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Modelling for sustainable cities: Conceptual approach and an audit of existing sectoral models for transport, air pollution, land use, and population modelling

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This report is the second one in the series of four reports prepared by the author within the Sustainable/Quantifiable City project conducted in 1994-1996 at the Environment Centre. The author wish to thank the grantholders: Prof. David Kay (Environment Centre), Prof. Tony May (Institute for Transport Studies) and Prof. Mike Pilling (School of Chemistry), as well as Dr Gordon Mitchell (co-researcher, Environment Centre) and Prof. Adrian McDonald (School of Geography) for their support.

Other reports in the series are:
“Computer implementation of the Quantifiable City Decision Support System (QCDSS)”,
“Modelling for sustainable cities: the transportation sector”, and
“MUPPETS: A computer tool for modelling and mapping emissions from urban tranport and stationary sources”.

Contents

A. Specification of the components of a sustainability model

A.1 Introduction

Urban modelling theories and operational models date back to the sixties and seventies, and have been constantly improved since then. It seems therefore that there should be no problem with addressing city sustainability issues. After all, these models claimed to be tools to help planners in choosing the best policies, exactly the same objectives that we need sustainability models to fulfil.

The problem is that urban models have ignored many problems considered today as most pressing. They have not only ignored environmental issues, but also most quality of life issues. If we look at diagrams by Wilson (1981, p.265; 1977, p.3) or Wegener (1994), it is clear that these models focus on land use (understood as location and intensity of activities) and transport problems. The name "urban model" might be then misleading. This does not mean that environmental problems were not modelled at all: they were, but this research area was outside the interests of urban researchers and planners.

One possibility for the way forward is to use old models, integrate them and extend them to include missing components. In order to do this, one should first specify the components to be included in the integrated model, taking the sustainability concept and the new modelling objectives as a point of reference.

A.2 Sustainability aims and a specification of the system of interest

One of the most often cited definitions of sustainable development (that given in the Brundtland report) states that it is "development that meets the needs of present without compromising the ability of future generations to meet their own needs" (WCED 1987). Another says that it is "development that improves the quality of human life while living within the carrying capacity of supporting ecosystems" (IUCN-UNEP-WWF 1991). The most important sustainability aims are:

- Preservation (or increase) of the quality of life;
- Intra-generational equity;

- Preservation of resource stocks;
- Preservation of environmental quality and climate;
- Preservation of biodiversity.

The difficulty lies in the conflicting nature of these aims: economic development leading to rising standards of living leads also to a less safe and unpleasant environment, while finite amount of resources means that the more we use the less is left for future generations.

Given the above listed issues it is clear that sustainability modelling must involve modelling processes from two sub-systems (Figure A-1), the human sub-system, and the

