make a distinction between road transport and other transport (MMRF-Green), split up transport production in land, water and air transport (GreenmodII, EPPA) or even consider road, rail, water and air separately (CGE model of Mayeres, EDIP).

Most models represent transport production at the national level. Only some SCGE models, like RAEM have the representation of transport production on the regional level. Such representation

allows one to look at specific effects of economic changes on the region-specific transport sector, but it makes the model more complicated.

The production technology of the transport sector will mostly be similar to the other sectors in the economy. This means that at the first level of aggregation Leontief will be used (to combine the KLE bundle with intermediate inputs) and at the other levels CES production technology or Cobb-Douglas (RAEM). At the lowest nest, different types of fuels are combined using (in most cases) a CES production function.

An example of a durable and non-durable linkage in the case of own-produced transport (cfr. section II.C.3) is used in the CGE model of Mayeres, EDIP and GEM-E-3.

An example of a durable and non-durable linkage in the case of a transport model is where a car vehicle (durable good) is linked to a minimum amount of fuel used when buying the good (non-durable linkage), while consumption of 'own passenger transport' with this car requires an input of fuels (non-durable consumption). GEM-E3, Mayeres (1999) and EDIP employ the concept of a variable expenditure function with quasi-fixed durable goods (car vehicles) as arguments in order to derive a demand system for nondurable goods (fuels) in prices of the non-durables, in the stocks of durables and in variables expenditure.

The market structure for the transportation sector is often modelled to be in perfect competition, like EPPA, CGEuropeII, MMRF-Green and even RAEM, but is modelled as a sector in oligopolistic competition in GreenModII. The choice for perfect competition for the representation of the transport sector is often guided by a lack of data.

None of the models considered here allows for an analysis of policies towards company cars that are also used for private travel.

## 2. Modelling of transport demand

When modelling the transport sector and transport decisions, many models make a distinction between passenger transport and freight transport. The distinction is logical, as passenger transport would normally appear in the consumption decisions of households, while the cost of freight transport will generally be a part of the cost function of firms. It should be noted however that firms also use business transport as an input.

In the modelling of freight transport, the transport service inputs are coupled with the inputs of the transported good. This can be done by using a Leontief approach, where the price of the transport service is added to the price of the transported good  $p = p_g + A \cdot p_t$ , where  $A$  is some Leontief factor and  $p_g$  and  $p_t$  stand for the price of the good and transport service respectively.

Another way to do this, is to use a tax representation of the transport service, this means that the price becomes  $p = p_g(1+A.p_t)$ .

Private passenger transport is a part of the consumption decisions of the households. This is done via integrating transport services into the households' utility function. The models use either the CES or Linear Expenditure System (LES) representations of the households' utility function. CES functions make it possible to use complex nesting structures, for example Mayeres (1999) uses 8 levels of direct utility of transport to consumers, where transport appears at the third level, making that the transport utility itself has 5 supplementary levels. (Peak and off-peak use, mode of transport, type of fuel, committed and supplementary mileage and diverse services at the lowest nest).

The EPPA model distinguishes 'transport' and 'other consumption' on the second level and then splits up transport into purchased transport and private car use. Private car use is split up into fuel use and a 'transport services nest'. The split-up into private transport and own-transport generates more realistic results, as they will generally not have the same elasticity of substitution. Both own-produced and purchased transport can be linked to different types of intermediate inputs, like fuels and services auxiliary to transport.

An alternative to the CES/LES approach is to use a 'trip generation' function. The generation of passenger trips in RAEM, with the exception of commuting, is done with a generation-distribution model, where the distribution model follows the structure of a constrained gravity model (see also the PLANET model). Outputs of the corresponding service sectors are used as attraction factors for the passenger trips. For example, a region with a high level of education production attracts more education trips. Higher transport costs between two regions lead to a lower number of trips between this origin-destination (OD) pair, but does not influence total number of passenger trips. While this approach can be used to derive the number of trips, it is less appropriate to derive the number of pkm.

Most of the models do not take into account different trip purposes. RAEM is an exception. In RAEM the attractions for the generation of the commuting trips are the labour endowment in the region of origin and the labour demand for labour in the region of destination. The amount of commuters is calculated through a 'coupling' function, using the generalised transport costs. When the transport cost increase the amount of commuters decreases exponentially.

Mayeres (1999) and EDIP are good examples of how complex transport decisions can be incorporated into a CGE model. In the EDIP model both households and domestic sectors use transport services in their consumption and production activities. Transport is subdivided into transport modes (road, air, inland waterways and air), three distance classes (long, short and urban) and 14 main vehicle categories. Each type of transport service is associated with the particular after tax price, which includes VAT taxes and other taxes. Public transport and freight

transport services are produced by several national transport sectors. These sectors use labour, capital and commodities, for example fuels and vehicles, as inputs to their production. Passenger transportation by car is produced by the households themselves using fuel and car vehicles. In order to own a passenger car vehicle a household has to pay the car ownership costs, which include different types of taxes, such as registration taxes.

### 3. Modelling the costs of passenger and freight transport

The share of transport services used per unit of the transport good and the initial level of transport costs are usually based on the calculations of an external transport model or on a transport survey/statistics. This means that in order to transport one unit of good between a pair of regions, a fixed amount of transport service (determined by the external model) is used. If a model evaluates a change in infrastructure, for example the widening of a road, this measure is implemented via a change in the fixed amount of transport services used per unit of the transported commodity.

GEM-E3 and MMRF-Green use transport costs from statistical sources and databases. CGEurope uses the outputs of the SCENES transportation model. The total transport costs used in CGEurope are calculated as the sum of distance-related costs and 'virtual' costs of impediments such as frontiers, language changes, bureaucratic formalities and so on. Logistic costs involved in trading at a distance are reported to be much more important than simple transport costs, and have to be calculated separately. The SCENES model has no network-elaborated intra-zonal element, or local transport/local network aspect. This means that local congestion-related costs are excluded from the total transport costs.

Calculation of the transport costs for RAEM was made by the SMART model, but other models can be used too, if transport costs are supplied in the right format.

EDIP uses the information from supply and use tables for the representation of transport and trade costs in the model. The shares of transport by distance type and by particular transport mode are calculated based on the outputs from TREMOVE model.

Some models, like CGEurope, model transport costs using the Samuelson iceberg assumption (1952). This means that a certain amount of the composite tradable, when transported from one region to another region, is used up ('melted') when delivering this good to that region. In modelling practice, this means that there is a fixed price increase  $\tau$  for the price of good in region  $i$ , when shipped to region  $j$ , expressed as  $p_j = (1+\tau)p_i$ . Of course, this means that the relative prices of the goods in this region, will always be  $(1+\tau)$ , meaning that there is no variability in relative prices. This also means that transport is produced with the production function of the good that is being transported.

The iceberg assumption simplifies modelling a lot, but it may be unrealistic, especially for modelling the service sector and for financial sectors, in particular. One feature of the iceberg assumption is that a decrease in the transport cost may actually lead to a decrease in production, due to the lower price of the good.

Therefore, many models do not use this iceberg assumption. Instead, models express the transport cost as a mark-up over prices, often produced by a separate transport sector. As the transport sector uses different factors of production or some factors of production with a different degree of intensity, the relative price does not need to be the same. Nevertheless, the more similar a sector is to the transport sector, the better will be the approximation of the iceberg costs (Koren, 2004).

#### 4. Modelling the external costs of transport and their impact on transport decisions

Modelling the external costs of transportation such as congestion, noise and accidents is often not treated within the models themselves. For example EDIP uses the TREMOVE model to calculate these external costs of the transport sector. This model estimates the transport demand, the modal split, the vehicle fleets, the emissions of air pollutants and the welfare level under different policy scenarios. All relevant transport modes are modelled, including air and maritime transport. Other externalities, like noise pollution and traffic safety (road accidents) can be treated in TREMOVE, but in a simple way.

Mayeres (1999) is one of the only models that incorporate congestion inside the model. Environmental externalities, traffic safety and health effects of transportation have a separable effect on the consumer utility. Congestion has a feedback effect on utility and influences final transportation demand. Congestion is modelled using a congestion function.

## H. Environmental aspects

### 1. Generation of emissions

The modelling of environmental aspects varies substantially with the model's purpose. Table 9 gives an overview for the models that consider environmental impacts. Extensive modelling of environmental effects is not done when the focus of the model is on land use, like RUBMRIO or RELU.

When a model assesses economic impact of mitigation strategies of global warming, the focus will be on greenhouse gas emissions (GreenModII, MMRF-Green). If the focus is more on the general environment and externalities, models can also incorporate substances with health effects and environmental damage other than global warming (see e.g., Mayeres (1999) and GEM-E3).

Even when models are modelling emissions, the purpose of the model does not need to be the same. Global warming concerns gave rise to a variety of economic models evaluating the effects of abatement policies on the global/local economy. The EDIP emissions/environmental module is less complex than the other modules, but EDIP focuses more on distributional effects between households and regions.

Many models focus only on air pollution. This is true for GEM-E-3, EPPA, NEMESIS, GreenModII, MMRF-Green. Almost all of these models have a more or less detailed environmental module for greenhouse gas emissions, acidifying emissions and other emissions with a proven health effect (such as small particles and ozone), but do not deal with local pollution and 'point' effects. This means that often pollution with a very local or transient effect, such as water pollution is not treated.

Emissions in GEM-E3 are differentiated by country, sector, fuel, and type of durable good. Inputs are linked to production and emissions for all energy conversions. Non-energy sources of emissions, like refinery and other processing are treated separately.

It is common sense that the emissions of a sector depend both on the type or the combination of fuels it uses, its production technology and characteristics specific for that industry. In MMRF-Green, emissions from combusting energy inputs are calculated as a certain share of the *output of sector  $s$ , using the fuel type  $f$* . Non-combustion emission relate directly to the "activity" or the output of the industry. A similar way to treat the generation of emission can be found in EPPA and GreenmodII.



**Table 9: Modelling the environmental aspects**

Model	Emissions	'Blame matrix'	Special aspects of environmental module	Abatement curve?	External model used?	Fuel prices?	Production technology?
GEM-E3	Greenhouse gases (CO <sub>2</sub> , CH <sub>4</sub> , HCFC, PFC, SF <sub>6</sub> ), acidifying emissions, VOC, PM <sub>10</sub>	Y	<ul style="list-style-type: none"> <li>- Behavioural, environmental and policy support module are used together to assess the effect of environmental policy.</li> <li>- Emission damages based on ExterneE and follow-up studies</li> </ul>	Y		<ul style="list-style-type: none"> <li>- Modelled endogenously, by the PRIMES sub-module</li> <li>- Initial data provided by EUROSTAT</li> </ul>	<ul style="list-style-type: none"> <li>- Electricity in the LEM bundle</li> <li>- Fuels in the labour, materials, fuels bundle in the next nest</li> <li>- Energy-savings technology (improves energy productivity)</li> </ul>
EPPA	Similar to GEM-E3, but more extensive modelling, adding aerosols (SO <sub>x</sub> , black carbon, organic carbon) and other substances (NH <sub>3</sub> , CO <sub>2</sub> ,...)	Y	<ul style="list-style-type: none"> <li>- Backstop technology</li> <li>- Depletion model for natural resources</li> <li>- Capital vintages</li> <li>- Autonomous energy efficiency improvement</li> </ul>	N	EPPA is part of IGSM; the other modules are a climate and ecosystems model	Modelled endogenously but can be set exogenously	<ul style="list-style-type: none"> <li>- Focus on energy inputs, treatment of fossil fuels /nuclear/hydro/advanced generation/wind/solar</li> <li>- All energy inputs are perfect substitutes except wind/solar</li> <li>- Energy bundle split up in electricity and non-electricity input</li> <li>- Separate coal-oil bundle besides gas inputs</li> </ul>

Model	Emissions	'Blame matrix'	Special aspects of environmental module	Abatement curve?	External model used?	Fuel prices?	Production technology?
NEMESIS	Similar to EPPA and GEM-E3, but more strongly linked to energy consumption	Y	Large scale energy demand module (NEEM), based on econometric estimations. Adding a variety of features and structural input for the model.	Y	Fuel price calculations within NEEM	Made by NEEM	Production process represented by cost-functions, having quasi-fixed factors, spill-over sources and variable inputs.
GreenModII	Focus on greenhouse gas emissions	N	Backstop technology	N	Micro-simulation model for distributional impacts of policies	Modelled endogenously based on initial dataset	<ul style="list-style-type: none"> <li>- Energy part of KE bundle</li> <li>- Distinction between non-electricity (combustion fuels) and electricity inputs in energy bundle.</li> <li>- Backstop technology for natural gas and carbon-free electricity</li> </ul>
GEEM-Alaska	Pollution that affects the modelled ecosystem	N	Ecological model, working separately from the CGE model	N	N	N	N

Model	Emissions	'Blame matrix'	Special aspects of environmental module	Abatement curve?	External model used?	Fuel prices?	Production technology?
MMRF-Green	Focus on greenhouse gas emissions	N	<ul style="list-style-type: none"> <li>- Inter-fuel substitution in electricity (energy) generation by region</li> <li>- Endogenous take-up of abatement measures</li> <li>- Emissions by emitting agent (residential + industries), by state and by activity</li> </ul>	N	N	Modelled endogenously based on initial dataset	<ul style="list-style-type: none"> <li>- Energy is treated as consumption good</li> <li>- Model does not allow changes in production process that decrease emissions per input of fuels.</li> <li>- Model allows energy savings.</li> </ul>
Mayeres (1999)	GHG and other pollutants with focus on Belgian transport sector.	N	<ul style="list-style-type: none"> <li>- Focus on transport</li> <li>- Damages of emissions based on ExternE study and follow-up studies</li> <li>- Impacts on different household types</li> </ul>	Y	N	Endogenously calculated	<ul style="list-style-type: none"> <li>- Distinction between energy for transport and non-transport.</li> <li>- Different fuel types</li> <li>- Durable/non-durable link</li> <li>- No endogenous technology representation</li> </ul>
EDIP	Emissions of all industrial activities and road traffic	Y	Impacts on different household types	Y	TREMOVE TRANSTOOLS	<ul style="list-style-type: none"> <li>- Endogenously calculated</li> <li>- Input from TRANSTOOLS and initial datasets</li> </ul>	<ul style="list-style-type: none"> <li>- KLE bundle with separate energy bundle</li> <li>- Energy bundle split up in electricity and non-electricity inputs</li> </ul>

In GreenmodII, but also in other models, the production sectors and production technology of the sectors are split-up in three types. The first nesting structure is used for the minerals & quarrying, nuclear & non-nuclear electricity, refining sectors. These are sectors that transform raw energy materials to energy used by other firms. The second nesting structure is a general nesting structure, similar to other models. The last nesting structure is used for agriculture and incorporates input of natural resources.

The modelling of the production technology of a sector can influence how emissions are modelled. For example it is assumed in most models (like in GEM-E-3), that the use of energy inputs can be traded off against higher capital inputs. Less energy inputs mean lower emissions, but paid at a higher capital investment, making the output more expensive. Often, nested CES production functions are used to model the substitution between capital and energy inputs or between different types of energy inputs or types of fuels. The nesting structure of the model both for production as for consumer utility can be quite different between models. Treating production, many models have a KLE bundle at the first nest, Value-Added and Energy at the second nest and then different types of energy in the following nests. At this level there is mostly a distinction between electricity and non-electricity output (combustion fuels). Here we should add that using the *CES functional form* here, supposes that the *substitution elasticity is the same for each fuel*.

Other, indirect forms of substitution are used within MMRF-GREEN for emission reduction. Inter-fuel substitution in electricity generated is handled using the "technology bundle" approach (see Hinchy and Hanslow, 1996). In the current version of the model, five power-generating industries are distinguished in each region based on the type of fuel used. There is also a separate end-use supplier (Electricity Supply). The electricity generated in each region flows directly to the local end-use supplier, which then distributes electricity to local and inter-state users. The end-use supplier can substitute between the five technologies in response to changes in their production costs. For example, the Electricity supply industry in NSW might reduce the amount of power sourced from coal-using generators and increase the amount sourced from gas-fired plants. Such substitution is price-induced.

## 2. The impact of technological progress on emissions

Many of the elements of the technological progress will be treated in the paragraph on R&D and technical progress (Section II.J.2). Here we will cover the aspects of technological progress that have a direct effect on abatement decisions, mitigation strategies and emissions.

Technological progress can increase the energy efficiency of the economy and lead to partial decoupling of economic growth and its burden on the environment. It usual to model these dynamic processes by means of exogenous time-trends applied to the input coefficients of energy

or fossil fuels. In EPPA this is called the AEEI or 'Autonomous Energy Efficiency Improvement'. This represents the non-price induced, technologically driven changes in energy demand and is imposed exogenously. The model also includes an exogenous set of productivity factors describing the evolution of the emission coefficients for non-CO<sub>2</sub> greenhouse gases.

In order to incorporate of new technology and its environmental effects, the extended model version of GEM-E-3 uses the term "energy savings". This term indicates technology that improves energy productivity. Producers evaluate investment in energy-saving technology through an inter-temporal marginal cost-benefit analysis. This is modelled as an additional demand for goods (for example equipment). Consumers can choose between two classes of durable goods: ordinary ones and energy efficient goods (advanced technology), at a higher price.

MMRF-Green uses a fixed relation between the fuel-usage in a specific process and the amount of emissions. The model does not allow any technological progress that changes this relation, for example by allowing coal-fired electricity producers to emit less CO<sub>2</sub> per tonne of coal burned. On the other hand, MMRF-GREEN does allow for input-saving technical progress. For example, the black coal electricity industry may reduce the amount of coal that it burns per kilowatt-hour of output. This sort of technical progress is imposed exogenously.

In NEMESIS, a distinction is made between demand related to the existing surviving equipment and new demand related to the net increases in energy needs and replacement of scrapped capacity. Regarding new energy demand, the model encapsulates the dynamic process of technological substitution in all sectors taking into account the technical and economic characteristics of the major available fuel/technology combinations.

A number of models, including EPPA and GreenmodII, include the representation of backstop technologies (cf. Section II.J). Backstop technologies are the technologies that might have a positive environmental effect, but are not competitive with 'dirtier' technology. The backstop technology is 'frozen' as long as it is not competitive. Increases in the price of conventional fuel can activate the technology. This means that the use of new technologies can change over time and that their use will become wide-spread. In EPPA 10 different backstop technologies are implemented, including the use of shale oil, energy from bio-mass, bio fuels (bio-ethanol), etc.

Besides backstop technologies, the EPPA model also includes a depletion model. In this way it can model the extraction of natural resources. All fossil energy resources are modelled as graded resources whose cost of production rises continuously as they are depleted. The resource grade structure is reflected by the elasticity of substitution between the resource and the capital-labour-materials bundle in the production function. Production in one period is limited by substitution and the value share of the resource: the technical coefficient on the fixed factor in the energy sector production functions. The resource value shares are determined and they represent the key

differences among regions and fuels (using cost of capital, labour and materials bundle and value of the resource).

The use of capital vintages (cf. Section II.B.1) is another tool often used in environmental models. By implementing capital vintages we can track the capital through time: 'recent capital' can be subject to energy efficiency improvements and is more mobile, while older 'dirty capital' will not improve.

In most models the fuel prices are fixed exogenously based on an initial dataset or a forecast of prices (provided for example by the OECD or IEA). In EPPA the user has an option to determine fuel prices endogenously, by using the depletion model and the various demands for energy inputs in the economy. In EPPA countries are allowed to trade energy inputs and their preferences with respect to own and imported energy are represented using the CES function with an Armington elasticity of substitution.

The fuel prices in GEM-E3 are determined using an energy sub-model that is a simplified version of the PRIMES model. The original data for the model were mainly supplied by EUROSTAT. The energy sub-model in GEM-E3 takes as given the demand of sectors for energy products and determines energy prices and the fuel mix that meets this demand. This information is then used in the optimisation decision of the economic agents who decide upon the energy demand at the new iteration. In equilibrium prices and quantities used by both models are equal.

The NEMESIS energy/environment module is a large scale energy demand module (NEEM) that simulates the formation of prices on the energy market and estimates the quantities demanded by the main energy market actors. It includes an aggregate energy supply part in order to enable the calculation of overall energy balances per country and incorporates energy-related greenhouse gas emissions, environment oriented policy instruments and emission abatement technologies. It combines the NEMESIS activity forecasts with demographic and structural inputs as well as fuel consumer prices to derive aggregate energy consumption functions defined by sector (industry, tertiary sector, households, transport). Long-term and short-term price effects are accounted for separately.

GEM-E3 contains an interesting split-up in its environmental module. The behavioural module includes the choice of abatement technologies by consumers and firms. The abatement curves for the firms are based on bottom-up engineering data for Germany. The results for Germany were extrapolated to the other countries in the model. Abatement decisions of firms in GEM-E3 are explicitly modelled through a cost-benefit assessment of the investment in abatement, compared to the price of permit or tax.