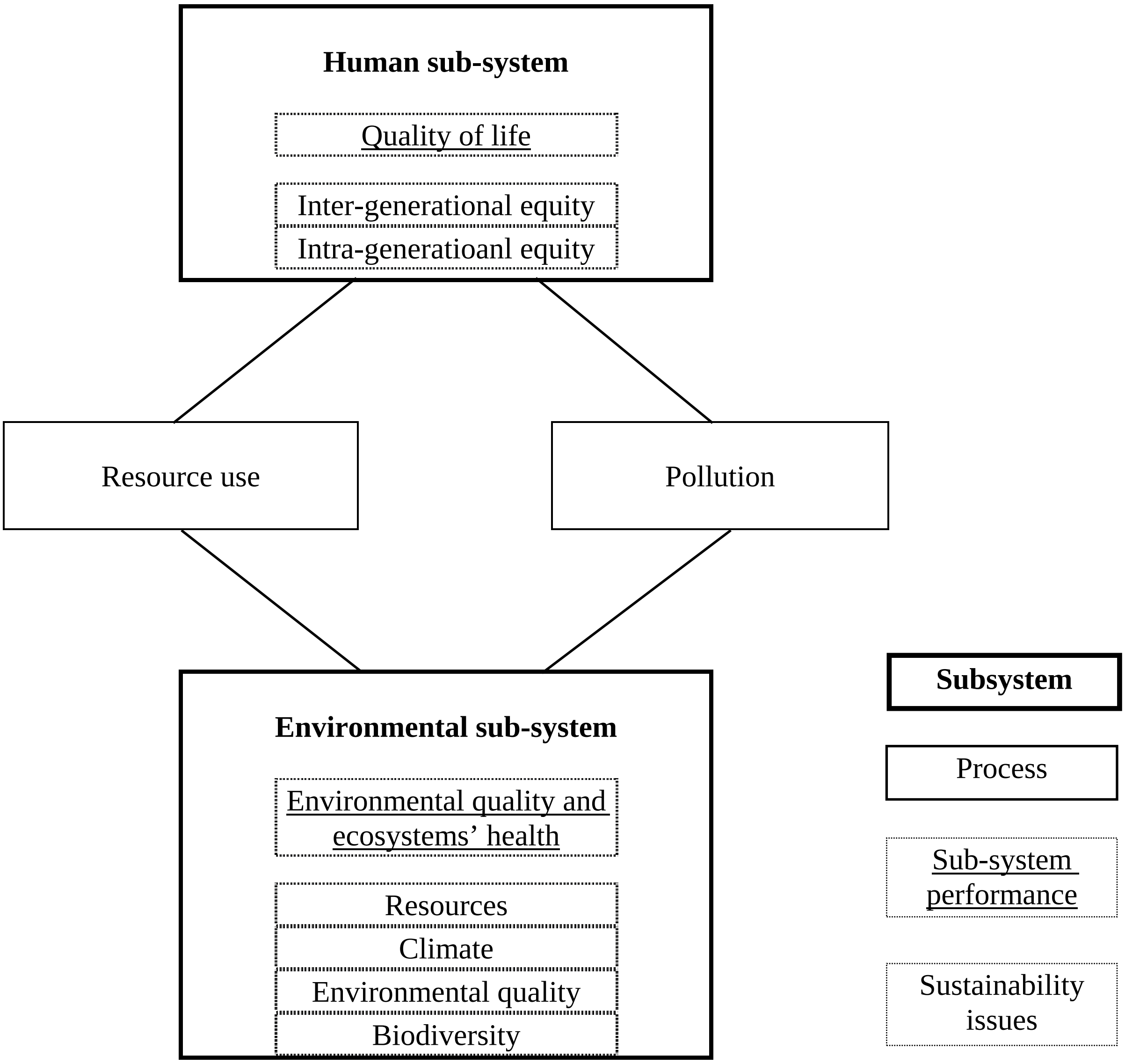


Figure A-1. Main sub-systems, interaction processes and sustainability issues.

environmental sub-system, and especially interactions between them. The main interactions are: resource use and consumption, and pollution, which have an immediate effect on the performance of both sub-systems, as presented on Figure A-1. This figure looks quite simple, but it hides an extremely complicated structure.

A.3 Identification of system components and linkages

When developing a quantitative model, a rigorous approach is required to identify all the components of the system: subjects, their characteristics and functions (e.g. activities, if we talk about people), interactions between them, as well as processes describing system dynamics. Table A-1 and Table A-2 present a classification of components that should be considered when modelling city sustainability and examples of components: obviously there are many more of them, and it would be difficult to list them all here. This is a luxury of working on a conceptual level: when implementing the model, every small bit must be explicitly represented by a variable.

Figure A-2 shows major linkages between component parts of the human sub-system and presents city metabolism as a main process of interaction between socio-economic activities and the environmental sub-system. Additional linkages between human and environmental subsystems are represented in Figure A-3, while Figure A-4 concentrates on a more detailed representation of land use, socio-economic activities and city metabolism.

Within the human sub-system the most important components are Population and Economy (Figure A-2). As stated in the consultation paper “UK Strategy for sustainable development” (DoE 1993): “Sustainable development requires changes both in the way economic activity is conducted and in the lifestyles of individual citizens”. Science and technology, and culture play their role as well. The role of science and technology in the progress towards sustainability might be in increasing the life-time of products (buildings and goods), increasing energy efficiency of processes and buildings, and in development of environment friendly technologies (e.g. for manufacturing, transport, re-use and re-cycling). Culture determines to a large extent people’s lifestyles and choices, and their perception of quality of life.

Table A-1. Components of the human sub-system and processes describing its dynamics.

<table>
<tr><th colspan="5">Human sub-system</th></tr>
<tr><td colspan="5">Performance measures: indicators of the quality of life, social equity, and level of economic development</td></tr>
<tr><td>Subjects
(actors)</td><td>Characteristics</td><td>Activities (intensity and location)</td><td>Processes</td><td>Infrastructure, goods and services (quality, quantity, location, prices)</td></tr>
<tr><td>Population
Individuals

Households

Social groups

Ethnic groups</td><td>Age, Sex
Education level
Health
Ethnicity
Lifestyle
Individual preferences
…
Size, Structure
Income, budget structure
Car ownership
Social class

Crime level
…
Cultural characteristics</td><td>Work
Travel
Education
Shopping
Personal business
Leisure outings
Tourism
Home-based activities</td><td rowspan="4">Demographic processes
Ageing
Changes in household size and structure

Social processes
Alienation
Reduction of social interaction
Change of crime levels
Change of leisure time

Socio-economic processes
Change of incomes and consumption level

Urbanisation
Suburbanisation
Counterurbanisation
Decline of inner cities

Economic processes
Decline of traditional sectors of industry
Growth of high-technology industries
Growth of service sector(finances, retailing, leisure)

Physical processes
material and energy flows</td><td rowspan="4">Infrastructure and means of production
Houses
Shops
Banks
Schools
Hospitals
Leisure centres
Telecommunication
Roads
Transport fleet
Factories and machinery
…

Intermediate and final consumption goods
Steel
Crops
Livestock
…
Food
Clothes
Furniture
Cars
…

Services
Retailing
Public transport
Health service
…</td></tr>
<tr><td>Economy sectors
Industry sectors (chemical, motor, engineering, food, printing, textile, construction, …)
Agriculture
Services (retailing, financial, health, education, leisure, …)</td><td>Number of employees
Type and size of production
Resources inputs
Waste and pollution generated</td><td>Mining
Construction
Manufacturing
Farming
Goods transport
Services supply</td></tr>
<tr><td colspan="2">Technology and science</td><td>Introduction of new technologies</td></tr>
<tr><td colspan="2">Political organisations
Central and local government

NGO, societies
International organisations</td><td>Law creation
Decision making
Lobbying
Policy creation</td></tr>
</table>

Table A-2. Components of the environmental sub-system.

Environmental sub-system				
Inanimate nature				
Performance measures: quantity and/or quality of resources				
Subjects/Media	Stocks	Quality/Characteristics	Natural phenomena	Environmental processes triggered by socio-economic activities
Local climate	—	Temperature Precipitation, humidity Duration of bright sunshine Wind Visibility	Meteorological processes	Formation of city microclimate
Air (boundary layer)	—	Concentrations of: NO_x, O_3, CO, SO_2, VOC, PM_{10}		Pollutants dispersion and chemical transformations Acid rain
Global atmosphere	—	Concentrations of greenhouse gases and stratospheric ozone Global climate	Greenhouse effect CO_2 intake by trees	Depletion of ozone layer Climate change, global warming
Water	✓	Class Acidity Concentrations of nitrates and phosphates	Water circulation Floods	Eutrophication Acidification
Fossil fuels Minerals	✓	✓	Resource formation	Stocks depletion
Land/Soil Landscape	✓	Land cover Derelict/Contaminated land area Soil types and quality Concentration of heavy metals	Soil processes Erosion Earth quakes Volcanoes eruptions	Land devastation Soil degradation/ fertilisation Visual intrusion by economic activities and infrastructure
Noise	—	Noise level		
Biotic sub-system				
Performance measures: biodiversity, ecosystems health and integrity				
Fauna (including fisheries) Flora (including forests)			Biological life	Habitat loss Decrease of wildlife diversity Decline of fish stock Deforestation Land cover change Changes in ecosystems composition and behaviour

Figure A-2. Elements relevant to modelling urban sustainability, and major linkages.