MMRF-Green does not incorporate the full representation of the abatement curves, but incorporates instead point estimates of how a higher carbon tax increases abatement of a firm. This endogenous uptake of abatement measures is most important for the agricultural sector.

In EPPA abatement costs are endogenous, but it does not use the explicit representation of an abatement curve.

Besides a behavioural module, GEM-E3 uses an environmental module and a policy module. The state of the environment is determined by (i) calculating emissions of air pollutants from economic activities, (ii) determining the transportation of these pollutants between countries and (iii) assessing the damages from the pollutants in monetary terms.

When treating pollution between countries/regions, we should take into account that the place of emission of the pollutant does not need to be the place where the damage of the pollutant is experienced. Pollutants can be transmitted by wind or rain, remain inactive until triggered by a specific chemical reaction or only have visible effects when crossing a threshold value in a specific region. To account for these effects, a 'blame' matrix can be used. This matrix, similar to an origin-destination matrix, relates the emission of the pollutant of one country/region (or more detailed, an industry in one country) to pollution in another country/region. Calculating this blame matrix inside a CGE model is much too complex, so a blame matrix has to be provided exogenously from a separate model, based on scientific research. For example, the blame matrix for the EDIP model was built based on the RAINS/GAINS model of the IIASA.

### 3. Impact of emissions

The majority of the models use a separable utility function to account for the influence of environmental damages on the households' utility function<sup>5</sup>. This means that the behaviour of the consumer is independent from the environmental damage. The 'dis' utility created by the pollution is subtracted from the utility of consumption. Emissions can lead to several kinds of damages, not only to the ecosystem, but also to public health and infrastructure. The monetary evaluation of emission damages Mayeres (1999) and GEM-E-3 were based on the ExternE study and its follow-up studies.

EPPA is actually a part of a larger model, the IGSM model. This model contains a climate model and a terrestrial ecosystems model. The effect of 'anthropogenic' emissions is assessed using these sub models.

GreenmodII uses a separate micro-simulation model of the Belgian economy to look at the distributional effects on households. This model was based on the work of Robillard et al. (2001).

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<sup>5</sup> Some models relax this assumption, see Section III.E.

It was constructed using the data from the Belgian household budget survey from 1997-1998. The dataset covers the 3 regions of Belgium. A micro-simulation model offers the researcher an interesting tool to look at the distributional effects of policy shocks.

In EDIP all production activities and in particular the transportation activity is associated with emissions and environmental damage. Environmental quality is one of the main factors of the households' utility function. Changes in the levels of emissions have a direct impact upon the utilities of the households. The welfare of each household type (population group) in the EDIP model is calculated as the 'equivalent variation measure' and depends upon consumption of commodities, consumption of leisure and the level of environmental quality.

Probably the most worked out environmental impact modelling is to be found in the GEEM Alaska model. It explicitly takes into account an ecology module, working side by side with a (simple) CGE model. GEEM is applied here to an oft studied marine ecosystem comprising Alaska's Aleutian Islands (AI) and the Eastern Bering Sea (EBS). The ecology model tracks the energy flows in the ecological module, first originating from the sun and then diverting itself through the ecosystem to (phyto) plankton and plants to a variety of animals. The ecology module works somewhat similar to conventional CGE, but here demand and supply originate from "energy prices". The biggest difference with the economy model is that in this case, there is no real exchange: the prey in the ecology model does not receive its energy price; full energy is taken up by the predator. As in economic CGE models, the prices play a central role in each individual's maximisation problem, because an individual's choice of prey will depend on the relative energy prices it pays.

## **I. Welfare and policy evaluation**

In evaluating different projects, there are two basic strands in the modelling practice. Most are very close to the Cost Benefit Analysis method, and thus try to make a full account of all effects on welfare. Changes in consumers' utility are then expressed in monetary terms. External effects are also expressed in monetary terms, usually on the basis of external studies. Of course, this will only resemble CBA when all effects are accounted for, which is not always the case, as we have seen in previous paragraph. Some models indeed fail to account for sources of investments or destinations of revenues. Other models, such as Mobilec and NEMESIS will depart from the CBA approach and present more specific project impacts, such as GDP or employment changes.

The CGEurope models, focusing on the cohesion between some 1372 regions, calculate the percentage gain / loss in equivalent variation of consumer utility per region. They calculate an additive social welfare function with constant relative inequality aversion. From this function, a measure of the change in welfare inequality is calculated: the extent to which the aggregated



percentage gain in welfare has to be adjusted downward or upward due to rising or falling inequality, respectively.

Outcomes in RAEM 3.0 are evaluated according to equivalent variation. Next to this welfare measure, a whole range of economic indicators can be calculated.

In performing policy simulations, the REMI model first calculates the direct effects of a wide variety of policy measures and translates this into variables within the model (such as travel time, labour productivity, supply of skilled workers). In a second stage the total output effect of the policy change is calculated. Outcomes are presented as the GDP change by production sector per 100 euro of investment, and projects are evaluated according to present value of cumulative GDP. Change in employment is also presented.

We found the most extensive treatment of welfare evaluation for the environmentally orientated models in the GEM-E3 model and the model of Mayeres. Welfare in GEM-E3 is calculated as the consumer's utility function, complemented with an environmental welfare index, which is based on the valuation of damage generated by policy. The welfare impact by country is aggregated by a constant relative inequality aversion function. Next to welfare, the present value of equivalent variation is calculated. 'Damage' is described as a function of the incremental change in deposition/concentration of a pollutant. Damages considered are damage to public health (morbidity and mortality), global warming and damage to ecosystems. The valuation of this (incremental change in) damage is based on various willingness-to-pay estimates taken from the ExternE project and its follow-up projects.

The EPPA model seems to use only economic cost measures, such as GDP, Equivalent Variation to evaluate the impact of different climate policies. An interesting discussion of the proper use of different economic cost measures (without including a valuation of environmental gain), with applications using EPPA, to evaluate the implementation of environmental policy is found in Paltsev et al. (2004).

In the Mayeres model, the consumer utility function takes into account not only purely economic elements, but also the level of congestion, accidents and pollution. The last two impacts enter utility in a separable way, while congestion has a feedback effect on consumer behaviour. From this utility function, the equivalent variation of policy changes is computed.

For the case with different income categories, a CRIA (Constant Relative Inequality Aversion) welfare function is computed. The change in welfare is computed as the social equivalent gain, obtained as the factor which should be added to each household's equivalent income before the reform to produce a level of social welfare equal to that obtained in the post reform equilibrium. The change in inequality is measured through the Atkinson-Kolm index.

In RELU the welfare function includes a random i.i.d. Gumbel parameter. To enhance understanding on the different effects, welfare is decomposed into terms representing changes in toll revenues, real estate value, wages, prices, rents, commuting costs and the cost of shopping.

## **J. Dynamics and technical change**

### **1. Dynamics**

There are two broad ways in which applied CGE models incorporate dynamics, depending on the way agent's expectations are treated. One is to introduce forward looking expectations, so that agents maximise their intertemporal objective functions taking into account future developments. Another is to have agents' expectations depend on past or present parameters, called static or backward looking expectations. In this case a recursive dynamic structure can be preserved, with the economy consisting of a sequence of equilibria. Between these equilibria a selection of variables are dynamically updated, either exogenously or endogenously. Due to their computational simplicity, the last way is overwhelmingly present among the models we reviewed. In this section we concentrate on the way saving and investment behaviour is treated in the various models. Saving is usually modelled in a very simple way, as a fixed share of households' income. The exception to this rule is GEM-E3, who allow for endogenous saving based on consumer utility maximisation. In this model the saving rate depends on the interest rate and consumer prices.

The treatment of investment behaviour is more interesting. In general, aggregate investment mimics domestic saving (sometimes supplemented by foreign capital), so that aggregate capital follows a permanent inventory-type path. Equality of savings and investment is then determined by a closure rule. However, it is the breakdown of investment by sector which is worth some more paragraphs. The way in which sectoral investment is endogenised, is crucial to the dynamic adjustment path of sectoral capital in response to shocks altering the rate of return. We found two broad ways of determining a sector's investment behaviour. One is the treatment of physical capital accumulation as explained in Dixon and Rimmer (2002), which forms the basis of the MONASH recursive dynamics. This way of modelling is used by RAEM 3.0, EDIP, GreenMod II, and MMRF-Green (even though the MONASH model on which MMRF-Green is based, allows for forward looking expectations as well). Another approach for modelling investment is found in GEM-E3.

In GEM-E3, firms must conjecture on the demand for capital in the next year for which they need to form expectations on future product prices and future demand. For future prices firms base their expectation on the current price level. Future demand is derived by taking into account the

expected growth rate of the sector. At the moment it is unclear how these expected growth rates are determined. When expectations on the future need of capital are formed, the firm compares this with the current stock of capital. Investment is determined by subtracting future needed capital by current capital minus depreciation. However, the process of adjustment is slowed down by the inclusion of a partial adjustment parameter in the equation determining investment.

The MONASH dynamics assume that sectoral capital is supplied to the sector according to an inverse logistic function, relating the rate of return to capital to the proportionate growth of the sectoral capital stock. The idea behind such a relationship is that investors require a higher rate of return to their investment, if capital growth is already high. The function is constrained by a minimal and maximal capital growth, in order to keep the rate of accumulation at a realistic level. Minimal capital growth is usually the inverse of depreciation, maximal capital growth is set by the modeller (MMRF–Green uses the trend growth of the sector + 0.06, while RAEM 3.0 uses the trend growth + 0.064). In order to properly pin down this capital supply function, one has to estimate the historical rate-of-return of the sector, the trend capital growth, as well as assign a value to the derivative of the rate of return to capital growth. Data on individual industries are sometimes hard to come by, but MMRF–Green uses investment functions used in Australian macro models to estimate this parameter, which governs the curvature of the capital supply function.

Given this function, an expression for the rate of return must be found. The rate of return is taken to be equal to the present value of investment in the sector, divided by the cost of capital in that sector. The expression for present value naturally includes an expression for the value of investment, or the rental rate of capital, in the future. Static expectations, however, assume that investors use the current rate to conjecture on the future rental rate.

These two equations are then combined to determine an expression for sectoral capital growth, and sectoral investment using the simple perpetual inventory equation.

## 2. R&D and technical change

In reviewing technical change we consider the following questions, which are summarised in Table 10. Is technical progress introduced exogenously in the model, or is it endogenous? In which direction does technical progress work? This concerns the classic question of the neutrality of technical progress, whether it is augmenting the contribution of a production factor, whether it saves an input or whether it is just Hicks neutral total factor productivity (TFP) growth. Some models introduce features such as learning by doing, R&D spill-overs and backstop technologies. Note that we do not consider in this paragraph the price induced substitution of inputs, nor the decision to abate by firms. The former effect has been dealt with in the paragraph regarding

producer behaviour (Section II.B). The latter is treated in the 'environment' paragraph (Section II.H).

**Table 10: The representation of innovation and technical change**

	<b>Endogenous Technical Change?</b>	<b>Direction of technical change</b>	<b>R&amp;D Spillovers?</b>	<b>Learning By Doing?</b>	<b>Backstop Technologies ?</b>
GEM-E3	Y in extension	TFP Growth Input Augmenting	Y	N	N
EPPA	N	Labour Augmenting Natural Resource Augmenting Energy Saving	N	Y	Y
Greenmod II	N	Flexible	N	N	Y
MMRF-Green	N	Flexible	N	N	N
REMI					
Mobilec	N	TFP Growth	N	N	N
NEMESIS	Y	Flexible	Y		

Few models find it useful to endogenise technical change. Not surprisingly, the environmentally oriented models pay most attention to the representation of innovation, and a few of them have endogenised the innovation process, notably GEM-E3 (in an extension) and NEMESIS.

Some dynamic models allow for an exogenous representation of technical progress. In these models the Cobb Douglas part of the production function contains a scaling parameter which can be used to make some exogenous assumptions on the rate of TFP growth. This way of representing technical progress is quite coarse, without the possibility to represent biased technical change and the response of innovation to price and policy changes.

The MMRF-Green model gives the user the possibility to specify technical progress exogenously through a wide range of shift parameters, which gives the user some flexibility in introducing TFP growth or a combination of input saving changes. No allowance is made for inventions that might allow producers to release less of a pollutant per unit of energy consumed. If the model is used for historical simulations, parameters are estimated econometrically from historical data.

EPPA imposes exogenously the augmentation of labour and natural resources. The growth factor of effective labour is specified by a logistic function. Initial and terminal growth rates must be set exogenously. As energy is concerned, the EPPA model recognises the fact that historically countries have seen a drop in the energy intensity of their economies as their GDP grew. The causes of this drop have been widely debated, but in order to respect this historical experience, the input coefficients for energy and fuels are endowed with an exogenous trend, controlling the evolution of demand reduction factors that scale the production sector's use of energy per unit of output. For developed countries this trend is assumed to display positive growth over time, but for developing countries energy efficiency is first assumed to drop for a few decades before it is allowed to rise.

EPPA and Greenmod II are the only models allowing for the introduction of backstop technologies in energy production. These new technologies enter endogenously when they are economically competitive with more conventional types of energy supply. Competitiveness depends on endogenously determined prices for inputs, which in turn depend on depletion, climate policy and the general growth of the economy. For each new technology, a mark-up factor is identified, which expresses the cost disadvantage of the new technology versus the conventional one in the base year. This factor can be interpreted as the rise of the conventional energy price necessary to make the new technology competitive.

The adoption of new technologies is generally seen as a gradual process. To replicate this gradual penetration, and to avoid unrealistically rapid responses of the supply of new technologies to price changes, the EPPA model makes capacity expansion dependent on the endowment of a specialised fixed factor. This specialised factor is initially only available in small amounts, thus limiting the capacity that can be built initially. However, the endowment of this factor is made dependent both on industry output, as well as its stock in the previous period. Thus, as output gradually expands, the endowment of the fixed factor rises, and after a while it ceases to be a constraint on the industry's capacity. The intuition behind this mechanism is the existence of a learning by doing mechanism. Only by actually producing the new technology, the engineering firm is able to train new specialised staff able to operate the innovation. In EPPA, the function which governs this mechanism is parameterised based on observations of the ability of nuclear power to expand since its introduction.

In Greenmod II, two endogenous backstop sectors are modelled, but it does not deal with the issue of gradual adoption. Other technical progress can be imposed exogenously through scaling parameters in the production function.

As has been noted, only two models integrate endogenous technical progress and R&D. We will dwell a bit longer on how they operationalise endogenous growth.

For GEM-E3, the DYN-GEM-E3 project has elaborated an endogenous growth module, compatible with the constant returns to scale perfect competition assumption that characterises the basic version of the model (Kypreos, 2004). Six types of technical change are allowed for: Hicks neutral technical change (TFP growth) and biased technical change augmenting the 5 production factors: fuel, electricity, capital, labour and materials. To formalise biased change, each factor is expressed in terms of efficiency units. Efficient inputs are expressed as a CES function, whose arguments are inputs and the stock of input specific innovation. Hicks neutral change (quality innovation) is being formalised by expressing total output as a CES function with the stock of quality innovation and a CES composite out of efficient inputs as arguments. This yields a general specification, which allows investigating whether a change in the direction of innovation accelerates growth or whether crowding-out effects decrease it.

Then a market for innovation is specified. The demand side consists of demands for the 6 kinds of innovation by firms, taken from a producer's cost minimisation program. The demand for innovation is a positive function of the price of inputs (output in the case of Hicks neutral change), and a negative function of the price of innovation. Innovations are supplied by a perfectly competitive, CRS innovation sector. R&D is transferred to real innovation by the productivity of the research sector. The productivity of this sector is determined by two externalities. Through the general knowledge externality, the stock of general knowledge, intra- and intersectoral, national and international has a positive effect on the productivity of the research sector. The current stock of specific knowledge accumulated by the research sector has a negative impact on the productivity of the research sector.

The effect on R&D of different environmental policies, raising the price of energy, is tested and is found positive. The ensuing rise in biased innovation adds to the efficiency of the economy, thus dampening the negative GDP effects of stricter policies.

Where GEM-E3 is one of the first applied general equilibrium models to endogenise technical progress, NEMESIS aims to be one of the first macro econometric models doing the same.

The starting point of the endogenous innovation framework is the specification of a cost function with three variable inputs (labour, energy and materials) and two quasi-fixed factors (physical capital and R&D capital). From the cost function, demand functions for variable inputs are derived from Shephard's Lemma. Desired growth rates of both quasi fixed factors are derived from a dynamic programming cost minimisation program. The derived factor demands allow, next to the usual own and cross price elasticities, for spill-overs on the cost of each factor by the R&D capital stock of the own sector and 5 other groups of sectors (namely, office machines, electrical goods, chemical products, other equipment goods, and the other sectors lumped together). The relevant R&D capital stock for the spill-overs consists of domestic and foreign

R&D stocks, where foreign stocks are weighted with the share of the foreign country's stock in total world stock.

The R&D growth rate depends on input prices, output, the cost of R&D and the cost of physical capital.

We note that it is not clear from the documentation in our possession how NEMESIS has implemented its intention to also represent endogenous *product* innovation (as voiced in Fougeyrollas et al., 2000). This is of interest, since in a monopolistic competition framework endogenous product innovations would entail the endogenous expansion of product varieties.

### III. State-of-the-art in theoretical modelling

After presenting a selection of current applied models, we wish to cover some of the recent developments in the theoretical fields. These may provide useful ideas which may be incorporated in a later stage. In turn, developments in the field of land use, endogenous growth and technological development, regional labour markets, ecological-economic modelling and the use of stochastic elements in CGE models are discussed.

#### A. Land use

A variety of modelling approaches are used for the analysis of land use change. In this chapter we focus on those models that are generally acknowledged in the recent literature as the most suitable for modelling contemporary complex land use systems.

Until a decade ago, the most frequently used models of land use change were statistical and econometric models, spatial interaction models and optimisation models (e.g. linear programming models). Nowadays, these models seem to be obsolete. Statistical models often suffer from problems like multicollinearity, spatial autocorrelation and violation of the linearity assumption. Econometric and spatial interaction models lack a sound underlying theoretical foundation, making their exploratory capacity very limited. The main criticism against the classic approaches to land use modelling is that several drivers of land use are not accounted for because the mathematical basis of the models (they need to be solved for closed-form analytical equilibrium solutions) makes them too rigid to cope with complex land use systems. In sum, they provide a rather simplistic treatment of land use.<sup>6</sup> For an overview and evaluation of these classical modelling approaches, and some references, we refer to Briassoulis (2000), Aspinall (2004) and Parker et al. (2003).

Recently new models have become available. Two major, spatially explicit, approaches can be discerned: models that are landscape-based and focus on patterns of change (so-called cellular

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<sup>6</sup> As Briassoulis (2000) summarises in her excellent overview of land use models: “reality is so complex; land use change comes about under the influence of many macro and micro factors, acting and interacting within varying time frames. Land use change problems are essentially metaproblems. Therefore, the reduction and simplification of this real world diversity to serve the purposes of model building is extremely difficult. The result may be either a very crude representation of reality or, on the contrary, a very complicated model structure that is impossible to handle within the bounds of reasonable time and other resources available to answer practical questions. A second reason is that many theories are cast in abstract terms which make their operationalisation difficult. Abstract theories are, in part, a reflection of real world complexity and of inability, on the part of the theoretician, to disentangle the complex world and discover order behind the apparent chaos.”



automata models), and models that are agent-based and focus on the underlying decision process<sup>7</sup> (Veldkamp and Verburg, 2004). The unit of analysis is thus either an individual pixel or an individual decision-maker. Both types of models acknowledge the importance of scale effects in studying spatial interactions (Evans and Kelley, 2004)

## 1. Cellulair automata based models

The cellular automata modelling framework is based on the theory of fractals and applies cellular automata concepts to model a variety of complex, dynamic, socio-economic and environmental phenomena (see e.g. Engelen, 1988; White and Engelen, 1993).

Engelen et al. (1995) define cellular automata as “mathematical objects that have been studied extensively in mathematics, physics, computer science and artificial intelligence (...). Tobler (1979) defined them as geographical models but they have only rarely been applied in human geography in the years since he proposed them. (...) A cellular automaton consists of an array of cells in which each cell can assume one of  $k$  discrete states at any one time. Time progresses in discrete steps, and all cells change state simultaneously as a function of their own state, together with the state of the cells in their neighbourhood, in accordance with a specified set of transition rules. Transition rules can be either quantitative or qualitative or both”. A cellular automata model consists of: “(a) a cellular space, normally two dimensional, (b) a definition of the neighbourhood of a cell, (c) a set of possible cell states, and (d) a set of transition rules” (White and Engelen, 1994).

Cellular automata models have some important advantages over conventional modelling approaches because they can integrate macro- and micro- spatial and temporal processes, and because they can cope with complex real world systems, using theoretical assumptions that can be specified by the user.