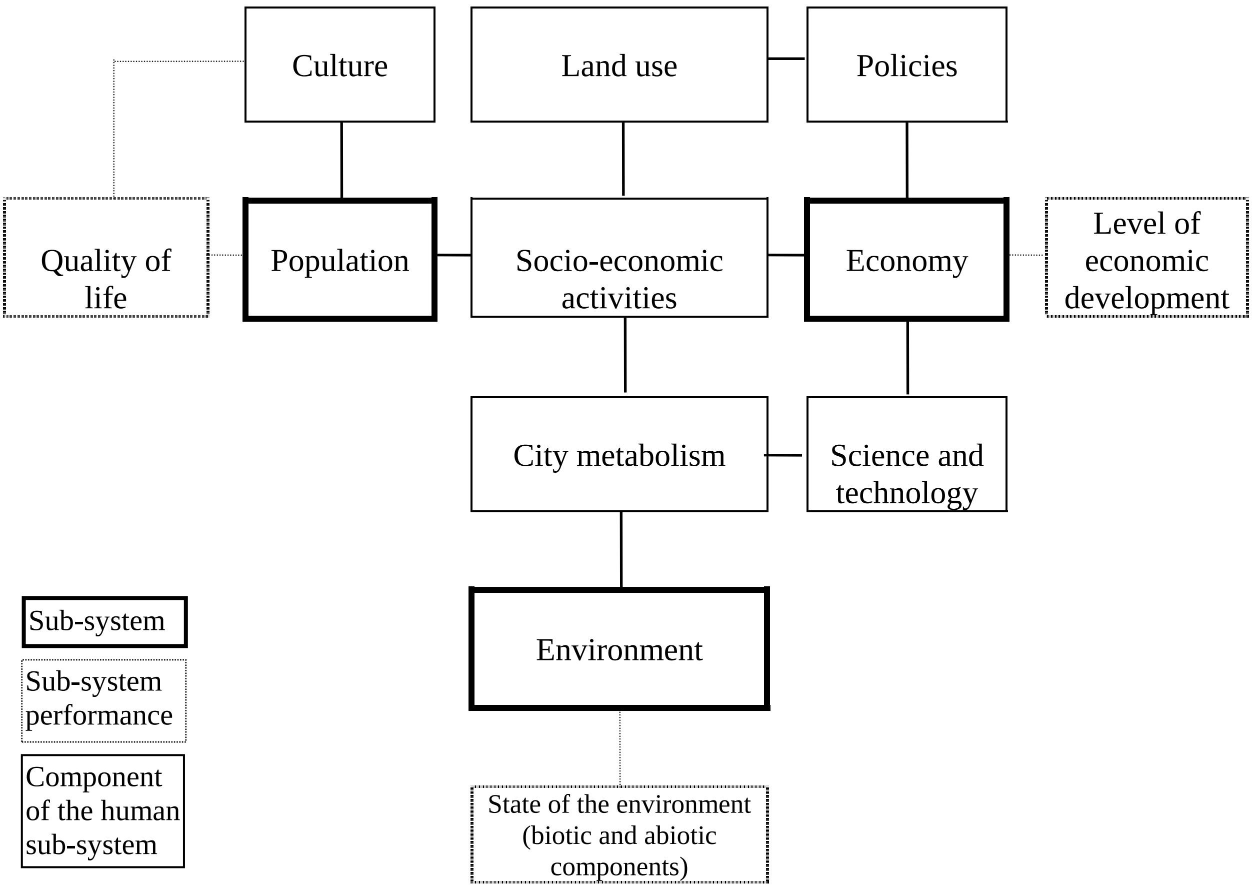


Figure A-3. Interactions between human and environmental sub-systems.

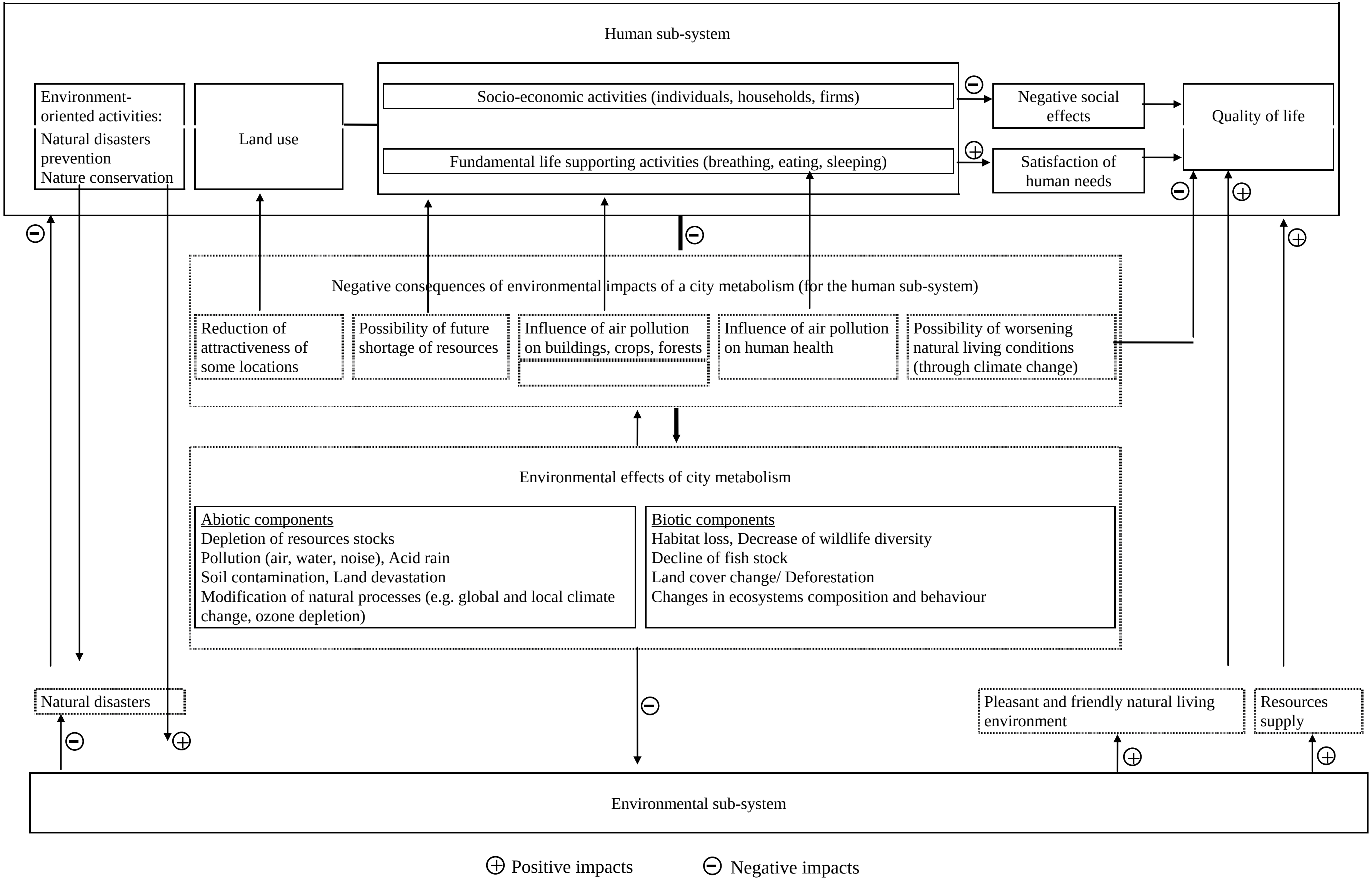