A well known and widely used example of a cellular automata based model is SLEUTH (slope, land use, exclusion, urban extent, transportation, hillshade), which is used in an urban context. It combines an urban growth model with a model of land cover changes. SLEUTH is essentially a pattern-extrapolation model that comprises two phases: based on simulations of urban development patterns over an historic time period (first phase), it forecast these patterns into the future (second phase). Four growth rules (types of change in urban land use) are used for the simulations, and are applied sequentially during a growth cycle or year. The growth rules are defined through five growth coefficients (between 1 and 100), the values of which are derived during the calibration process in which different parameter sets are tested for their ability to replicate historic growth patterns. (Jantz and Goetz, 2005)

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<sup>7</sup> For a discussion in an urban context, see Batty (2005).

Another example of a cellular automata approach at the regional level is given by Engelen et al. (1995). The model operates at two spatial levels: an upper (macro) level and a lower (micro) level. The iterative modelling process proceeds in four steps:

- 1) the basic geographic data needed by the upper level model is retrieved from the database, aggregated to the regions used in the upper level model and passed to it;
- 2) the upper level model calculates the values of the variables in each region and passes them to the lower level, the cellular model;
- 3) the cellular model allocates these values at a micro level, using – if necessary–more information from the database;
- 4) the results from the previous step are used to update the database, and the model returns to the first step for the next iteration.

The cellular automata approach is a discrete approach that is very flexible since (i) it can accept various specifications of the rules governing the conversion of land uses in the cells of the study area, (ii) it incorporates environmental and other considerations in the assessment of the potentials for change and (iii) it can be linked to higher level models as well as to GIS for more efficient use and manipulation of input and output spatial information. Some shortcomings of the model are that it does not consider the transportation system explicitly, it is based on stationary transition rules and therefore has limited ability to reflect feedbacks in the system under study, and the spatial subdivision assumed by the model (the cellular array and the magnitude of the cells) may not be congruent with the actual spatial formations which emerge under the complex interplay of the forces which drive land use change. (Parker et al. 2003; Briassoulis, 2000). Most of these constraints are addressed by a new generation of cellular automata based models, which are more flexible because they relax many of the assumptions of classic cellular automata theory (homogeneity of space, uniformity of neighbourhood interactions, universal transition functions). (Jantz and Goetz, 2005)

The main disadvantage of cellular automata models is that the units of analysis and the simulations do not match with the units of decision making. As Parker et al. (2003) conclude their review of this type of models: “In sum, cellular models have proven utility for modelling ecological aspects of LUCC<sup>8</sup>, but they face challenges when incorporating human decision making”. A recent and rapidly expanding group of models use individual agents as units of simulation. (Verburg and Overmars, 2007) The next section deals with these so-called agent-based models.

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<sup>8</sup> LUCC = land-use/cover change.

## 2. Agent-based models

In contrast to cellular automata based models that focus on landscapes and transitions, agent-based models focus on human action. They thus emphasise the decision-making process of the agent (which can represent any level of organisation) and the social organisation and landscape in which these individuals are embedded. Since adequately representing agent behaviour and linking it to actual land areas is a very difficult task, well established agent-based models have become available only recently. (Verburg and Overmars, 2007). They employ some variant of bounded rationality, because perfect rationality is not very realistic given the complexity of land use systems. Boundedly rational agents “have goals that relate their actions to the environment. Rather than implementing an optimal solution that fully anticipates all future states of the system of which they are part, they make inductive, discrete, and evolving choices that move them toward achieving goals.” (Parker et. al, 2003)

For an extensive explanation of agent-based modelling, see Gilbert (2007).

Evans and Kelley (2004) give an example of an agent-based, spatially explicit, modelling framework. Each of the landownership units of the landscape (parcels, composed of a set of regular sized cells) is associated with individual simulated agents (households). Both the cells and the households have characteristics. At each time point, households evaluate the land uses of the cells they own and, if they judge it necessary, make land conversion decisions. The general model consists of a set of discrete modules, including agent-decision-making dynamics, household demographics, land use change and biophysical processes and crop price. Within these modules, system processes are programmed.

Other examples of agent-based models include SIMPOP (Sanders et al., 1997), SIMPOP2 (Bretagnolle et al., 2006) and MameLuke (Huigen, 2004).

The choice between pixel-based and agent-based models is not an easy one and depends both on the objectives of the study and the available information and resources. Given the complexity of the land use system, the use of different model approaches, the results of which are afterwards compared, might be appropriate. Another possibility is to use different approaches sequentially, e.g. first use agent-based models to explore mechanisms that can later on be included in spatial simulation models. (Verburg and Overmars, 2007) In multi-agent system models of land-use/cover change (LUCC), both key components are integrated through specification of interdependencies and feedbacks between agents and their environment. This allows to simulate the complex interactions among agents and between agents and their environment in a manner that assumes no equilibrium conditions, to link observations at a range of spatial and temporal scales and to generate observable behaviour at multiple levels. (Parker et al., 2003)

Apart from these two large 'families' of recently developed models, some 'hybrid' models exist, which cannot be classified into a single model category. Probably the best known hybrid model is the CLUE model, described in the next section.

### 3. The CLUE modelling framework

Hybrid models are a new generation of models that combine a 'classic' estimation model with a simulation model (Irwin and Geoghegan, 2001). A recent example of such a hybrid, spatially explicit model is the CLUE (Conversion of Land Use and its Effects) model, developed at the Wageningen Agricultural University (the Netherlands) to model land use changes as a function of their driving factors. The first version was published in 1996 and the model is now one of the most widely applied modelling frameworks. The CLUE framework is an "integrated, spatially explicit, multi-scale, dynamic, economy-environment-society-land use model". (Briassoulis, 2000) It can be considered a cross-disciplinary model since it integrates environmental modelling and a geographic information system (Veldkamp and Fresco, 1996a). For an extensive description of the model, see Veldkamp and Fresco 1996a, 1996b, 1998; Verburg et al., 1997; de Koning et al., 1998; Verburg et al., 1999; Verburg and Overmars, 2007; [www.cluemodel.nl](http://www.cluemodel.nl)).

In a first step, multiple regression analysis is used to analyse past and present land use patterns at various levels of spatial aggregation. In this way, the most important bio-physical and socio-economic determinants of land use at each level of aggregation as well as the quantitative relationships between them and the area of various land use types are determined. The results of the analysis of the first step are used in the second step to explore possible future land use changes within a spatially explicit framework using scenarios of future socio-economic development.

The CLUE modelling framework is composed of four modules. The demand for various types of land use is taken up by the Demand Module. The calculations of the demand module are based on the national level demand for various commodities, which consists of domestic consumption and exports. Domestic consumption is assessed as a function of population size, composition (urban and rural) and consumption patterns, while exports are assessed exogenously and they are related to international prices and national subsidies. The necessary demographic input to the demand module is given by the Population Module. Consumption patterns may be related to macro-economic indicators like GNP, purchasing power and price levels. Different scenarios are formulated to account for difficult-to-predict changes in demand. The Yield Module assesses the yield of each of the main land use/cover types as a function of their surface area (in each cell of the study area), bio-physical conditions, technology level, management level and their general intrinsic cover value. The Allocation Module provides for the actual allocation of the demand for land by land use/cover type generated by the Demand Module to the cells of the study area in accordance with the ability of land in each cell to support the actual demand as assessed by the

Yield Module. A nested scale approach is applied for this allocation drawing on the idea that local land use change is the product of changes in both the drivers of land use at higher scales as well as of changes in local bio-physical and socio-economic conditions.<sup>9</sup> The regression equations estimated from the first step of the modelling procedure are used to calculate the land use changes at each spatial level. This allocation procedure attempts to integrate top-down with bottom-up demands and constraints to simulate the effects of future changes in the drivers of land use. (de Koning et al., 1998)

Recently, a modified version of the CLUE model, the CLUE-s model, was developed which makes possible high resolution representation of land use with homogeneous pixels (each pixel only contains one land use type). Improved computer capacity and data availability now allow to simulate high-resolution land use changes for large areas, e.g. the European Union. (Verburg and Overmars, 2007).

Until recently, there has always been a relatively strict subdivision between urban and rural models of land use change, with distinctly different modelling procedures: urban models primarily used neighbourhood functions such as cellular automata and infrastructure, rural models were generally based on land-quality assessments as the basis of simulation. The CLUE modelling framework offers the possibility to combine different procedures for land allocation within one modelling framework. (Verburg and Overmars, 2007) According to Briassoulis, the CLUE modelling framework is “a worthwhile attempt to address the land use change issues as it is sensitive to the requirements of integration along all dimensions with a special emphasis on the critical spatial dimension. It adopts a macro-, aggregate approach to the analysis of land use change and it is intended primarily to serve as a predictive tool in analyzing the land use impacts of future development scenarios at large scales—regional and national. It is relatively simple to comprehend and functional to use.” However, the CLUE research group itself emphasises that to become a reliable policy support instrument, the modelling framework requires further elaboration (high spatial resolution data, linkages to farming systems analysis, land evaluation systems, and optimisation planning models). Furthermore, the explanatory capability of the CLUE modelling framework is limited because of its use of statistical procedures, which, as Briassoulis (2000) argues, should be complemented by thorough analysis using other, mostly qualitative techniques. A final and very important weakness of CLUE is the absence of a rigorous theoretical basis.

The main disadvantage of CLUE is the same as that of the cellular automata models: the unit of observation is not the individual decision-maker: “Because the underlying decision-making unit behaviour is imposed, it is not possible to model a behavioural response to a change in any variable included in the models” (Irwin and Geoghegan, 2001).

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<sup>9</sup> More details on the multi-scale approach of the CLUE model can be found in Veldkamp et al. (2001a,b).

## B. Endogenous Growth and Technical Change

### 1. Endogenous Growth and New Economic Geography

New theories of endogenous growth and the New Economic Geography literature share some important assumptions. Both rely extensively on increasing returns and imperfect competition which lie at the basis of their most important results, so it should not be surprising that both strands of theories have been successfully integrated. In this paragraph we review some of the implications of the symbiosis of New Growth Theory and New Economic Geography. The paragraph draws heavily upon chapter 7 in Baldwin et al. (2003).

Baldwin et al. (2003) describe a model which builds on Romer's model of technical change (see also chapter 6 in Barro and Sala-i-Martin, 2004). The driving force of economic growth in Romer's model is the continuous expansion of varieties due to sustained R&D effort. This growth model is embedded in a two region economic geography model. In both regions capital as well as labour is assumed to immobile across borders. The regional capital stock is owned by the regional labour force, so capital income is being spent locally. Capital is used as a fixed factor of production, where one unit of capital is used to produce one variety. Capital should thus be thought of as an 'idea' instead of a physical unit. Capital depreciation is modelled as a constant probability of the obsolescence of an idea. Labour is the only variable cost, production does not use any intermediate good. Research activity is modelled through an artificial research sector. The modelling of the research process is crucial to the eventual outcome. The cost of research is assumed to fall with the number of existing varieties/ideas. Research is thus assumed to follow a so-called learning curve, which is crucial to undercut the mechanism implied by the Dixit-Stiglitz setting, where expanding varieties imply falling profits due to increased competition. Different assumptions could be made on the stock of existing ideas which can be used to describe the learning curve. In the 'global spill-over' case, the relevant number of ideas consists of the whole stock of varieties existing in the world. In the 'local spill-over' case the relevant number of ideas only consists of the regional stock of varieties. This case is a way of modelling the importance of proximity and networking in the research process. The distinction matters for the strength of agglomeration forces, as can be expected.

In both cases, agglomeration dynamics are driven by forces that are able to influence the willingness to invest in new technologies (in the model captured by Tobin's  $q$ ). In the global spill-over case, two forces influence the research sector's incentive to invent new ideas. The well-known demand linkage works to enhance research: an exogenous shock leading to a rise in a region's capital stock will boost capital income, which in turn raises expenditure, which raises profits and thus the incentive to invest. This positive effect is countered by the market crowding effect: an increased number of varieties in a region raises competition, which lowers the value of new investment. In the local spill-over case these two well-known effects are supplemented by a novel effect, working to encourage regional growth. Since the productivity of the regional

research sector depends on the regional stock of inventions, an exogenous positive disturbance raises the attractiveness of research in one region, thus raising growth in that region. This effect has been named “localised spill-over effect”.

As in all NEG models, the strength of these spatial effects depends on trade freeness, and thus on the level of transport costs. The local spill-overs version has been used to analyze the impact of different kinds of infrastructure investments (i.e. intraregional or interregional) on regional development. (See Martin and Ottaviano (1999) and Martin and Rogers (1995))

Agglomeration forces in this model do not work through migration of labour, or through the mobility of capital, but through different endogenously determined growth rates between regions. The model relates closely to the literature describing agglomeration through ‘growth poles’ and ‘growth sinks’. (See e.g. Perroux, 1995).

## 2. Endogenous Technical Change and environmental modelling

There is a widespread agreement that the reaction of technology to policy is crucial in estimating the impact of different policies on issues like energy and the environment. Pizer and Popp (2007) take stock of recent empirical evidence of the endogeneity of technical change, and of the way in which the modelling profession has attempted to introduce these effects in applied models.

A first important issue concerns the private R&D process. It is well known that the social returns to R&D far outweigh the private return. Due to the public good nature of most knowledge embodied in an invention, the general public will benefit from research done by a private innovator. Due to this divergence between the private and the social rate of return, the private sector will in general not provide the socially optimal amount of research. For environmental policy modelling, this creates two challenges. First, the impact of policies to encourage more R&D should be modelled properly. Is the government able to encourage more research? Second, the true cost of funnelling resources to environmental R&D should be properly estimated. If there is at least partial displacement of other kinds of R&D, a dollar invested in environmental R&D should be valued by the proper opportunity cost, namely the high social rate of return that could be achieved through other R&D.

There exists mixed evidence of the impact of policy on R&D. Lanjouw and Mody (1996) and Brunmeier and Cohen (2003) look at the relationship between pollution-abatement expenditures and environmental patents. Pollution control expenditures are taken as a proxy of the stringency of environmental regulation. Both find positive, albeit small effects. Popp (2002) finds positive effects of lagged energy prices and energy R&D activity.

Modellers have responded in various ways to the range of empirical evidence described above. A choice has to be made on the form of the model (whether R&D works to improve emissions intensity, abatement costs or sectoral productivity) and the parameterisation of effects (the social rate of return and displacement effects). Nordhaus (2002) for example links the rate of growth of

carbon intensity to R&D input and expresses the cost of one unit of R&D input as 4 units of output reflecting the above displacement effect. Buonanno et al. (2003) links the level of carbon intensity to the total stock of accumulated R&D and relate the productivity of environmental R&D positively to R&D performed elsewhere. Goulder and Mathai (2000) let abatement costs depend on the stock of existing knowledge, whereas in the multi-sectoral model of Goulder and Schneider (1999) the stock of knowledge influences sectoral productivity. In the latter model, no sectoral spillovers exist given the lack of research on the existence of positive spillovers and crowding out between sectors.

Next to private R&D efforts, Pizer and Popp (2007) consider the effect of learning by doing mechanisms. These effects could be very important from a welfare point of view compared to R&D, since the former does not entail such a high opportunity cost. Gauging the relative importance of learning by doing and R&D in influencing is done by estimating a learning curve (cost in function of cumulative capacity) augmented by a term for the stock of R&D. The few studies in this field have found only modest impacts of learning by doing, compared to R&D. Moreover, studies on the learning curve have suffered from concerns about the direction of causality, and the possible endogeneity of regressors. Nevertheless, learning curves have been applied in models (see e.g. Goulder and Mathai, 2000).

The precise impact of government R&D is even less understood. The wedge between the private and the social rate of return has been documented for private R&D, but the return of government R&D is less well known, due to its usually fundamental and long term nature. This uncertainty about the precise impact of government research creates difficulties for policy oriented research. Given the divergence in private and social rate of returns one would expect government intervention, through R&D subsidies or tax cuts to be beneficial. Unfortunately one does not know whether existing policy corrects for the rate of return difference or not. In other words, in applied models, government research enters the baseline scenario of a policy model in a hidden way, making it difficult to judge upon the value of an incremental change in policy.

Another issue to be tackled is the gradual adaptation of a new technology. Although empirical evidence exists on the nature of the diffusion process, the gradual adoption of technologies is still modelled in an ad hoc way. Empirical evidence has shown, however, that the process of adoption varies according to the nature of the technology, and the incentives faced by firms. In the environmental field, end-of-pipe technologies are more likely to be adopted quickly under pressure of government regulation, while energy efficiency technologies are more likely to be adopted at the rate of the well documented S-curve. (See e.g. Popp, 2005 and Rose and Joskow, 1990) Ideally, models of technological change should then distinguish among different kinds of technologies, which is rarely done in practice.



### C. Location decisions of households and firms

A case in point of a situation where an individual or household has to choose among a set of discrete alternatives, is housing consumption. Discrete choice models<sup>10</sup> are therefore the straightforward techniques of modelling household decisions regarding housing. The basic framework underlying these models is random utility theory. According to this theory, the decision-maker evaluates the attributes associated with a set of discrete alternatives and chooses the alternative which maximises utility, subject to his tastes and constraints.

Because of its computational simplicity, the multinomial logit model is the most commonly used discrete choice model in this context. However, this computational simplicity is paid for by the unrealistic Independence of Irrelevant Alternatives (IIA) assumption. This assumption states that the ratio of choice probabilities is independent of the presence or absence of any other alternative in a choice set (Hensher et al., 2005).

To model a more flexible pattern of substitution, the multinomial logit model has been generalised to a nested multinomial logit model (McFadden, 1978, 1981; Fischer and Nijkamp, 1985, Clark and Van Lierop, 1986). In a nested multinomial model, the utilities of alternatives in common groups may be correlated. This possibility is accounted for by introducing a scale parameter (associated with the 'inclusive value') into the variance of each of the unobserved components of utility. The variances within any nest are assumed to be equal but they may vary between nests.

The framework of the nested logit model was designed by McFadden in his seminal work of 1978. Quigley (1976) pioneered this technique in a housing market context with a study of short-term housing demand in Pittsburgh. Since the 1980s, a wide range of disaggregate models of housing choice have been developed. Only few of them, however, explicitly take into account the institutionalised and regulated nature of the housing markets in Western Europe.<sup>11</sup>

According to Koppelman and Wen (1998) the applications of the nested multinomial model can be divided into two main categories: the McFadden nested logit model, derived from random utility theory, and the Daly non-normalised nested logit model, based on probability relationships that are not consistent with utility maximisation. In the former, the non-normalised parameters are constrained to be the same across all nodes within the same level of a tree. In the latter this is not the case.

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<sup>10</sup> For an overview of discrete choice modelling methods, see amongst others Ben-Akiva and Lerman (1985), Hensher et al. (2005), Hutchinson (1985), Long (1997), Pitfield (1984), McFadden (2001) and Train (2003).

<sup>11</sup> In the United States governmental control and interventions on housing markets is nearly non-existent, which makes an analysis based on the economic theory of competitive markets less problematic.

Although the nested logit model addresses the IIA assumption that underpins the multinomial model, it has a severe drawback: the tree structure is intuitively constructed and imposes a hierarchical choice that is not always a good reflection of the real choice process. Moreover, the IIA assumption is only partially relaxed since the variance is partitioned into nests (similar alternatives are nested). In order to obtain a completely unrestricted estimation procedure, one would have to implement the heteroscedastic extreme value discrete choice model (Louviere et al., 2000), a model that can reveal tree structures that may not always be intuitively obvious.

The discrete choice framework has also been applied to model firm location decisions. Carlton (1983) was the first to apply the conditional logit model to industrial location decisions. However, the IIA assumption hindered further progress in this line of research. More recently, Poisson models have been applied in empirical studies of industrial location, but these studies are not based on the random utility maximisation framework. In their paper of 2004, Guimarães et al. show how the potential IIA violation can be effectively controlled for in complex choice scenarios, by “taking advantage of an equivalence relation between the likelihood functions of the conditional logit model and the Poisson regression” (Guimarães et al., 2004). Moreover, such approach has a sound theoretical foundation, which is missing in the Poisson models.

## **D. The labour market**

### **1. Regional labour markets**

Job search theory is currently the main theoretical and empirical framework to analyze labour markets, building on the work of Stigler (1961, 1962). Search theory allows for market imperfections (lack of information, moving costs), contrasting with the standard urban economics model which assumes that markets are perfect (Anas, 1982; Hamilton, 1982). The most general search model is the job matching model where search behaviour of job seekers and employers are both explicitly modelled and commuting costs, wages, number of unemployed and number of vacancies are endogenously determined (Rouwendal, 1998).

The imperfectness of the labour market is related to its spatial dimension. A searcher may be unaware of employment opportunities because he does not visit the place where information about them is available. Information on job conditions and candidates aptitudes is not freely and immediately available to all market participants as would be the case in a perfect market. Due to these information-based market imperfections, time consuming search is necessary to match searchers with vacant positions.

A spatial job search model adds an additional dimension to the non-spatial job search literature. The spatial dimension is unimportant if workers are willing to move to a residential location close to any offered job and are able to realise such moves at a low cost. It seems unlikely that

these conditions are fulfilled. In general, residential mobility is very costly and commuting is also costly. The duration of unemployment is determined in part by the acceptance behaviour of the unemployed concerning job offers. This acceptance behaviour is related to the spatial dimension of the labour market.

In a perfect market there can only be one price for a commodity. In the case of the labour market this means that identical jobs will be offered at the same wage. Therefore the question arises why employers offer different wages for identical jobs. If similar jobs are offered at different locations and job searchers are spread over the labour market, the utilities of offered jobs depend on the locations of the job and of the searcher to which it is offered, even if all employers offer the same wages. Only in the special case when employers completely compensate their worker's generalised commuting costs will there be no variation in net wages on a spatial labour market.

Van Ommeren and Rietveld (2002) describe the functioning of a multi-regional equilibrium search model for the labour market. They assume that regional labour supply is fixed, and that the number of vacancies, the number of unemployed and wage levels are endogenously determined given productivity levels. Due to search frictions, in each region, unemployment and vacancies exist at the same time.

Rouwendal and Rietveld (1994) noticed the potential relevance of search theory for analyzing commuting distance distributions. They estimated reduced form equations for commutes with wages and a number of worker characteristics as explanatory variables. Even though their results do not provide direct information on the values of the parameters of the individual searcher's utility functions, they are suggestive of some of the determinants.

Rouwendal (1999) developed a much more elaborate model that allows for estimation of the structural parameters of the search model. The model is intended to explain the observed combinations of wages and commuting distances in cross section data.

In urban economics, attention for models based on optimal spatial job search has been limited thus far; papers on this topic include Rouwendal (1998), Wasmer and Zenou (2002, 2006). Rouwendal and van Vlist (2005) develops a model for a spatial labour market in which employment is concentrated at discrete points in space. The employment centres are surrounded by residential areas and workers can be employed in their city of residence as well as in another city. Unemployment is larger where there is less accessibility to jobs. Employed workers generate value added. Two main frictions can be identified within this model: First, travel costs cause some of the value added to leak away, on the other hand, because of vacant positions there is a gap between actual and potential total value added. The model allows for welfare economic analysis of improvements in traffic infrastructure.

The benefit of more commuting is a flexible labour supply and more efficient labour markets with lower unemployment. The costs are mainly the negative externalities created through transportation activities. Therefore, commuting has costs and benefits that are traded off in

equilibrium. Pilegaard (2003) formulates a theoretical framework that combines imperfect labour markets with a transport externality (congestion) in a spatial framework. Structural unemployment is included in the analysis.

## 2. Non-competitive wage formation in NEG models

The earliest theoretical literature in the “New Economic Geography” has not paid a lot of attention to the functioning of the labour market. In the major theoretical models presented in the book of Baldwin et al. (2003) for example, the labour market is routinely taken to be of the competitive kind. Wages are thus assumed to be able to fully react to changes in labour supply and demand.

Recently however, European theorists in the NEG school have been paying attention to the role of the labour market assumptions in driving the main results of the canonical NEG models. A notable contribution has been made by Puga (1999). In the context of European integration, he asks whether the so-called Tomahawk, namely the inevitable clustering of economic activity at low trade costs can somehow be avoided. This is of course of prime interest to European policy makers. European integration has caused a rapid and sustained falling of trade costs in Europe, which has led to increased pressure on peripheral regions due to strengthening agglomeration forces. Given current labour immobility in Europe, both across nations as well as across regions, it is therefore interesting to ask out of social and political concern whether this process of agglomeration is inevitable or can be reversed by further integration.

In order to lay the theoretical foundations, Puga (1999) constructs a model integrating and extending some of the canonical NEG models. His model displays the well known demand and cost linkages of Krugman (1991) as well as the vertical linkages of Krugman and Venables (1995). He adds to this the finitely elastic supply of ‘agricultural’ labour to the ‘industrial’ sector. This last feature will induce a counterbalancing affect to agglomeration. The expansion of ‘industry’ in a region will (if labour is not mobile across regional borders!) inevitably cause wages to rise compared to the losing regions thus discouraging clustering. At lower levels of trade costs, this effect will come to dominate the agglomeration forces (which fall in strength as trade costs fall, while the other effect does not), so dispersion sets in again as integration continues to deepen. Note that wages play the same role as the housing and land price do in the model of Helpman (1998) (cf. supra). There is thus at least a theoretical possibility that European integration will not cause peripheral regions to lag behind indefinitely. However, although he does not work this idea out formally, Puga goes on by suggesting that wage inflexibility caused by supra-regional wage setting will null the above equilibrating mechanism, and thus lock peripheral regions in their vulnerable position. Of course, the same line of reasoning may explain the current situation of Eastern Germany, the Italian Mezzogiorno, and possibly Wallonia. It is assumed that in these countries an insider dominated union sets wages to appropriate the rents of agglomeration, while

at the same time these wages based on conditions in the core are imposed on the periphery to maintain these rents.

Formal theoretical models integrating non-competitive wage setting are scarce. De Bruyne (2005) constructs a theoretical model where wages are bargained either at different levels (nationally, regionally or at the firm level). She shows how peripheral regions would lose from collective, supra-regional bargaining, whereas core regions win from such a regime.

## **E. Ecological–Economic modelling**

An extensive literature has analyzed optimal taxation and tax reform in the presence of externalities in a second-best framework. Most papers assume that environmental quality enters the utility function in a separable way and therefore ignore the feedback effect of environmental quality on the behaviour of the economic agents. The implications of taking into account the feedback effects are considered in Mayeres and Proost (1997, 2001), Schwartz and Repetto (2000) and Williams (2002, 2003). Mayeres and Proost (1997) derive optimal tax rules in the presence of an externality with a feedback effect for an economy with distortionary taxes. They show that the optimal tax on an externality generating good equals the sum of a revenue-raising component and the net social Pigouvian tax. The net social Pigouvian tax takes into account the damage imposed by the externality on consumers and producers. It will be smaller if a higher level of the externality leads to more consumption of the taxed commodities. Williams (2002) demonstrates that the welfare effect of an externality tax consists not only of a tax interaction and revenue recycling effect, two well-known effects, but also of a benefit side tax interaction effect. Williams considers four possible routes through which air pollution may affect the pre-existing distortions. First, if improved air quality leads to less medical spending, this creates an income effect that reduces labour supply, thereby worsening existing distortions. Secondly, if better air quality reduces time lost to illness, the benefit side tax interaction effect is ambiguous. Thirdly, when cleaner air leads to higher labour productivity, labour supply is boosted and the existing distortions are mitigated. Finally, if a cleaner environment improves the productivity of a fixed factor, the benefits of the externality tax are reduced.

Though many CGE models aiming at evaluating environmental policies consider only the costs of environmental policy measures, in the standard GEM-E3 model and some other CGE models, the benefits of environmental policies are modelled, through an index of environmental quality that depends on emissions and that provides an ex-post contribution to the consumers' welfare<sup>12</sup>. These models consider a one-way link between the evolution of the economic variables and the level of environmental quality.

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<sup>12</sup> See also Glomsrod et al. (1992), Ballard and Medema (1993), Boyd et al. (1995), and Brendemoen and Vennemo (1996).

However, the level of environmental quality or the level of other externalities (congestion, accidents,...) may also affect economic performance. A number of CGE models incorporate some of these feedback effects. Examples of such CGE models<sup>13</sup> are Nordhaus (1994), Vennemo (1997), Mayeres (1999), Bergman and Hill (2000), Conrad and Heng (2002), Chung-Li (2002) and Mayeres and Van Regemorter (2008). Nordhaus (1994) models the impact on production of the accumulation of CO<sub>2</sub> emissions which increases the temperature of the earth. Vennemo (1997) evaluates the external effects of economic activity in terms of their costs on the economy. The paper produces damage estimates for acidification of lakes and of forests, for health and annoyance from emissions of NO<sub>x</sub>, SO<sub>2</sub>, CO and particulates, for corrosion, noise, traffic accidents, congestion and road depreciation. Vennemo finds that the feedback on environmental quality is much more significant for consumer welfare than the feedback in the form of increased depreciation and a decline in productivity. Bergman and Hill (2000) consider the productivity effects of environmental stock and flow pollution by including the effects from pollution accumulation on production. To model the feedback effects, the resource endowments are included in the model and the externality is linked to these endowments. The feedback of traffic and congestion on economic variables is considered by Mayeres (1999) and Conrad and Heng (2002). Mayeres and Van Regemorter (2008) explore how the health related benefits of environmental policies can be modelled in a more realistic way in GEM-E3 and what the implications for the welfare evaluation of environmental policies are. A similar exercise for Thailand is presented by Chung-Li (2002), who explores the economy-wide repercussions of improved air quality through its effect on labour supply and medical expenditure. The extension of the GEM-E3 model in Mayeres and Van Regemorter (2003) concentrates on the health impacts of air pollution, as they are the largest gain from an improvement in air quality. The effects of air pollution on vegetation, materials and visibility are still taken into account ex-post. Within the health impacts, a distinction is made between the impact on medical spending by the consumers and the public sector, the impact on the available time of the consumers and the impact on labour productivity. Thus the analysis considers three of the four sources of the benefit side tax interaction effect presented by Williams (2002). A health production function is used that relates a continuous health variable to pollution and the consumption of medical care. This approach is most appropriate for modelling the morbidity effects of air pollution. A realistic treatment of the mortality impacts would require modelling health states rather than a continuous health variable (see, e.g., Freeman (2003)). Mayeres and Van Regemorter (2008) focuses on the morbidity effects, while the mortality impacts continue to be modelled in the traditional way, i.e. ex-post, except for the medical costs related to them.

A more realistic modelling of the non-health related effects of air pollution in GEM-E3 is presented in Bergman and Hill (2000).

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<sup>13</sup> For an overview, see Conrad (2002).

## F. Stochastic elements in general equilibrium models

The class of general equilibrium models that incorporate stochastic elements, is called Dynamic Stochastic General Equilibrium (DSGE) models. These models differ from the traditional general equilibrium models in that they incorporate one or several model elements, which are estimated econometrically using the time-series data and include a stochastic element in the form of the error term of the estimated regression equation. Regression equations used as parts of the DSGE models can be both linear and nonlinear. They can also include autoregressive terms.

In the case of extremely good data availability, all the coefficients of the DSGE model can be estimated econometrically. In that case the DSGE models are linearised by applying a logarithm transformation and afterwards estimated on the time-series data using either maximum likelihood method or the generalised method of moments. Such estimated DSGE models usually have a very simple structure, which is closer to the structure of the traditional macro-economic models than to the structure of the CGE models.

DSGE models have become a standard tool in various fields of Economics, most notably in Macroeconomics and International Economics. DSGE models are attractive because they explicitly specify the objectives and constraints faced by households and firms, and then determine the prices and allocations that result from their market interaction in an uncertain environment.

The main elements of the DSGE models, which are estimated econometrically and incorporate uncertainty about the future development of the economy, include:

- Technological progress: in order to account for the technological development in the DSGE models, they include an exponential first order autoregressive process which explains development in time of the total factor productivity coefficient of the production functions. The level of total factor productivity at time  $t$  is assumed to be fully explained by the constant term, the last period total factor productivity and the stochastic error term. It is possible to extend this regression equation and incorporate other factors explaining the development of the total factor productivity of the country such as the last period R&D investments, share of the highly educated persons in the country, governmental spending on education etc.
- Development of the knowledge capital: the development of knowledge capital in the economy is introduced in the same way as technological progress via a regression equation which explains the present level of the knowledge capital by its last period level and by the public and private investment in education made during the previous time period plus an error term.
- Flow of Foreign Direct Investments (FDI): the flow of FDI to the economy is captured by the regression equation, which explains the level of FDI by the capacity of the market, availability of the qualified labour in the country, the stock of the national natural resources plus the error term.

Another way of introducing uncertainty into the DSGE models is the introduction of structural shocks associated with the different model variables. The structural shocks can be associated with supply and demand, labour productivity and labour supply. The demand shocks can include preference shocks, governmental consumption shocks and investment consumption shocks. The shocks in the DSGE models are the stochastic processes/variables estimated on the time series data. The introduction of these shocks allow for explaining the economic fluctuations which are not captured by the structure of the model.



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**LINES AND SERVICES IN A STRATEGIC MULTI-MODAL FREIGHT  
NETWORK MODEL  
METHODOLOGY AND APPLICATION**

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## **Abstract**

Strategic multi-modal freight transportation network models often lack some kinds of refinements. For instance, those models typically only compute one or more shortest paths, which may not correspond to the actual existing routes (lines) defined for railway transport. Hence, beside the fact that the rail paths may not be entirely correctly rendered, the total costs for railway transport is likely to be underestimated so that the market-share for railway transport can be overestimated.

The main objective of this paper is to propose a methodology that takes explicitly railway lines into account and, by extension, railway services in a multi-modal freight transportation network model.

After an outline of the methodological issues, a case study based on a railway corridor embedded in a multi-modal network is described and the results of the implementation of the new model is compared to those obtained by means of a more classical assignment.

## 1 Introduction

The presentation of transportation models is obviously not the main topic of this paper. The interested reader can for instance read Ortúzar and Willumsen (1990) for an overview of several aspects related to transport modelling. One of these aspects is the assignment of the demand on a network.

Assignment methods are looking for a way to model the distribution of traffic over a network according to a set of constraints, related to transport capacity, time and cost (Thomas, 1991). This type of problems can be solved using optimization methods.

Traditional assignment models are based on cheapest path algorithms. They use networks in which every road (or railway, waterway, ...) can be represented by a weighted edge (cost). The total cost of a trip is simply the sum of the costs associated to each link along the path.

Transport models are still imperfect and many refinements can be proposed. Trains for instance, have to follow a predefined planned route, which can differ from the shortest or cheapest one, and is thus not identified by shortest path algorithms. In other words, if the broad transport corridors are in most cases rather well identified, railway transport is often spread over several routes, which is not the way trains are operated in the real World. This is an issue, because track capacity is often an important problem that cannot be ignored. Therefore, the lines defined by the railway infrastructure operators should be explicitly taken into by the network models.

If not, the cost of the computed path will be often lower than the cost on the real route (defined line). Indeed, and especially for freight transport, the lines are mostly designed in order to avoid as much as possible mixed traffic with passenger trains. This increases the quality of service, but makes the routes often longer. This is illustrated by figure 1: the shortest rail path between Antwerp and Athus, two Belgian cities, is 262 km long, but the actual route followed by freight trains passes along Leuven and, in the South of Belgium, uses an alternative track, closer to the French border. Beside the fact that this route is

longer, it offers also the possibility to separate trains for freight and for passengers, resulting in a better balanced flow over the whole network.

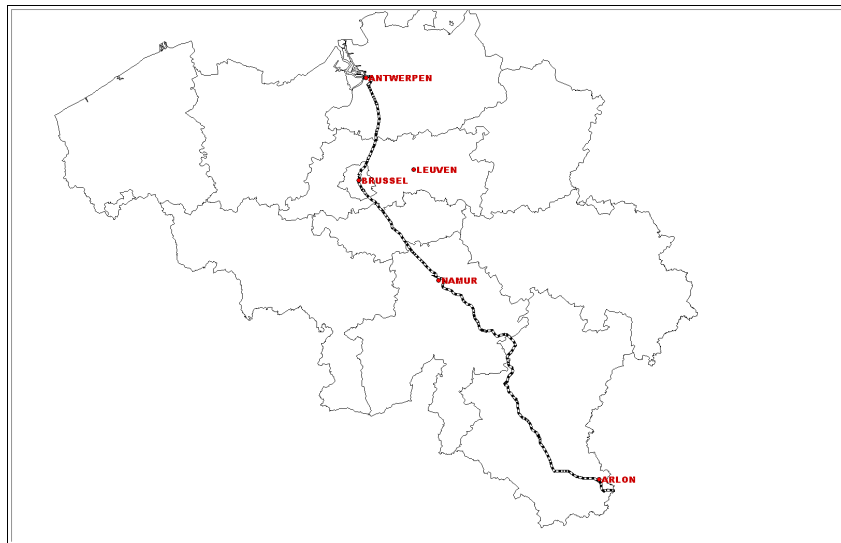


Figure 1a : Shortest path between Antwerp and Athus (262 km)

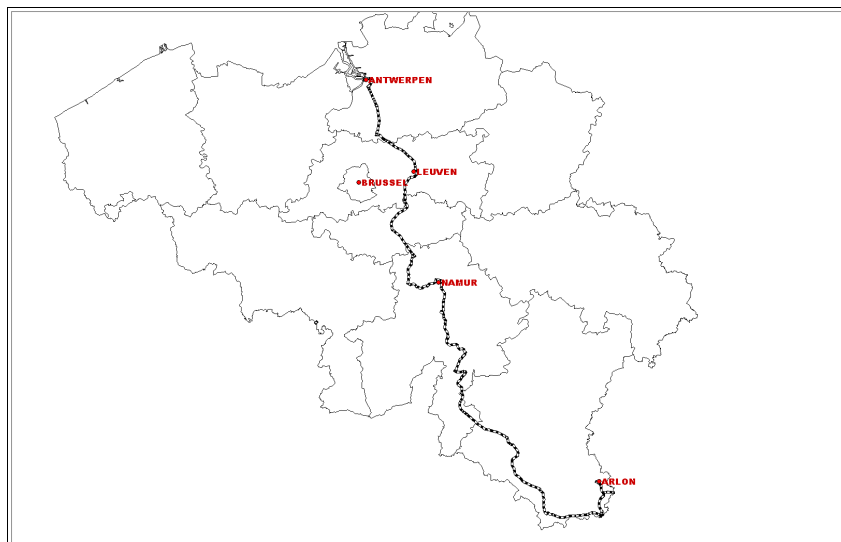


Figure 1a : Actual route between Antwerp and Athus (317 km)

## 2 Lines and strategic models

The line concept is defined by Delorme (2003) as an ordered sequence of links and nodes along a path. In this definition, the origin node of each link must coincide with the destination node of the preceding link. The route followed by a train coincides partially or totally with a set of lines.

Railway lines are seldom (or never?) taken into account in large strategic multi-modal network models, because it is often claimed that their implementation only has a limited impact on the results. Lines are however modelled in most tactical or operational railway models such as CAPRES (Lucchini *et al*, 2000) or FASTA (Curchod *et al*, 1992).

Two broad families of strategic models can be identified. The first one, or classical approach, uses separate network layers for the different transportation modes. Therefore, a mix of free and “line” flows can be rather easily implemented as “lines” can be directly encoded in the network database. The demand (embedded in a set of origin-destination matrices, one per mode) can then be directly assigned on each “modal” network.

A second approach uses so called “super networks” or “virtual networks”. The idea here is to work on a single network, in which each link represents a particular transportation task. Indeed, a simple geographic network does not provide an adequate basis for detailed analyses of transport operations as the same infrastructure, link or node, can be used in different ways. The basic idea, initially proposed by Harker (1987) and Crainic *et al*. (1990), is to create a virtual link with specific costs for a particular use of an infrastructure. The concept of “supernetworks” proposed by Sheffi (1985), that proposed “transfer” links between modal networks also provides a somewhat similar framework. The NODUS software proposes a methodology and an algorithm which creates in a systematic and automatic way a complete virtual network with all the virtual links corresponding to the different operations which are feasible on every real link or node of a geographic network. This systematic and automatic approach, built upon a special codification of the virtual node labels, is probably the biggest benefit over other software tools such as STAN (Crainic *et al*. 1990), in which most of the tasks that are possible at a given node are to be introduced “by hand”.

In these virtual networks, all the “modal” networks are thus embedded in one single and large network. Mixing free and “line” flows in such a network is not an immediate task, and the main objective of this paper is to propose a methodology that is able to fully integrate “lines” in virtual networks.

### **3 Towards a new definition of virtual networks**

The original definition of the virtual networks were already discussed in Jourquin (1995) and Jourquin and Beuthe (1996). The basics will be outlined in this section, followed by a complete explanation of a new, extended definition that integrates the “line” concept.

#### **3.1 Virtual network basics**

To start with, let us examine the network illustrated by Figure 2, that contains 6 nodes (“A” to “F”) and 9 links (1 to 9). The plain lines represent inland waterways (W) and the dotted lines railways (R). Diesel trains (R1) can be used everywhere on the railway network, but electric powered trains (R2) can only be used on the bold links “1”, “2”, “3”, “5” and “6”. In the same way, small barges (W1) can be used without restrictions on the waterways, but large barges (W2) are allowed only on the bold links “7” and “8”. Some of these real links can thus be used by several types of vehicles (transportation means), which have different operating costs. The bold nodes “A”, “B”, “C” and “E” are also locations where (un)loading and transshipments between modes are possible.

Building a virtual network requires all the possible transport operations to be identified. Each operation leads to the creation a virtual link, identified by its two end virtual nodes.

The label of each virtual node is composed of four informations :

- The label of the real node it is generated from ;
- The label of the real link it is attached to ;
- The label of the transportation mode it refers to (“R” or “W” in this case) ;
- The label of the transportation means it refers to (“1” (diesel train or small barge) or “2” (electric train or large barge) in this case).