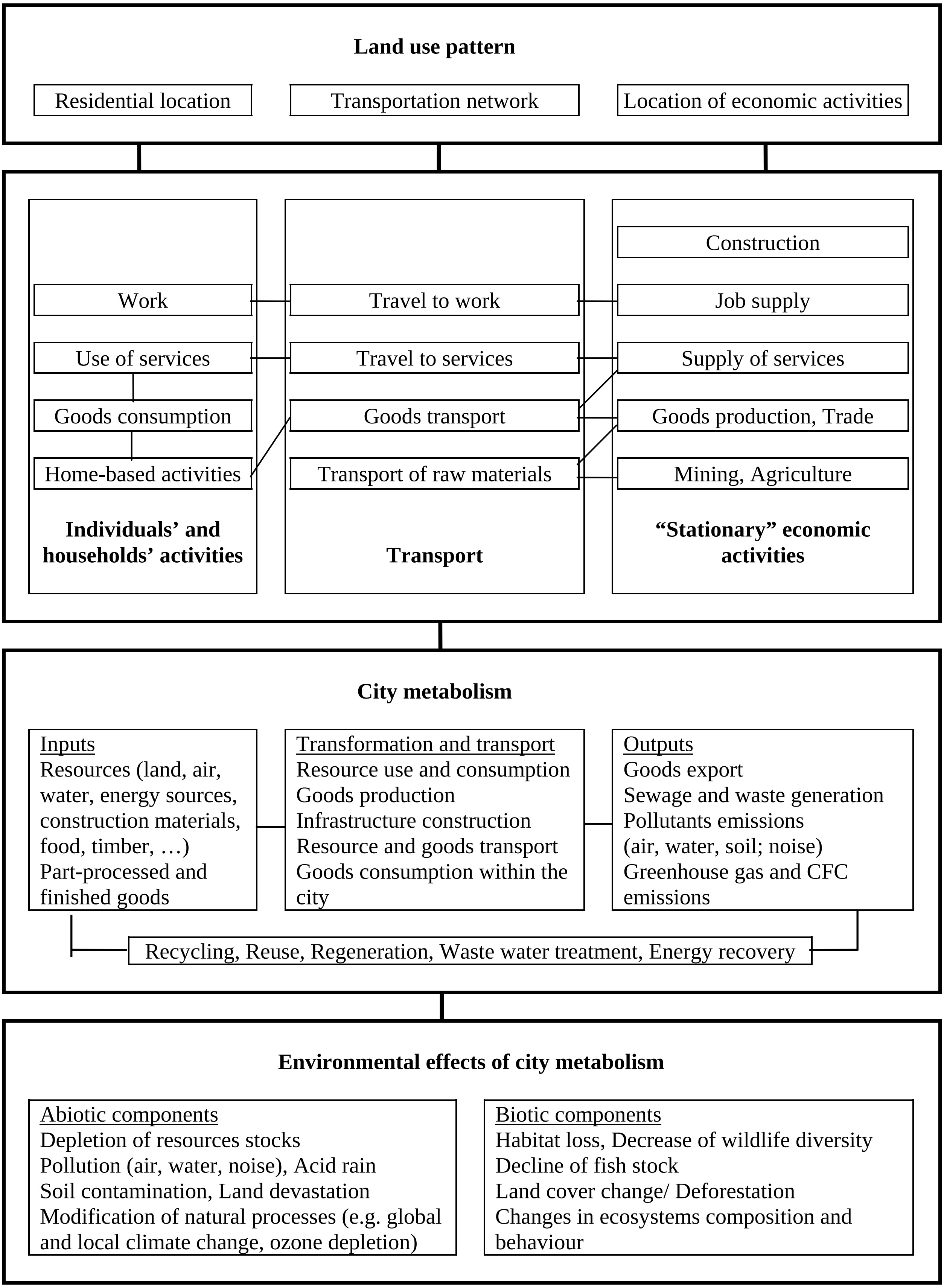