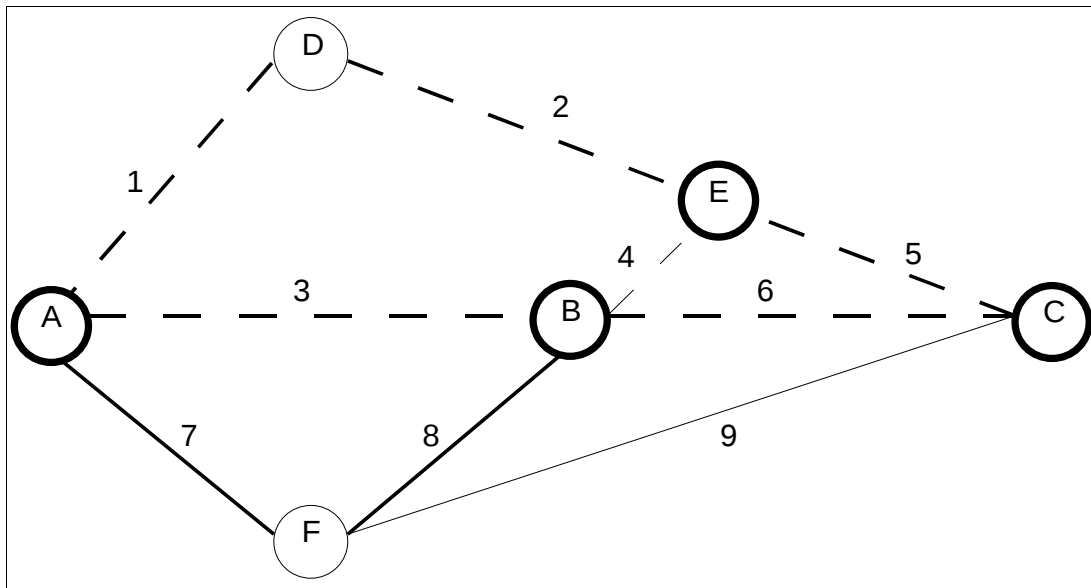


Figure 2 : Sample multi-modal network

Note that the weight given to a virtual link can vary with the direction it is used. To solve that problem, in the computer implementation of the methodology, all the virtual nodes are doubled at generation time by adding a + or a - sign to their label ; by the same token, all the links are split into two oriented arrows connecting these new nodes. With the exception of Figure 4, these oriented links will not be represented in this paper in order not to clutter the diagrams.

Obviously, the codification used in the presented figures is not suitable for real applications. Using a single letter for a node label would indeed limit the size of the real network to 26 nodes. That's why the virtual nodes are coded in the following way :

- A plus or minus sign ;
- 6 digits for the node number ;
- 6 digits for the link number ;
- 2 digits for the mode and 2 digits for the means.

Each label is thus represented by a 16 digits number preceded by a sign.

Figure 3 is a simplified representation of the virtual network that can be generated from the information gathered in Figure 2. Three types of transport operations can be identified :



- The bold lines are virtual links which represent a movement of a vehicle on the real network. The labels of the two end virtual nodes of such virtual links make reference to two different real nodes. The link going from “A1R1” to “D1R1” represents for instance the displacement of a diesel train (R1) between nodes “A” and “D” on link “1”, for which a relevant cost can be computed.
- The curved lines represent transshipment operations that can be performed at a node. Therefore, the labels of the two end virtual nodes always refer to the same real node. Moreover, the mode and/or means indicated in the same label vary. For instance, the virtual link that connects “B3R2” to “B8W1” represents a transshipment operation that takes place at node “B”, between an electric train (R2) coming from link “3” onto a small barge “W1” that will sail on link “8”. Again, the information provided by the labels of the two end virtual nodes allows for the computing of the relevant cost. Note that transshipment operations are not allowed at regular nodes such as “D” or “F”.
- The other straight lines represent transit operations inside a node. The link between “F7W2” to “F8W2” is thus to be interpreted as the transit of a large barge (W2) come from link “7” and going to link “8” through node “F”. Here also, the information provided by the labels of the end virtual nodes makes it possible to compute a relevant costs, that may eventually be null.

Again, Figure 3 is a simplified representation of the virtual network, as the “doubled” virtual links (see above) are not represented. Moreover, the (un) loading operations are also not drawn. These are indeed needed in order to have the possibility to enter and to leave the network. Figure 4 illustrates the full virtual network at node “C”. In this figure, the (un)loading virtual node are labelled “+C000” and “-C000”.

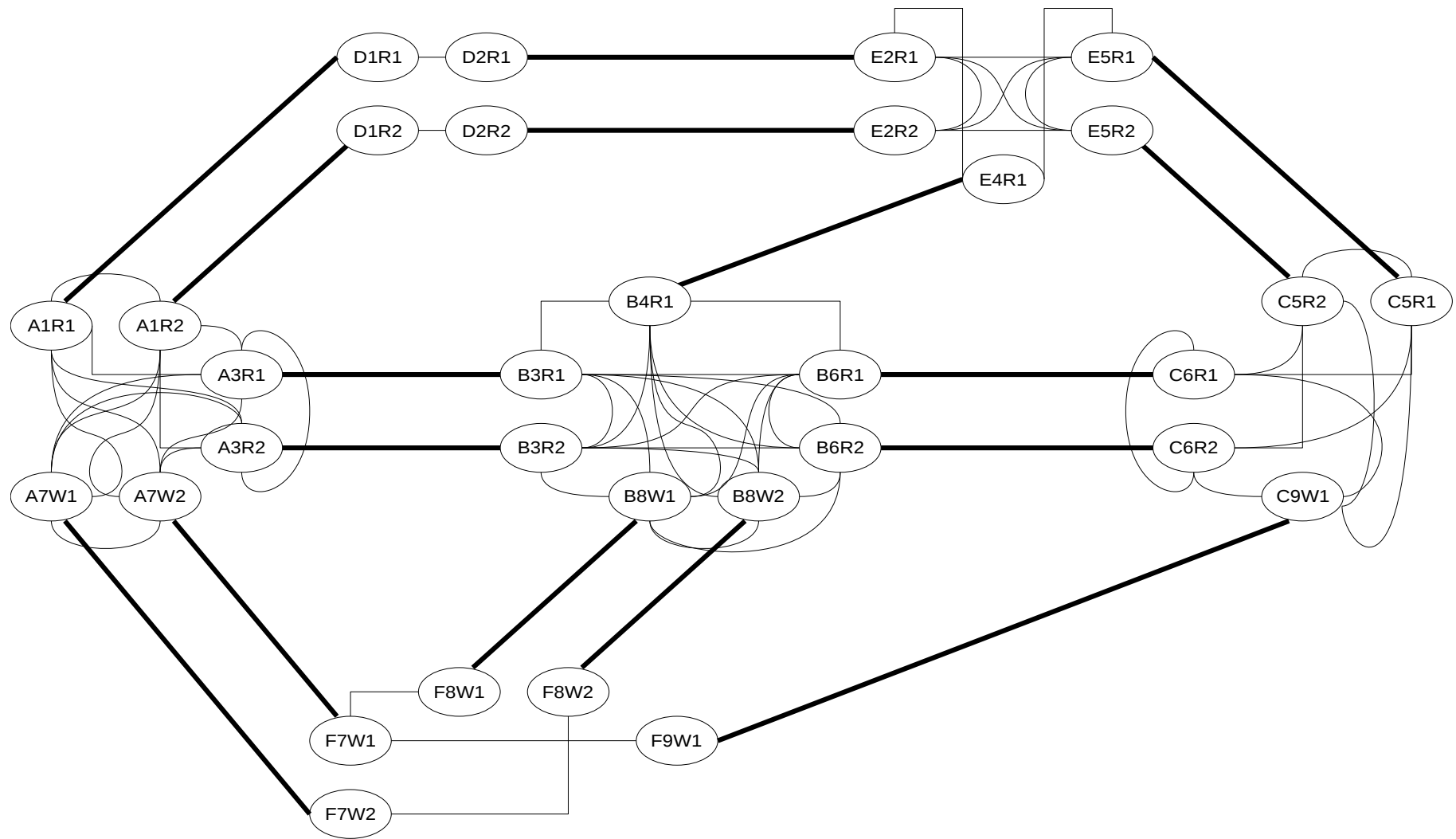


Figure 3 : Simplified virtual network

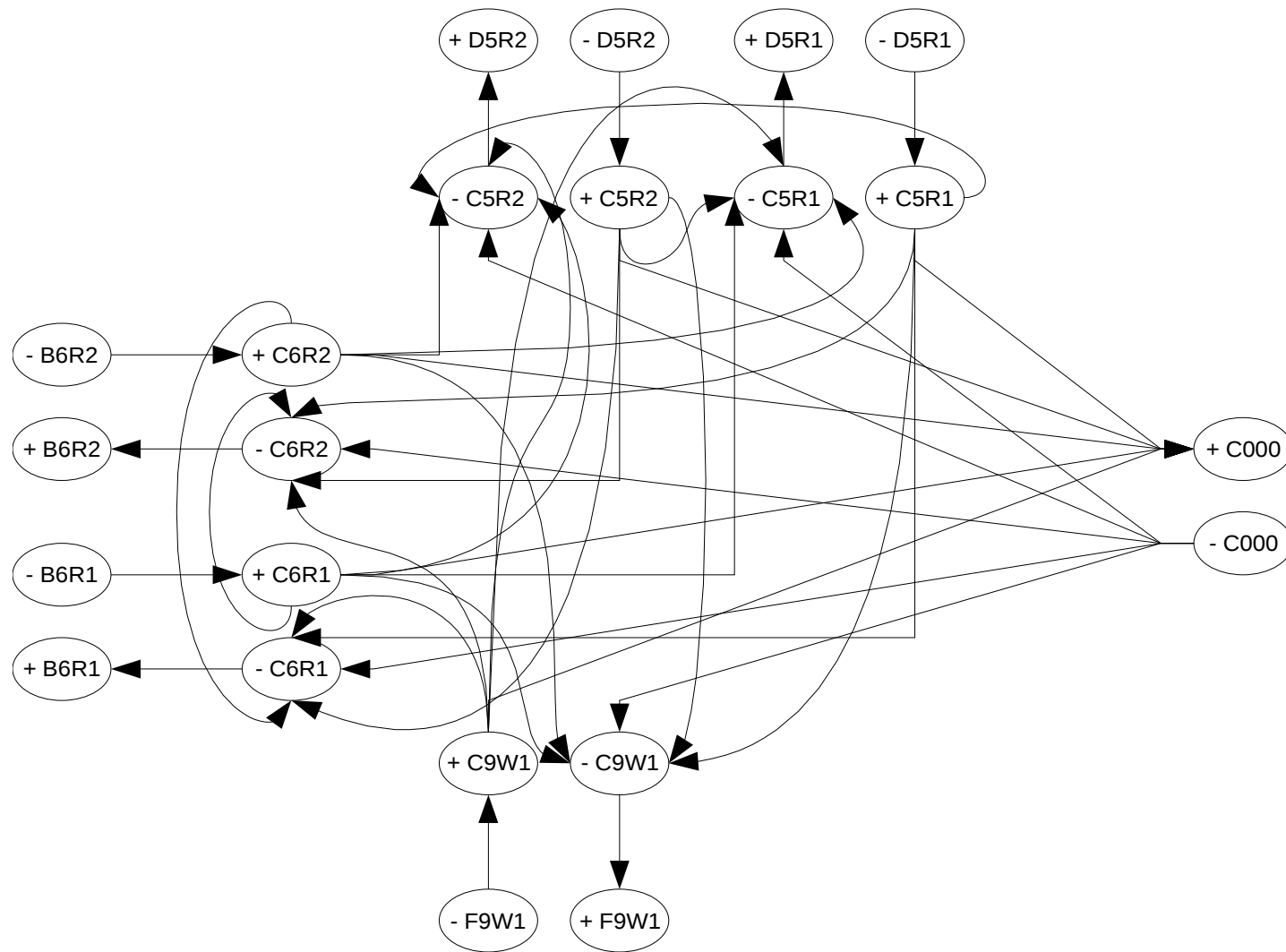


Figure 4 : Complete virtual network at node C

A virtual network becomes thus rather complex, and it rapidly can contain thousands of nodes and links. It has however an important advantage over classical networks: a shortest (cheapest) path computed in a virtual network can indeed combine *de facto* several transport operations and several transport modes and means. A path can be intermodal, including all the costs involved in the needed handling operations. The interested reader will find more on the methodological aspects of virtual networks in Jourquin and Beuthe (1996), on example applications in Jourquin and Beuthe (2006), and on topics related to flow assignments on virtual networks in Jourquin (2005) , Jourquin and Limbourg (2006) and Jourquin and Limbourg (2007).

### **3.2 Lines and virtual networks**

A virtual network is thus a large network in which the different possible transport operations related to several transportation modes and means are represented. Movements of trucks, barges and trains are embedded in the same network. Lines are in fact completely ignored in the original definition of virtual networks, because the different virtual links only take the physical characteristics of the real network into account. This only allows to avoid the use of some types of vehicles on some links: In Figure 3, no virtual link was created for electric trains on link “4” or for large barges on link “9”.

However, cargo trains that operate on the network described in Figure 2 could very well circulate only on the lines illustrated by Figure 5. The first line is operated by diesel and electric trains and joins nodes “A” and “C”, passing along “D” and “E”. The second line is only operated by diesel trains and joins also nodes “A” and “C”, but along nodes “D”, “E” and “B”. Thus, the railway tracks between nodes “A” and “B” are not used for freight transport, and electric powered trains are not operated between “B” and “C” for cargo, even if it is technically possible.

As a consequence, if lines are not explicitly modelled, an assignment on the (virtual) network will most probably use the link between “A” and “B”, because it is on the shortest (cheapest) path between “A” and “C”, that are both potential origins or destinations for freight.

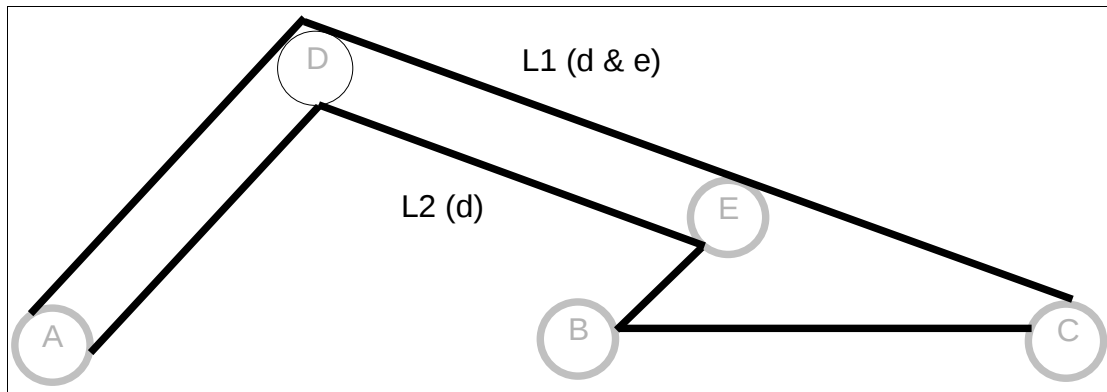


Figure 5 : Lines operated on real network (Figure 2)

The definition of the virtual network must be adapted if the lines have to be modelled. To achieve this, a virtual link will now be created not only for every possible transportation means on each real link, but also for every line that uses this link. This is illustrated by Figure 6.

A “line” label is added to the label of each new virtual node, and connectors are created only between virtual nodes that refer to the same line. This prevents unwanted switches to another line at regular nodes. Switches can however be proposed at stop points, such as node “E” where a diesel train that circulates on line “2” could switch to line “1”.

Note that, in order to keep the structure of the labels of the virtual nodes consistent, the labels that refer to free flow modes (such as barges in the given example) will use “0” as “line” label, which means “no line”.

The lines themselves must be stored in a database in the way there are defined by Delorme (2003, see section 2). In addition the following informations must also be retained:

- The transportation means that can be used on the line ;
- The list of nodes along the line where a “stop” (and thus also line switching) is allowed.

As an example, Table 1 contains the information that was needed to generate the virtual network represented by Figure 6. This data is systematically checked by the algorithm that

generates the virtual network, in order to limit the creation of the virtual nodes and links to the needed ones.

Line	Links	Means	Stop nodes
1	1, 2, 5	1, 2	A, E, C
2	1, 2, 4, 6	1	A, E, C

Table 1 : The lines related data

In stop nodes, it is made possible to switch from one line to another. Such switches are for instance possible at node “E”, and illustrated in Figure 6 by dotted curved lines.

Note that a same real link can belong to more than one line. In the example illustrated by Figure 5, both lines use for instance links “1” and “2”.

This new virtual network with line implementation can now be used as a generic graph on which any assignment procedure can be applied, exactly as for the original virtual networks.

### 3.3 From lines to services

From all what is preceding, one can conclude that a line is a particular way to use a given infrastructure. In section 3.2, the methodology for modelling lines in virtual networks was outlined. During an assignment, and if the relevant information is encoded, the flows that are transported by “line” modes will now be forced to follow the pre-defined lines, while the other modes still can circulate freely. In other words, the new definition of the virtual networks allows to mix “free” and “line” flows inside a single (virtual) network.

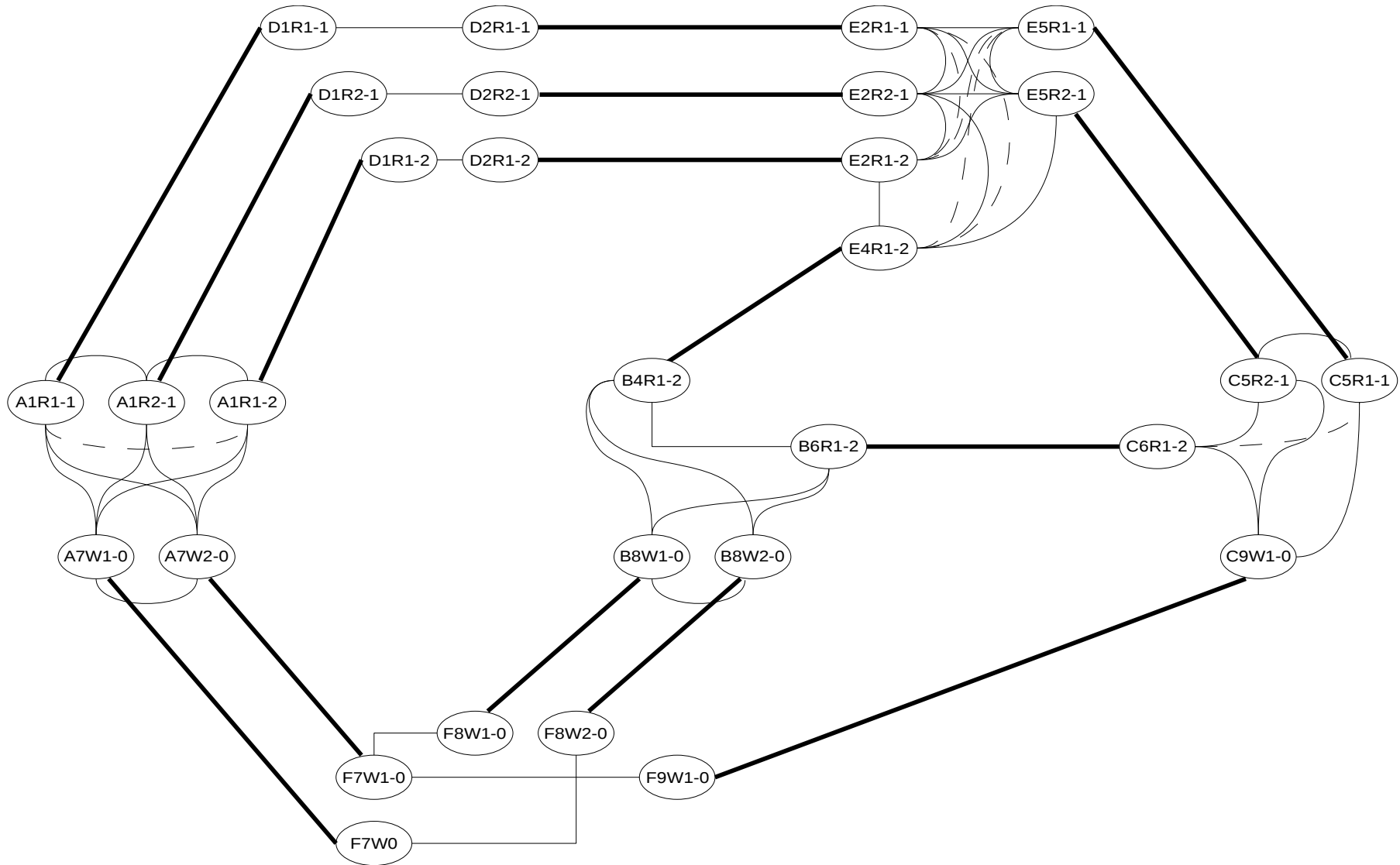


Figure 6 : Virtual network with line implementation

Many authors (Crainic and Laporte, 1997 ; Crainic, 2000 ; Cascetta and Papola, 2003) extend the concept of “lines” to the one of “services”. The latest concept is broader as it also includes additional characteristics, such as frequency for instance.

The frequency has a important impact on the modal choice, as waiting times can be very long for low frequencies, making transport less attractive. The frequency has however no impact on the topology of a (virtual) network, but it has an impact on the cost to be computed on some virtual links. For instance, the cost related to the average waiting time can be added to the virtual links that correspond to the relevant loading or transshipment operations, including those that represent line switching. The algorithm used to generate the virtual networks doesn't have to be modified, but the data that must be maintained to model the lines must be completed in order to keep track of the frequency on each line. This is illustrated in Table 2. The additional data contained in the last column will be used during the computation of the costs on the virtual links.

<b>Line</b>	<b>Links</b>	<b>Means</b>	<b>Stop nodes</b>	<b>Frequency</b>
1	1, 2, 5	1, 2	A, E, C	1/day
2	1, 2, 4, 6	1	A, E, C	2/day

Table 2 : The lines related data with frequency

#### **4 Illustration on a real case**

The methodology can now be illustrated by means of a real case, based on the “C” railway corridor.

The « C » Corridor (Antwerp / Basel-Lyon), with a total length of about 1840 km, goes through Belgium, the Grand Duchy of Luxembourg, France and Switzerland. This is a strategic corridor for transporting cargo since it connects Antwerp, one of the biggest European ports, to industrial centres.

The potential growth of the corridor will rise by 60%, with a traffic of 16 million tonnes expected in 2020, thanks to considerable gains in travel time. From this date on, the



various socio-economic benefits (improvement of road congestion, reducing of CO2 emissions,...) are estimated to 140 million euros per year (webtrains.net, august 2007).

Five different signalling systems coexist currently on the corridor. The generalisation of a common ETCS signalling system will facilitate the growth of cargo traffic, contributing to the fluidity and regularity of traffic. The deployment of ETCS on corridor C will run from 2008 to 2018, in successive stages and sections.

Note that the goal of this exercise is not to provide an alternative en exhaustive socio-economic analysis of the corridor, but only to illustrate the implementation of lines and services using virtual networks. Therefore, some simplistic hypothesis will we taken.

#### **4.1 The demand for transport**

Matrices for the three transportation modes that are included in our networks (road, rail, inland waterways) were published by NEA Transport Research and Training and contain data for the year 2000. They give information about the type of transported commodities (10 NST-R chapters), at the European NUTS 2 regional level. A complete model of the C corridor would need an identification of all the origins and destinations that are concerned by the C corridor. However, in our example, only the NUTS 2 regions in which Antwerp, Lyon and Basel are located will be taken into account.

#### **4.2 The networks**

A detailed representation of the networks for the different transportation modes is also needed. The railroads and roads networks were taken from the Digital Chart of the World, and further updated.

The Digital Chart of the World (DCW) is an Environmental Systems Research Institute, Inc. (ESRI) product originally developed for the US Defense Mapping Agency (DMA) using DMA data. The DMA data sources are aeronautical charts, which emphasize landmarks important from flying altitudes. ESRI, when compiling the DCW, also

eliminated some detail and made some assumptions for handling tiny polygons and edge matching.

The inland waterways network doesn't exist in the DCW. There is a "drainage" layer, but that is much too detailed, and doesn't correspond to the waterways on which barges can be used. Therefore, it was decided to digitize the corresponding network.

The borders of the NUTS 2 regions were provided by Geophysical Instrument Supply Co. (GISCO) and a centroid for each region was located at the centre of the most urbanised area of the zone. These centroids are taken as the origins or destinations for the commodities.

All these layers (roads, railways and inland waterways) were connected together, using "connectors" from each centroid to each modal layer. The road network contains about 68.000 links. The figures are respectively about 40.000 and 1.100 for the railway and inland waterway networks. However, only a small portion of this complete European network will be used in the framework of this exercise.

### **4.3 Base model and lines**

As stated in section 3.1, several assignment techniques can be applied to virtual networks in NODUS. For the scenario presented in this paper, a deterministic multi-flow assignment (Jourquin, 2005) is used.

Similarly to what was illustrated by Figure 1, there is a difference between the "free flow" model and "line model". Indeed, the fastest railway route (Figure 7a, dark lines<sup>1</sup>) between Antwerp and Lyon goes along Paris, while all the trains are expected to go to the South of Belgium (Athus), before running further to Lyon or Basel (Figure 7b). The spread of the flows is clearly different between these two maps, even if the lengths of both railway routes are almost the same.

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<sup>1</sup>Waterways are not represented in order to clutter the maps. The use of the road network is illustrated by light grey lines.

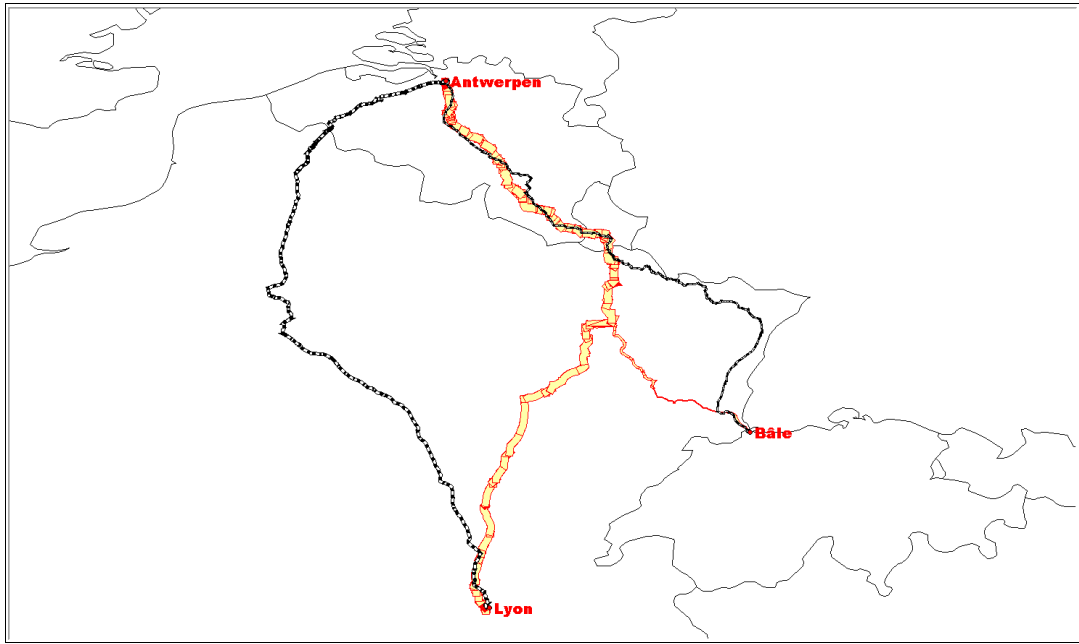


Figure 7a : Free-flow routes on the C corridor

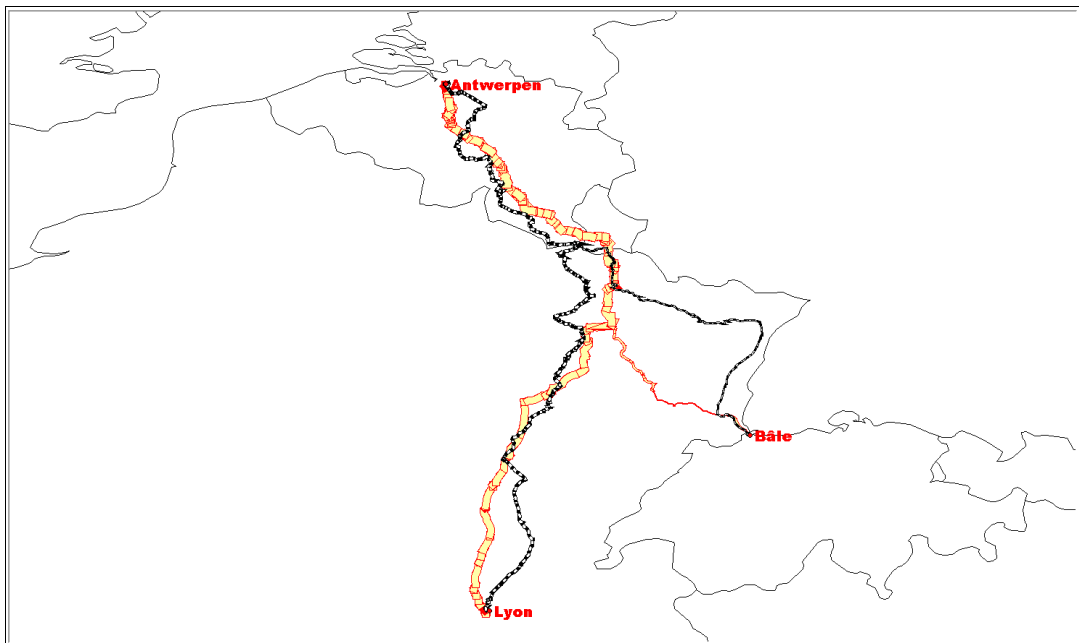


Figure 7b : Correctly modelled C corridor, using lines

After some calibration, the global performance of the assignment (Table 3) can be considered as satisfactory in the framework of the exercise proposed in this paper.

		<b>Data</b>	<b>Reference Model</b>
<b>Tons</b>	<b>Barges</b>	3.14 %	3.69%
	<b>Trains</b>	20.51 %	19.88%
	<b>Trucks</b>	76.34 %	76.43%
<b>Tons.km</b>	<b>Barges</b>	3.78 %	4.44%
	<b>Trains</b>	20.86 %	21.78%
	<b>Trucks</b>	75.36 %	73.78%

Table 3 : Global performance of the reference assignment (with lines)

#### 4.4 Impact of service frequencies

In section 3.3, the way the lines concept can be further developed to model services was outlined. In the previous section, it was clearly shown that the introduction of lines can clearly influence the way the flow is spread over the networks. Nevertheless, the implicit assumption that a trip can start at whatever time of the day or of the week was still present, as frequencies were not explicitly taken into account.

The introduction of service frequencies can be considered if the costs related to waiting times and stops are introduced in the cost functions. An in-depth discussion about this can be found in De Jong (2000) and Blauwens (2003), but can be summarized by the following idea: The average waiting time is equal to planning period divided by 2 times the frequency. Thus, if the demand data is available at a yearly basis (52 weeks) and that one train runs per week, the average waiting time is half a week.

Several authors, among which Beuthe *et al* (2008), have tried to estimate the value of time for freight transport. The values published by this author have been introduced in our cost functions, for frequencies of one train a day, one a week and one a month. The impact of the introduction of these different frequencies on the modal share are published in Table 4. If it appears that when high frequencies (one per day) are modelled, the results are very similar to the reference model (Table 3), the modal shares can be significantly modified when lower frequencies are introduced. In other words, ignoring frequencies, even in strategic large scale models can have an important impact on the estimated modal share of railway transport. Indeed, train services that are operated only once a week are not seldom...

		Frequency		
		1/day	1/week	1/month
<b>Loaded tons</b>	<b>Barges</b>	+0.01%	+0.07%	+0.24%
	<b>Trains</b>	-0.24%	-1.59%	-5.39%
	<b>Trucks</b>	+0.23%	+1.52%	+5.14%

Table 4 : Impact of frequencies on modal share

## 5 Conclusions and further prospects

Multimodal strategic freight transportation network models are rather complex and have to cope with several shortcomings, sometimes simply related to the lack of complete and accurate data on demand and supply. They also barely take considerations on operational logistics into account.

Among the identified missing links between strategic and operational models, the fact that some transportation modes such as trains should follow a predefined path, or line, is an issue. Indeed, ignoring this can lead to an improper spread of the flow on the networks, or even to an underestimation of total railway costs and trip lengths.

This paper presents a procedure than can be applied to virtual networks, which allows to perform assignments that fully and explicitly model lines.

The use of the improved virtual network has been applied on a case, based on the so-called “C” railway corridor, that links Antwerp (Belgium) to Lyon (France) and Basel (Switzerland). We can conclude that the proposed methodology clearly improves the realism of multi-modal assignments.

The line concept can further be enlarged to model services. The latest can indeed be defined as a line, to which some other additional characteristics are added, such as frequency for instance. This is has also been illustrated use the “C” corridor case.

## Acknowledgement

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# Inventory and forecasting of maritime emissions in the Belgian sea territory, an activity-based emission model

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## Abstract

Air quality policy has focussed on land-based emissions for decades. In recent years, it has become increasingly clear that emissions from sea-going vessels can no longer be ignored. There is a growing need for detailed emission inventories to evaluate the impact of this transport mode on air quality and health.

In this paper we present MOPSEA, an activity-based emission model to determine emissions from sea-going vessels. The model considers shipping activities of sea-going vessels on Belgian territory, combined with individual vessel characteristics. We apply this model to study the effects of recent international efforts to reduce emissions from sea-going vessels in Belgian territorial waters for the current fleet and for two scenarios up to 2010.

The emission model for Belgium, based on different vessel operating areas, reveals that most maritime emissions from the main engines will increase. CO<sub>2</sub> emissions will increase by 2–9% over the 2004–2010 period due to an increase in shipping activity. NO<sub>x</sub> emissions are projected to rise between 1% and 8% because the increase in activity offsets the reductions from the international maritime organisation (IMO) and European regulations. In contrast, SO<sub>2</sub> emissions will decrease by at least 50% in 6 years time. The switch of auxiliaries from heavy fuel oil to diesel oil at berth results in a large emission reduction (33%) for PM and small reductions for CO<sub>2</sub>, NO<sub>x</sub>, CO and HC (4–5%).

The choice between a bottom-up versus top-down approach can have important implications for the allocation of maritime emissions. The MOPSEA bottom-up model allocates only 0.7 Mton CO<sub>2</sub> to Belgium, compared to 24.2 Mton CO<sub>2</sub> based on bunker fuel inventories.

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*Keywords:* Sea-going vessels; Activity-based; Maritime emissions; Air pollution; Forecasting; Legislation

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## 1. Introduction

Maritime transport has the potential to make a considerable contribution to the efficiency of the transport system and to the required increase

in capacity of global transport in order to meet current and future demands arising from economic growth.

Emissions of sea-going vessels are generally not accounted for national emission inventories, and have been widely ignored in national air quality programs because they occur mostly in international waters. In order to tackle this problem the international maritime organisation (IMO)

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adopted Annex VI to the Marpol 73/78 Convention. This is the main international convention that covers prevention of pollution of the marine environment by vessels from operational or accidental causes and was adopted in November 1973 by IMO. Annex VI, 'prevention of air pollution from vessels', was adopted in 1997 and entered into force on 19 May 2005. With this annex, worldwide limits have been placed on sulphur dioxide (SO<sub>2</sub>) and nitrogen oxide (NO<sub>x</sub>) emissions from sea-going vessels. Currently an extension to all greenhouse gases emitted from vessels is also being considered.

However, there is still a considerable margin for improvement, especially with regard to NO<sub>x</sub> and SO<sub>2</sub> emissions. During the preparation of the clean air for Europe (CAFE) programme, it was concluded that emissions from maritime transport would become increasingly important. Under a current legislation scenario, it was even projected that sea-based emissions of NO<sub>x</sub> and SO<sub>2</sub> would surpass the total land-based emissions in Europe in 2020 (Amann et al., 2005, CAFE baseline scenario report 1 and scenario report 2). Even with MARPOL Annex VI in operation, the share of emissions from sea-going vessels will increase in the future as the exhaust emissions of other transport modes decrease even more. This is due to the more stringent emission standards and fuel specifications for road transport, railway traffic and inland navigation, and due to the slow turnover of sea vessel technologies. The average age of the world merchant fleet is about 12.5 years, compared to only 7 years for heavy trucks (UNCTAD, 2005; BTS, 2004). The trend towards an increasing share of emissions from sea-going vessels will continue in the coming years with the implementation of the European Directives 98/69/EC (passenger cars), 98/69/EC (light duty vehicles) and 1999/96/EC (heavy duty vehicles). These Directives ensure that road transport improves its environmental impact at a fast rate. This is partly possible by the short economic lifecycle of trucks so that the newest technological developments are rapidly implemented. Maritime transport, however, is lagging behind in this respect due to the (very) long economic lifespan of vessels. For vessels, there is no such tradition of European Directives. But recently, a new EU Directive to reduce atmospheric emissions from sea-going vessels entered into force on 11 August 2005 (EU Directive 2005/33/EC).

Reporting methodologies and monitoring programmes exist for other transport modes (road, rail, inland navigation, etc.) and industrial emissions. The related emissions are the outcome of models which have a strong scientific basis, mostly based on a bottom-up approach. Generally, until now emissions from sea-going vessels are derived from the quantity of international bunker fuels sold within a country. Within the intergovernmental panel on climate change (IPCC) methodology, emissions from sea-going vessels are not attributed to countries due to the lack of a relationship between the location where fuels are bought and the regions where pollutants are emitted. Depending on the allocation method, the emission levels attributed to a country can differ to a large extent (ENTEC, 2005).

Within the Kyoto protocol, there are no carbon dioxide (CO<sub>2</sub>) emission targets for international ocean shipping. The protocol gives IMO authority to limit and reduce greenhouse gas emissions from merchant vessels. In the future, these emissions may also be allocated to individual countries. So, for the major maritime bunkering countries, it may be strategic to understand the effect that alternative approaches have on the emission levels of sea-going vessels.

The current IPCC methodology (common reporting format) for the estimation of emissions from sea-going vessels is based on bunker fuels sold in the country (top-down approach). In this paper, we discuss an alternative activity-based methodology (bottom-up approach).

Our comparison of both alternative methodologies provides valuable new information to policy makers that can be useful in international discussions concerning the allocation of greenhouse gases and other air pollutants from sea-going vessels.

## 2. Methodology

In Section 2.1, we briefly discuss existing top-down emission inventories for maritime transport. Section 2.2 provides an up-to-date description of the latest IMO and European legislation. In Section 2.3, we explain in detail the development of the activity-based bottom-up emission inventory model MOPSEA. Finally, we will explain how we forecast the Belgian maritime emissions for the year 2010 (Section 2.4).

### 2.1. Current methodology

At this moment, the official emission calculations for maritime transport are based upon the total amount of bunker fuels for maritime transport sold in Belgium (top-down). The emissions are not spatially allocated. The total quantity of bunker fuels has been defined as the sum of ‘international bunkering’ and ‘local bunkering’ which is reported in the national energy statistics. There is thus an overestimation of the Belgian maritime fuels due to the summation of local and international bunkers. In addition, companies selling bunker fuels tend to attribute as much heavy diesel fuel as possible to international bunkering because these are then free from duties.

### 2.2. Current legislation

On 19 May 2005, the MARPOL Annex VI convention—established by the IMO—came into force (IMO, 2005). One of the requirements is that the sulphur content of heavy fuel oil may not exceed 4%. A lower 1.5% cap is in force in two “sulphur emission control areas (SECA’s)”, the North and Baltic seas. The sulphur content of 1.5 mass% for heavy fuel oil is also prescribed by the 2005/33/EC Directive. This Directive also imposes the use of maximum 0.1 mass% sulphur in fuel for vessels at berth with a minimum berth duration of 2 h (with effect from 2010). In order to reduce emissions from sea-going vessels, Annex IV also includes limit values for nitrogen oxides ( $\text{NO}_x$ ) from diesel engines on vessels constructed after 1 January 2000 and all engines that undergo a major conversion after 1 January 2000, but was not effective until 19 May 2005. Interviews with ship owners confirmed that for activities before 19 May 2005, this  $\text{NO}_x$  standard in practice only applied to passenger ships. All other vessels built after 1999 have adjusted their motor characteristics after 19 May 2005 to be in rule with the IMO regulation for  $\text{NO}_x$ . The  $\text{NO}_x$  standards depend on the engine maximum operating speed and apply to all geographical areas (IMO, 2005).

### 2.3. Description of the activity-based inventory approach

The scope of the activity-based maritime transport emission model MOPSEA is to determine the

energy consumption as well as the carbon dioxide ( $\text{CO}_2$ ), sulphur dioxide ( $\text{SO}_2$ ), nitrogen oxides ( $\text{NO}_x$ ), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) exhaust emissions of transport activities from sea-going vessels. Sea-going vessels are sea-going merchant and passenger vessels including short sea shipping. The vessels are divided into the following categories: chemical tankers, container ships, dry bulk carriers, gas tankers, general cargo, liquefied natural gas (LNG) tankers, oil bulk (crude), passenger ships, refrigerated cargo and RoRo vessels. Fishing boats, pleasure crafts, dredgers, tugs, tank barges and navy vessels are excluded.

We evaluated different European activity-based methodologies such as MEET (1999), ENTEC (2002), ENTEC (2005), EMS (2003) and TRENDS (2003) that have been used by others to estimate emissions for maritime transport. We screened the usefulness of each methodology for mapping emissions from sea-going vessels described in literature. Transparency, reproducibility, the integration of technical aspects (of the vessels) and the amount of detail were important selection criteria for the methodology. Therefore, we finally decided upon an approach similar to the one used in the Netherlands (EMS, 2003; Gommers et al., 2007) adapted to the specific Belgian situation.

For its application to Belgium, we defined six different vessel operating areas: four harbours, the river Scheldt and the North sea (12 mile zone) (Fig. 1).

The MOPSEA model contains data on all shipping activities (time periods) of sea-going vessels for the year 2004, for each of the Belgian harbours (Antwerp, Ghent, Oostende and Zeebrugge) for the activities in the different harbours and the Belgian part of the river Scheldt and from the Belgian/Dutch vessel traffic system for the activities in the Belgian jurisdiction of the North sea (12 mile zone). Table 1 presents the number of ship calls per vessel type in Belgium for the year 2004.

The model is designed to calculate emissions and energy consumption for the different stages of navigation for every voyage and hotelling period. Therefore, detailed activity data in the form of the duration of the different stages of navigation for every voyage (cruise speed, reduced speed, manoeuvring, hotelling and anchoring) is an essential input parameter in the emission model. Currently, the energy consumption and the emissions resulting from loading and unloading are out of scope of the

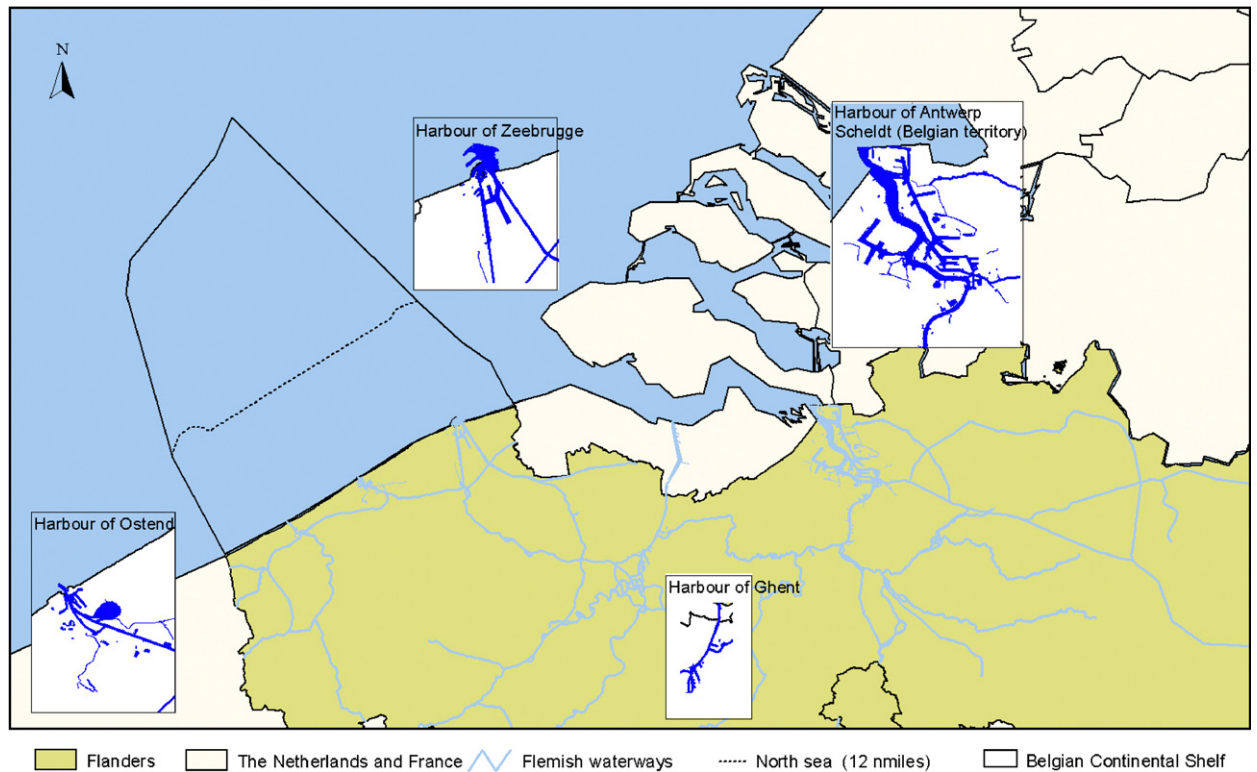


Fig. 1. Six different vessel operating areas in MOPSEA for the Belgian sea territory.

model, because these emissions are generally not allocated to transport modes. This energy can either be supplied from the vessel engines or from the harbour energy facilities. A study on off-road energy use and emissions for mobile machinery, in which harbour energy facilities are one aspect, is in progress in Flanders.

We determined the emissions by multiplying specific emission functions with the energy use for technology dependent emissions ( $\text{NO}_x$ , CO, HC and PM) on the one hand and with the fuel use for fuel related emissions ( $\text{CO}_2$  and  $\text{SO}_2$ ) on the other hand.

Technology related emission functions from EMS (2003) were used to compute the  $\text{NO}_x$ , CO, HC and PM emissions. The emission functions are dependent on the year of construction of the vessel, the percentage of the maximum continuous rate (MCR) and the prevailing  $\text{NO}_x$  regulation (CorrAge, CorrMCR and Corr $\text{NO}_x$ , respectively, in formula (1)).

The emission factors for  $\text{CO}_2$  are in line with the IPCC (1997)  $\text{CO}_2$  emission factors for the different maritime fuels (3110 kg  $\text{CO}_2$  per ton heavy fuel oil, 3100 kg  $\text{CO}_2$  per ton diesel and gas oil and 2930 kg  $\text{CO}_2$  per ton gas boil off). The standard fuel composition in the MOPSEA model until the inventory year 2004 takes into account the worldwide average sulphur content of 2.7 mass% in heavy fuel oil—which is below the recently imposed regulations (see Section 2.2)—and 0.2 mass% in diesel and gas oil (EC, 2002). In addition, from 2005 on the recent European (EC, 2005) and international (IMO, 2005) regulations for the sulphur content of maritime fuels (see Section 2.2) are introduced in the emission calculations.

Energy use (formula (2)) and fuel use (formula (3)) depend on the vessels' technical characteristics (length, building year, engine type, RPM, fuel type and refrigerated TEU) and the power use during

$$\text{emission function (g kWh}^{-1}\text{)} = \text{emission factor (g kWh}^{-1}\text{)} \times \text{CorrAge} \times \text{CorrMCR} \times \text{CorrNO}_x \quad (1)$$

Table 1

Number of ship calls, average main engine power and CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub> and PM emissions of sea-going vessels in Belgian sea territory for the year 2004

2004	No. of ship calls	Power (10 <sup>3</sup> kW)	CO <sub>2</sub> (kton)	SO <sub>2</sub> (kton)	NO <sub>x</sub> (kton)	PM (kton)
Chemical tanker	2670	4.2	51	0.82	1.1	0.08
Containers	3780	24.9	201	3.32	5.3	0.48
Dry bulk carrier	1242	7.6	51	0.72	1.3	0.10
Gas tanker	1129	3.4	21	0.33	0.5	0.03
General cargo	7398	2.8	127	1.71	2.7	0.17
LNG tanker	41	28.4	5	0.00	0.0	0.00
Oil bulk (crude)	579	6.0	16	0.27	0.4	0.03
Passenger ship	3529	17.0	38	0.52	0.8	0.04
Refrigerated cargo	859	10.4	34	0.53	0.9	0.07
RoRo	7540	10.1	174	2.69	3.9	0.26
Total	28,767		720	10.92	16.9	1.28

each stage of navigation.

$$\text{energy use (kWh)} = \% \text{ of MCR} \times \text{maximum installed power (kW)} \times \text{duration (h)} \quad (2)$$

$$\text{fuel use (ton)} = \text{energy use (kWh)} \times \text{specific fuel consumption (g kWh}^{-1}) \times 1.1 \times 10^{-6} \quad (3)$$

The technical characteristics of each individual vessel were extracted from the Lloyd's register fairplay database. The average installed main engine power is presented in Table 1. A distinction is made between the exhaust emissions of auxiliaries (e.g. for on board electricity production) and the main propulsion engines. For the latter, we distinguish three types of main engines: 2-stroke engines, 4-stroke engines and steam turbines.

#### 2.4. Description of the forecasting module

The technology related emissions PM, NO<sub>x</sub>, HC and CO emissions depend on the type, age and the percentage of the MCR of the engines. As bunker fuel sales do not give any information about this, it's not possible to use a classical top-down assessment on bunker fuel sales to predict the evolution of maritime emissions as a function of technology. The activity-based emission model MOPSEA allows to forecast the emissions from sea-going vessels for the near future. To compute the effect of the current IMO and European legislation, we defined two scenarios: an autonomous growth scenario and a current legislation scenario. We evaluated both scenarios under low and high economic growth.

In the autonomous growth scenario, we only take into account the traffic and fleet evolution per vessel

Table 2

Yearly growth in terms of percentage for different goods per harbour in the period 2004–2015

Yearly growth in 2004–2015 (%)	Antwerp	Ghent	Ostend	Zeebrugge
<i>Low</i>				
Dry bulk	−1.79	0.78	−0.51	4.16
Liquid bulk	−1.77	0.78		4.16
Containers	5.11	3.47	11.37	3.38
RoRo	1.67	3.47	5.58	5.81
General cargo	1.27	3.47	−0.51	4.18
<i>High</i>				
Dry bulk	0	3.69	1.08	8.32
Liquid bulk	0	3.69		8.32
Containers	6.92	10.10	17.3	6.76
RoRo	3.44	10.10	6.6	11.61
General cargo	3.05	10.10	1.08	8.36

type, based on activity growth rates per vessel type per harbour and techno-economic improvements (fuel, vessel size, engine management, etc.). None of the recent environmental legislation is included. The determination of the activity growth factors is exogenous to the model. We use economic growth rates to model future activities.

For the merchant vessels, the basis is the amount of transported freight (in metric tonnes) by sea-going

vessels per harbour in the year 2004 and projected tonnages for the year 2010 according to a low and high autonomous growth scenario (based on strategic plans of each harbour). Table 2 presents the yearly growth in terms of percentage of different goods per harbour for the period 2004–2015.

In consultation with an expert committee, we assumed that the increase in traffic of merchant vessels would be filled in by newly built sea-going vessels which imply a further enlargement of the size of the vessels. The extra freight will be transported to the different harbours with these new vessels. We determined how many extra visits the new vessels would have to make by taking into account their gross tonnage. For some types of freight transport negative growth is expected. This decrease is evenly distributed over all vessel size categories.

From 2004 until the year 2010 and for each harbour, we assumed an annual growth rate for passenger vessels of 1% in a low autonomous scenario and 2% in a high autonomous scenario (DG Environment, 2005). The growth rates have an effect on all vessel categories in the model. We increased the activity data of the passenger vessels with accumulated growth rates over 6 years, 6% in a low scenario and 13% in a high scenario.

The characteristics of the new sea-going vessels for each harbour and each vessel type, taking into account geometry of the harbours and the docks, are based on the assumption that new vessels have the length of the largest vessel visiting in 2004 and the characteristics of a new vessel are based on average vessel characteristics from all available vessels in the Lloyd's register fairplay database with the corresponding length that were built from 2000 onwards. So, no linear trend of ship calls is assumed compared to the freight trend.

We implemented extra measures in the current legislation scenario compared to the autonomous growth scenario to meet the IMO and European legislation (see Section 2.2). This required the implementation of a NO<sub>x</sub> correction factor in the emission model for all vessels built from 2000 onwards, a sulphur content of 1.5 mass% for heavy fuel oil and a sulphur content of 0.1 mass% for all vessels at berth (this implies the use of diesel oil at berth).

### 3. Results

First, we present the maritime emission results calculated with the activity-based emission model

Table 3

Emissions of sea-going vessels in 2004 and 2010 in a low and high economic growth scenario with current legislation and the effect of the current legislation in 2010 (Belgian sea territory)

Emission (kton)	Current legislation scenario			Current legislation/autonomous growth (%)
	2004	2010 (low)	2010 (high)	
CO <sub>2</sub>	720	735	783	–2
SO <sub>2</sub>	10.92	5.16	5.48	–55
NO <sub>x</sub>	16.9	17.1	18.1	–2
PM	1.28	1.25	1.34	–6
CO	2.77	2.89	3.11	–1
HC	0.57	0.58	0.61	–1

MOPSEA for the years 2004 and 2010. In addition, we indicate in scenario analyses what the effect of the IMO and European legislation will be on the emissions of sea-going vessels.

#### 3.1. Emission figures for the years 2004 and 2010

Table 3 gives an overview of the emissions of the sea-going vessels (in Belgian sea territory) for the year 2004 and for the year 2010 according to the current low and high growth legislation scenarios.

This is the sum of the emissions in all regions (North sea (12 mile zone), the Belgian part of the river Scheldt and the four harbours) and for all different stages of navigation (cruise speed, reduced speed, manoeuvring, anchoring and hotelling). The CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub> and PM emissions (Belgium, 2004) of the different vessel types are presented in Table 1. The container, general cargo and RoRo vessels emit about 70% of the total CO<sub>2</sub>-, NO<sub>x</sub>-, and SO<sub>2</sub> emissions of maritime transport in Belgium. Fig. 2 shows the share of CO<sub>2</sub> emissions by main engines versus auxiliaries for the year 2004 per vessel type.

The auxiliaries of the general cargo vessels emit more CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub> emissions than the main engines of these vessels. This is due to the large amount of auxiliary power used compared to the main engine power use. The opposite is true for containers, LNG tankers and RoRo vessels. The contribution of the auxiliaries is small because of the large amount of main engine power used compared to the use of auxiliary power (total energy consumption (TJ) of auxiliaries <20%).

Depending on a low or high economic growth, the CO<sub>2</sub> emissions will increase with, respectively,

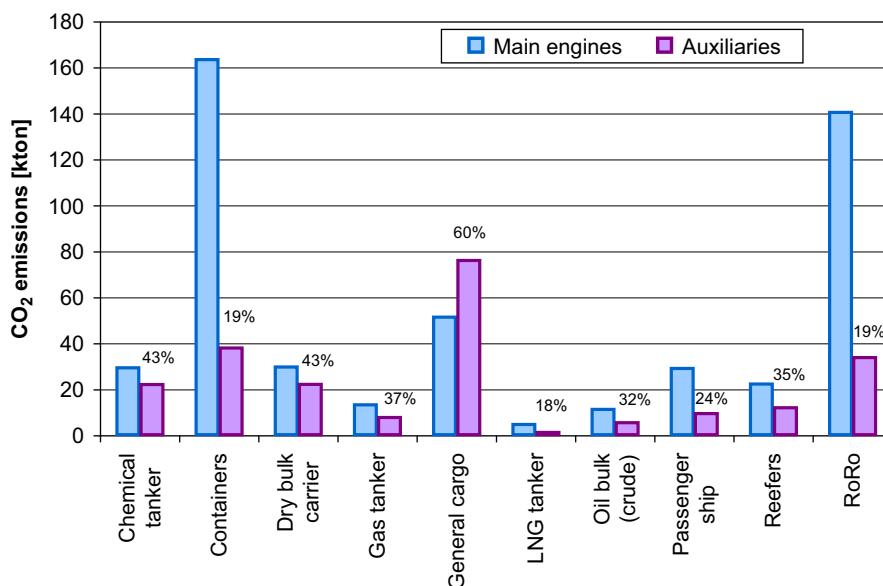


Fig. 2. CO<sub>2</sub> emissions of the different vessel types for the year 2004 in Belgian sea territory: main engines versus auxiliaries.

Table 4  
SO<sub>2</sub> and NO<sub>x</sub> emissions for the year 2010 (Belgian sea territory) in the current legislation scenario

Current legislation scenario 2010	SO <sub>2</sub> (kton)		NO <sub>x</sub> (kton)	
	Low	High	Low	High
Chemical tanker	0.30	0.33	1.0	1.1
Containers	1.75	1.80	5.6	5.8
Dry bulk carrier	0.28	0.33	1.2	1.4
Gas tanker	0.13	0.15	0.4	0.5
General cargo	0.60	0.62	2.7	2.8
LNG tanker	0.00	0.00	0.0	0.0
Oil bulk (crude)	0.11	0.12	0.4	0.4
Passenger ship	0.29	0.30	0.8	0.9
Refrigerated cargo	0.24	0.25	0.9	1.0
RoRo	1.47	1.57	4.0	4.3
Total	5.16	5.48	17.1	18.1

2% and 9% in the current legislation scenario over the period 2004–2010 due to an increase in activity. The NO<sub>x</sub> emissions will rise slightly (1%) in the low current legislation scenario, the increase in activity offsets the reductions of the IMO and European regulations. An increase of 8% of the NO<sub>x</sub> emissions takes place in the high current legislation scenario between the years 2004 and 2010. A decrease of 53% (low) and 50% (high) in SO<sub>2</sub> emissions is accomplished notwithstanding the increase in activity between the years 2004 and 2010. Table 4 illustrates the SO<sub>2</sub> and NO<sub>x</sub> emissions

for the year 2010 per vessel type in the current legislation scenario.

The CO<sub>2</sub> emission for sailing represent about 74% of the total CO<sub>2</sub> emissions for sea-going vessels, the SO<sub>2</sub> and NO<sub>x</sub> emissions about 79% and the PM emissions even 85%. Auxiliary engines during mooring at quays are responsible for about 93% of the total mooring emissions due to the long mooring times at quays. Anchoring represents about 4% of the total mooring emissions and mooring at locks only about 3%. When comparing the emissions of the sailing periods (cruise, reduced and manoeuvring speed) to the emissions of the mooring periods (hotelling periods at locks and quays), we can conclude that the emissions for sailing are more dominant than those for mooring periods (loading and unloading not included).

### 3.2. Effect of the IMO and European regulation on emissions of sea-going vessels

The difference between the autonomous growth scenario and the current legislation scenario quantifies the effect of the IMO and European regulation.

As mentioned in Section 1, the technological evolution of sea-going vessels is slower than that of other transport modes. An increase in activity between 2004 and 2010 offsets the technological improvements for most pollutants.

The implementation of the IMO Annex VI regulation for passenger vessels built after 1999 results in a NO<sub>x</sub> reduction of merely 45 ton or 0.3% of the total NO<sub>x</sub> emissions for sea-going vessels in the year 2004 in Belgium.

The IMO regulation that has an impact on all vessels built after 1999, results in a reduction of 1% of the NO<sub>x</sub> emissions of the main engines in the year 2010. The IMO and European regulations are most effective for the reduction in SO<sub>2</sub> emissions. The total reduction of 55% in SO<sub>2</sub> emissions is due to both the IMO and European regulations where a decrease of the sulphur content for heavy fuel oil and fuels used at berth is prescribed. The last one implies a switch from heavy fuel oil to diesel oil for vessels at berth built after 1984. Switch of auxiliaries from heavy fuel oil to diesel oil at berth results in a large emission reduction (33%) for PM and a small emission reductions for CO<sub>2</sub> (5%), NO<sub>x</sub> (5%), CO (4%) and HC (4%).

Dore et al. (2007) published similar results. They found that SO<sub>2</sub> emissions from international shipping in the North Sea and the English Channel will decrease 33% between 2002 and 2010 due to the introduction of a 1% sulphur limit on marine fuels.

#### 4. Discussion and conclusions

This paper describes the development and use of the activity-based emission model MOPSEA for maritime transport. The development of such a bottom-up methodology was intended to inform policy makers about the difference in emission estimations of maritime transport by using a top-down versus bottom-up approach and about the effect of the current legislation for maritime transport emissions.

##### 4.1. Sensitivity of the emissions factors

ENTEC UK Limited has conducted a study on behalf of the European Commission, to quantify among other things the vessel emissions of SO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub> and HC for the year 2000 in the North sea, Irish sea, English channel, Baltic sea and Mediterranean (ENTEC, 2002). They presented average emission factors for emissions “at sea”, “manoeuvring” and “in port” per vessel type for maritime transport in and between ports in the European Community (ENTEC, 2005).

The emission factors used combine the technological characteristics of the main and auxiliary

engines for the year 2000 and the share between the main and auxiliary engines. Therefore, the user is unable to adjust these average emission factors to take into account specific legislation on fuel types, main engines or auxiliaries.

For the purpose of sensitivity analysis, we have also ran the MOPSEA model with the widely used ENTEC (2005) emission factors. We calculated the emissions for the year 2004 by using ENTEC average emission factors per vessel type instead of the emission functions in MOPSEA per individual vessel. The emission figures calculated with the ENTEC emission factors are higher than those calculated with the emission functions in MOPSEA, namely 13% for CO<sub>2</sub>, 25% for SO<sub>2</sub>, 3% for NO<sub>x</sub> and 39% for HC. A possible explanation could be a different share in main engine power and auxiliary power which is not explicitly given in ENTEC (2005).

##### 4.2. Bottom-up versus top-down approach

In the case study for Belgium, reported in this paper, the results for CO<sub>2</sub> are 24.2 Mton CO<sub>2</sub> for the allocation based on bunker fuel sales (Aernouts and Jespers, 2005) and 0.7 Mton CO<sub>2</sub> for the activity-based methodology for 2004. The activity-based approach makes an inventory of the CO<sub>2</sub> emissions emitted in the Belgian sea territory, whereas the top-down approach makes an inventory of the worldwide CO<sub>2</sub> emissions of fuels sold on Belgian territory. We believe that an activity-based approach is better suited for an emission inventory for sea-going vessels for Belgium. First of all, in air quality management, command and control is a simple but efficient measure to improve air quality (from a policy perspective). Secondly, emissions are aggregated by vessel types and technologies, and hence emission reductions through technological improvements are easy to calculate and their cost-efficiency can be measured. It is important to allocate the necessary emission reduction to the different sectors in society to achieve the best result at the lowest cost to society and the different stakeholders. The activity-based methodology makes the identification of specific policy measures for air quality improvement in Belgium possible, whereas the top-down approach is not suited for this purpose. Finally, it is important to achieve the highest reduction in air pollution where exposure of the population is expected to occur. This means that emission reductions of vessels need to be disaggregated by port to assess whether additional

measures are necessary in ports and harbours close to densely populated urban areas.

National policy makers have to be aware, within the scope of post-Kyoto 2012 negotiations that the activity-based methodology (bottom-up) and the methodology based on the amount of bunker fuel sales (top-down) result in a completely different allocation of maritime emissions. Countries that sell large amounts of marine fuels, like Belgium, would over estimate emissions attributed to that nation by using the top-down methodology. Certainly, other nations that do not sell much bunker fuel would correspondingly underestimate emissions from ship activity if they only counted marine fuel sales.

Another top-down approach, as presented in Wang et al. (2007), is based on global bunker fuel amounts that are partially spread. Their top-down approach shows closer agreements between fuel sales and activity-based estimates as both methodologies represent emissions emitted in the same territory. Their top-down approach, however, does not take into account the vessel types and therefore is not able to calculate technology related emissions in an accurate way.

#### 4.3. Level of detail

Making use of average activity data per vessel type for a specific region can result in different emission figures. Recently, another maritime emission model was constructed by the Maritime Institute of the University of Ghent, namely the ECOSONOS model (Maes et al., 2007). While MOPSEA performed a very detailed inventory, ECOSONOS focussed more on producing a conceptual model with aggregate assumptions. The scope of both projects differed, but even when comparing the same activities, there is a large difference between both models. The MOPSEA results are about 43% lower than those of ECOSONOS. Nevertheless, the difference between the two bottom-up methodologies is much smaller than the difference between a top-down and a bottom-up methodology. It would be interesting to collect and test detailed data over several years and see whether this way, one can distil more accurate average times for the different stages of navigation per vessel type for each port and more accurate sailing times for activities at sea.

#### 4.4. Comparison with other transport modes

The relative emission contribution of maritime transport in Belgium compared to the road, rail and

inland waterway-based transport modes (De Vlieger et al., 2005) increases with time for all four pollutants. Maritime transport is responsible for only 3% of the CO<sub>2</sub> emissions. This is rather small compared to the relative SO<sub>2</sub> contribution (92% in 2004 and 95% in 2010). The decrease in SO<sub>2</sub> emissions due to the IMO and European regulations is important, but relatively small when compared to the decrease in SO<sub>2</sub> emissions achieved by the other transport modes. This is due to the more stringent European regulation on sulphur content in gasoline and diesel fuels for road vehicles. The same conclusions apply to the relative NO<sub>x</sub> and PM emission contribution of maritime transport. The effect of the very strict European NO<sub>x</sub> and PM emissions standards for new road vehicles is larger than the effect of the IMO and European regulation for maritime transport. Maritime transport is responsible for 10–13% of the NO<sub>x</sub> and 16–24% of the PM emissions, respectively, in the years 2004 and 2010.

At this moment, maritime transport is no longer negligible for acidifying emissions like SO<sub>2</sub> and NO<sub>x</sub> and for PM emissions compared to those of other transport modes, and is even dominant for SO<sub>2</sub>. Discussions are held to include the maritime transport in the future national emission ceilings (Cofala et al., 2007). Policy makers have to be aware that the total amount of national emissions may increase significantly when maritime transport is included in the national emission ceilings for countries with important harbours.

#### 4.5. Future work

Updating the new activity-based emission model for maritime transport with the newest data on vessel technologies, vessel movements, etc. remains necessary. In a cost–benefit analyses, for example this information is crucial in cases where costs and benefits are expected to be high, but where the ratio between costs and benefits is close to one (see for example Schrooten et al., 2006). In order to develop well-founded analyses to feed policy makers, different activity databases could be harmonized; provided with the most accurate data and made available for research. The assumptions on fuel use and percentage of MCR can be further refined by monitoring these parameters in practice. Data from Lloyd's register fairplay has to be updated at least every 5 years to get a good insight in the technological evolution for sea-going vessels in



future statistical years. The emission factors for the PM are based on a small number of measurements, completed with estimations on the basis of assumptions. PM emission measurements are necessary to derive more accurate emission factors.

The new activity-based emission model for maritime transport could be the basis for developing straightforward efficient tools to assess emissions from sea-going vessels. This will be carried out in the Ex-TREMIS project (Exploring TRansport EMISsions) commissioned by the Institute for Prospective Technological Studies of the European Commission Directorate—General Joint Research Centre (JRC-IPTS). The project aims to build a comprehensive database of specific energy consumption, emission factors and total emissions covering the 27 EU member states for the year 1980 up to 2030. Besides maritime transport also rail and air transport are issues of research. At the end (spring 2008) collected data and results can be extracted through a web-based interface and directly plugged into models or used by the general public.

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## **Forecasting maritime emissions: an activity based approach**

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### **ABSTRACT**

Most efforts to estimate ship emissions are currently based on bunker fuel sales allocated to specific port cities and countries. The amount of bunker fuels results in relatively high emission estimates for small countries hosting important sea ports.

An alternative approach based on activity-based traffic data was applied to build the maritime emission model MOPSEA. This paper presents how this methodology was developed and presents the results of a case study for Belgium. Input data for this model are activity data. This consists of durations of the voyages of the individual ships traveling combined with data on the ships technical characteristics obtained from the Lloyds database. This allowed to estimate the time spent in different stages of navigation (cruise, manoeuvring, docking and berthing) and derive emissions for each of these stages based on the energy use. Technology-related emission factors were used to compute the NO<sub>x</sub>, CO, HC and PM emissions. The emission factors depend on the age, engine type (2-stroke, 4-stroke engines and steam turbines) and the percentage of the maximum continuous rate. Recent IMO and EU sulphur regulations were taken into account to estimate emissions of SO<sub>2</sub>. The new model makes it possible to construct current emission inventories and forecast the impact of legislation implemented to reduce emissions. We demonstrate this by applying the model to compute the effect of the current IMO and EU legislation for emissions in Belgian territorial waters and sea ports. A combination of the IMO and EU regulations will lead to a total reduction of 56% in SO<sub>2</sub> emissions. In any case the estimation of the amount of pollutants emitted by sea-going vessels in areas under Belgian jurisdiction (including a part of the North Sea) is much lower than the previous emission estimates based on the use of fuels bunkered in Belgium.

In ongoing work we are using the new model to predict the benefits of emission reductions on air quality and health impacts in sea ports. Potential environmental benefits from new maritime technologies (e.g. reduced friction of novel anti-fouling coatings, scrubbers, ...) are examined using MOPSEA forecasts.

## **1 INTRODUCTION**

Most efforts to estimate ship emissions are currently based on bunker fuel sales. Official emission calculations (IPCC guidelines) for CO<sub>2</sub> are based on the bunker fuel emission inventory method, which is a top-down approach. The total quantity of bunker fuels is defined as the sum of 'international bunkering' and 'local bunkering' as reported in the national energy statistics. Bunker fuels are allocated to specific port cities and countries resulting in relatively high emission estimates for small countries hosting important sea ports.

In this paper we propose an alternative approach to model emissions from sea-going vessels: a detailed bottom-up model MOPSEA based on activity data (MOPSEA, 2007). MOPSEA is the acronym for MOnitoring Programme on air pollution from SEA-going vessels. We demonstrate that it is possible to make forecasts with this model, taking into account specific legislation. We also discuss the importance of the level of detail of activity data and vessel characteristics.

## **2 METHODOLOGY**

The activity based technology model MOPSEA (bottom-up approach) was built to calculate the energy consumption and carbon dioxide (CO<sub>2</sub>), sulphur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) exhaust emissions from sea-going vessels. It is designed to calculate emissions and energy consumption for the different stages of navigation for every voyage and hotelling period (cruise speed, reduced speed, manoeuvring, hotelling and anchoring).

Detailed activity data, time spent in different stages of navigation (cruise, manoeuvring, docking, berthing) for every voyage, is an essential input parameter in the emission model. We demonstrate the MOPSEA methodology for Belgium where we have extracted data for all ships traveling to one of the 4 Belgian sea ports (Antwerp, Ghent, Ostend and Zeebrugge) and in the Belgian part of the North Sea.

The model determines the emissions through the energy use, taking into account the length, building year, RPM, amount of refrigerated TEU of the individual sea-going vessels, and the power use during each stage of navigation. We obtained the technical characteristics for all individual sea-going vessels from the Lloyds database. A distinction is made between the exhaust emissions of auxiliaries (e.g for on board electricity production) and the main propulsion engines. For the latter, we distinguish 3 types of main engines: 2-stroke engines, 4-stroke engines and steam turbines.

To link activity data with emission data we evaluated different existing European methodologies to estimate emissions for maritime transport. MEET (1999), ENTEC (2002), ENTEC (2005), EMS (2003) and TRENDS (2003) Emission factors developed in EMS (2003) were found to be the most transparent, reproducible and detailed of all. They are also disaggregated by different technical ship characteristics aspects.

The emission factors depend on the building year of the vessel and the percentage of the maximum continuous rate (MCR). Also the latest IMO regulations for the main engines built after 1999 are taken into account (IMO, 2005). The emission factors for CO<sub>2</sub> correspond with those advocated by the IPCC. The present average sulphur content in maritime fuels was taken from EC (2002). For 2010 the IMO (2005) and EC (2005) regulations for the sulphur content of maritime fuels were taken into account.

Emission Factor [kg/ton]	Period	Heavy fuel oil	Diesel & gas oil	Gas boil off
CO <sub>2</sub>	-	3110	3100	2930
SO <sub>2</sub>	(... – 18/05/2006)	54	4	~0
SO <sub>2</sub>	(19/05/2006 – 2009)	30	4	~0
SO <sub>2</sub>	(2010 - ...)	30	4 or 2 <sup>1</sup>	~0

Table 2: overview of the CO<sub>2</sub> and SO<sub>2</sub> emission factors (kg/ton fuel).

<sup>1</sup> 2 kg SO<sub>2</sub>/ton diesel or gas oil at berth (minimum duration of 2 hours)

Energy for loading and unloading can either be supplied from the vessel engines or from the harbour energy facilities. Currently, the energy consumption and the emissions resulting from it for loading and unloading are not included into the model (similar assumption are taken for rail and road transport in other emission models).

## 3 RESULTS

### 3.1 EMISSION FIGURES FOR THE YEAR 2004

Table 1 presents for the year 2004 the emissions of the main engines and auxiliaries of the sea-going vessels travelling in Belgian territory according to the MOPSEA model. This calculation shows that exhaust emissions caused by auxiliary engines are a significant emission source. Depending on the pollutant approximately one fifth to half of the total emissions is caused by auxiliaries.

kton	Main engines	Auxiliaries	Total
CO <sub>2</sub>	494	226	720
SO <sub>2</sub>	8,09	2,82	10,9

<i>NO<sub>x</sub></i>	12,7	4,21	16,9
<i>PM</i>	1,04	0,236	1,28
<i>CO</i>	1,97	0,801	2,77
<i>HC</i>	0,389	0,179	0,569

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Table 2: emissions (kton) of sea-going vessels for the year 2004 in Belgium

The reported CO<sub>2</sub> emissions that are officially reported for maritime transport in Belgium, using the top-down methodology based on bunker fuel sales, are equal to 24.2 Mton for the year 2004 which is more than thirty-five times higher than the new estimations with the bottom-up approach (MOPSEA).

In addition to the point of view taken, there is an additional overestimation of the Belgian maritime fuels is due to:

- the summation of local and international bunkers (~5 %);
- the attribution of as much heavy diesel fuel as possible to international bunkering because these are free from duties (~20%);

There exists also a discrepancy between the bottom-up and top-down approach with respect to where the CO<sub>2</sub> emissions are emitted. The bottom-up approach makes an inventory of the CO<sub>2</sub> emissions emitted in Belgian territory, whereas the top-down approach makes an inventory of the CO<sub>2</sub> emissions of fuels sold on Belgian territory. National policy makers have to be aware that the use of the top-down or bottom-up methodology for emission assignment, within the scope of post-Kyoto 2012, makes an enormous difference for countries that sell large amount of maritime bunker fuels.

Figure 1 presents the CO<sub>2</sub> emissions (Belgium, 2004) of the different vessel types, calculated with the MOPSEA model.

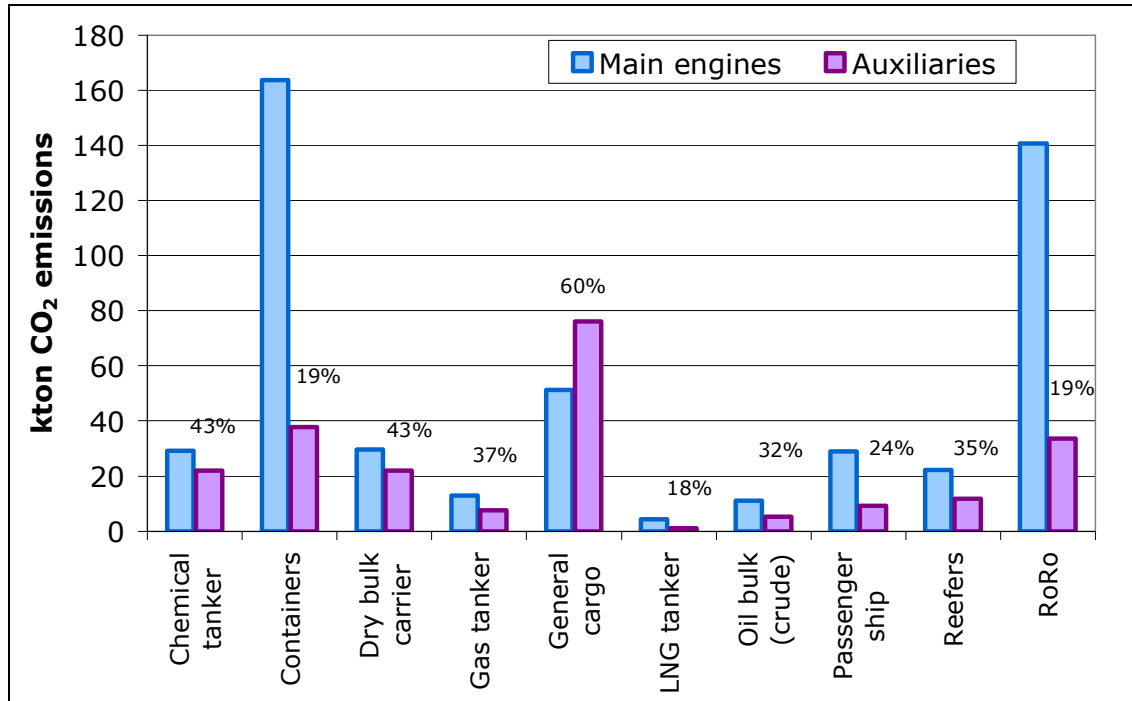


Figure 1: CO<sub>2</sub> emissions of the different vessel types for the year 2004 in Belgium

The container, general cargo and RoRo vessels emit ~70 % of the total CO<sub>2</sub>-NO<sub>x</sub>- and SO<sub>2</sub> emissions of maritime transport for the year 2004 in Belgium.

When we compare the emissions of the sailing periods (cruise, reduced and manoeuvring speed) to the emissions of the mooring periods (hotelling periods at locks/quays and anchoring), we can conclude that the emissions for sailing are more dominant than those for mooring periods (loading and unloading not included). The CO<sub>2</sub> emission for sailing represent about 74% of the total CO<sub>2</sub> emissions, about 79% for the SO<sub>2</sub> and NO<sub>x</sub> emissions and even 85% for the PM emissions.

### 3.2 COMPARISON WITH OTHER TRANSPORT MODES

Emission levels for road transport, rail traffic and inland navigation for Belgium can be found in the SUSATRANS project (De Vlieger et al., pers. comm.). The relative CO<sub>2</sub> and SO<sub>2</sub> emission contribution of maritime transport compared to the transport modes road, rail and inland waterway in Belgium are respectively 3% for CO<sub>2</sub> and more than 90% for SO<sub>2</sub>. The relative CO<sub>2</sub> contribution is rather small compared to the relative SO<sub>2</sub> contribution. The decrease in SO<sub>2</sub> emissions due to the IMO and EU regulations is small compared to the decrease in SO<sub>2</sub> emissions that was achieved for the other transport modes. This is due to the more stringent European regulation on sulphur content in gasoline and diesel fuels for road vehicles.

### 3.3 EFFECT OF LEGISLATION IN THE YEAR 2010

We made predictions of the emissions of maritime transport in Belgium in an autonomous growth scenario by taking into account, the traffic evolution, the fleet evolution and the existing legislation (IMO and EU). To compute the effect of the existing legislation, we calculated the emissions only taking into account the traffic and fleet evolution (current legislation scenario).

Table 2 presents the effect of the IMO and EU regulations for emissions of maritime transport in the year 2010 by comparing the autonomous growth scenario with the current legislation scenario for Belgium.

	<i>Main engines</i>	<i>Auxiliaries</i>	<i>Total</i>
<i>CO<sub>2</sub></i>	0%	-5%	-2%
<i>SO<sub>2</sub></i>	-44%	-84%	-55%
<i>NO<sub>x</sub></i>	-1%	-5%	-2%
<i>PM</i>	0%	-33%	-6%
<i>CO</i>	0%	-4%	-1%
<i>HC</i>	0%	-4%	-1%

Table 4: emission reduction in the year 2010 due to the IMO en EU regulations

The IMO regulation results in a reduction of merely 1% of the NO<sub>x</sub> emissions of main engines in the year 2010. The total reduction of 55% in SO<sub>2</sub> emissions is due to both the IMO and EU regulations where a decrease of the sulphur content for heavy fuel oil and for fuels used at berth is prescribed. The latter also implies a switch from heavy fuel oil to diesel oil for vessels that make use of heavy fuel oil for their auxiliaries.

## 4 FUTURE WORK

We would like to refine the MOPSEA model, make it more user friendly and feed the model with statistical data for different historical years. Updating the activity based emission model for maritime transport with the newest information remains necessary to provide well-founded information to policy makers. The assumptions on fuel use and percentage of MCR (maximum continuous rate) can be further refined by monitoring these parameters in practice. Data extracted from Lloyd's Register Fairplay have to be updated at least every 5 years to get a good insight in the technological evolution for sea-going vessels in future statistical years. The emission factors for the pollutant PM are based on a small number of measurements, completed with estimations on the basis of assumptions. Emission measurements are necessary to get a better idea of these factors.

In ongoing work we are using the new model to predict the benefits of emission reductions on air quality and health impacts in sea ports. Environmental benefits from new maritime technologies (e.g. reduced friction of novel anti-fouling coatings, scrubbers, ...) are evaluated.

## 5 CONCLUSIONS

The technological evolution of sea-going vessels is slower than that of other transport modes. An increase in activity, due to economic growth and increased trade with Asia, between 2004 and 2010 offsets the technological improvements for most pollutants. CO<sub>2</sub> emissions increase with 2 - 9 % between 2004 and 2010. The IMO and EU legislation have the largest impact on the SO<sub>2</sub> emissions. A decrease of 50 -53 % between 2004 and 2010 was calculated in the baseline scenario. The IMO regulation has only a small reducing effect on the total NO<sub>x</sub> emissions of sea-going vessels in the year 2010.

Comparing a top-down with an activity based approach leads to large differences in the estimated amount of pollutants emitted in areas under Belgian jurisdiction (including a part of the North Sea). Applying an activity-based approach leads to much smaller estimates than the total emission resulting from the use of fuels bunkered in Belgium. As emissions of sea going vessels will be considered within the scope of post-Kyoto 2012, national policy makers have to be aware that the two methodologies result in a completely different allocation of maritime emissions which is important for small countries with important maritime activities.

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