Figure A-4. Human activities, land use, city metabolism: Components and environmental impacts.



A.3.1 Human sub-system

The components of the human subsystem are

- Subjects (individuals, households, firms, scientific institutions, and political and similar organisations)
- Subjects' characteristics
- Subjects activities
- Outputs of production processes: infrastructure, consumption goods and services.

Human sub-system dynamics is described by interrelated processes: demographic, social, economic, political and physical.

Quality of life is an ultimate indicator of performance of combined socio-economic and environmental sub-systems, as refers to humans. Quality of life refers to all aspects of people's activities, their work, leisure, services. It is influenced by the following factors:

- Population characteristics (employment status, health, income, education level, etc.)
- Quality, availability of and accessibility to goods and services.
- Living and working conditions, including climate characteristics and quality of the environment.

Accordingly, sustainability indicators can be classified as in Table A-3. Each main issue in the assessment of the quality of life (health, work, travel, housing, education, leisure, social relations, security/safety, political activities) can be characterised by a set of indicators belonging to groups (a), (b), and (c). Services quality indicators have been put into Group (b), services infrastructure and accessibility in Group (c).

A.3.2 Environmental sub-system and processes of interaction between the human and the environmental sub-system (flows and causal links)

The environmental sub-system is composed of two major parts: biotic and abiotic. The abiotic part is composed of a number of resources, characterised by stock size and /or resources quality. Dynamic changes in the environmental sub-system are of two types: natural phenomena, and processes triggered by socio-economic activities. Sustainability indicators relating to environment can be classified into three groups (Table A-4): state indicators describing the state of the environment; pressure indicators referring to the city metabolism; and policy indicators referring to activities aiming at reducing negative impacts of city metabolism.

Table A-3. Classification and examples of sustainability indicators referring to the quality of life.

Quality of life indicators			
(a) Population and social environment - related	(b) Activities-related	(c) Infrastructure and goods - related	(d) Natural environment-related
Employment status Health Income Crime rate Distribution of values of all sust. ind. by social group, age sex, geographical area.	Working time Safety at work Time spent for travel to work Road accidents Time for leisure Level of public participation in decision making Quality of health service Quality of education	Housing quality Quality of drinking water Car ownership Goods prices structure in relation to income Accessibility to shops and other services.	Drinking and bathing water quality Air quality Noise level Green space area

Table A-4. Classification and examples of sustainability indicators referring to the environment and resources.

State indicators	Pressure indicators	Policy indicators
Water quality Air pollutant concentrations	Pollutant emissions	% of cars with catalytic converters
Resource stocks	Resource use	% of energy produced from renewable sources
	Waste generation	Recycling rate
Area of green land/open space	Area of open land taken for development each year	
	Greenhouse gas emissions Traffic volume	Length of cycling paths built each year

Note: Pressure and response indicators should be evaluated for each sector of economy (including households activities).

Interactions between human and environmental sub-systems are represented on Figure A-3 and Figure A-4, with the city metabolism being the main process responsible for environmental impacts of urban activities.

A.3.3 City metabolism

It has been suggested that one might imagine a city as a living organism, taking substances from the environment, transforming them into products supporting lives of its inhabitants, and expelling by-products back into the environment. Originally, the concept of city metabolism included material and energy flows, but it can be extended into all resource necessary for city existence, including land. City metabolism would be therefore a process involving the following elements:

1. Inputs into the city: resources (land, air, water, energy sources, food, timber, construction materials), part processed and finished goods
2. Transformation and transport: resource use and consumption, goods production, infrastructure construction, resource and goods transport, goods consumption within the city
3. Outputs: goods export, sewage and waste generation, pollutants emission (air, water, soil; noise), greenhouse gas and CFC emissions, derelict land
4. Outputs-Inputs loop: re-cycling and re-use, regeneration, waste water treatment, energy recovery

All these four stages involve transport. From the point of view of the environmental sustainability distance should be reduced, but this reduction might undercut the economic sustainability.

Metabolism concept assumes that a living organism take substances from and expel to the environment, without affecting significantly the environment. As presented at Figure A-3 it is not the case for a contemporary city, but certainly it should be the aim for future. We should aim at minimising changes in the environment (preventing natural disasters is an exception) and replace two-way relationship between human and environmental systems into a one-way one, in the sense that man depends on the environment (this is inevitable) but does not influence it in a significant way. The question is if we can achieve it. It is rather hard to imagine: it would mean stopping cities' (and other settlements') expansion, stopping extraction of non-renewable resources, stopping new transport infrastructures.

Current situation might be imagined as an "ill", badly functioning metabolism, with toxic substances poisoning the city organism. City activities' impacts on the environment influence negatively also the city itself (e.g. air pollution impact on human health, crops, infrastructure). Shortly, at the moment man dominates the environment and recovery from "ill metabolism" will be painful, if at all successful.

A.3.4 Geographical scale

An important issue in modelling city sustainability is the geographical scale of influences and impacts (Figure A-5). City footprints extends all over the world, both for inputs (mainly through natural resources and goods), as well as outputs (e.g. transboundary pollution).

A.4 <u>Approaches to modelling city sustainability</u>

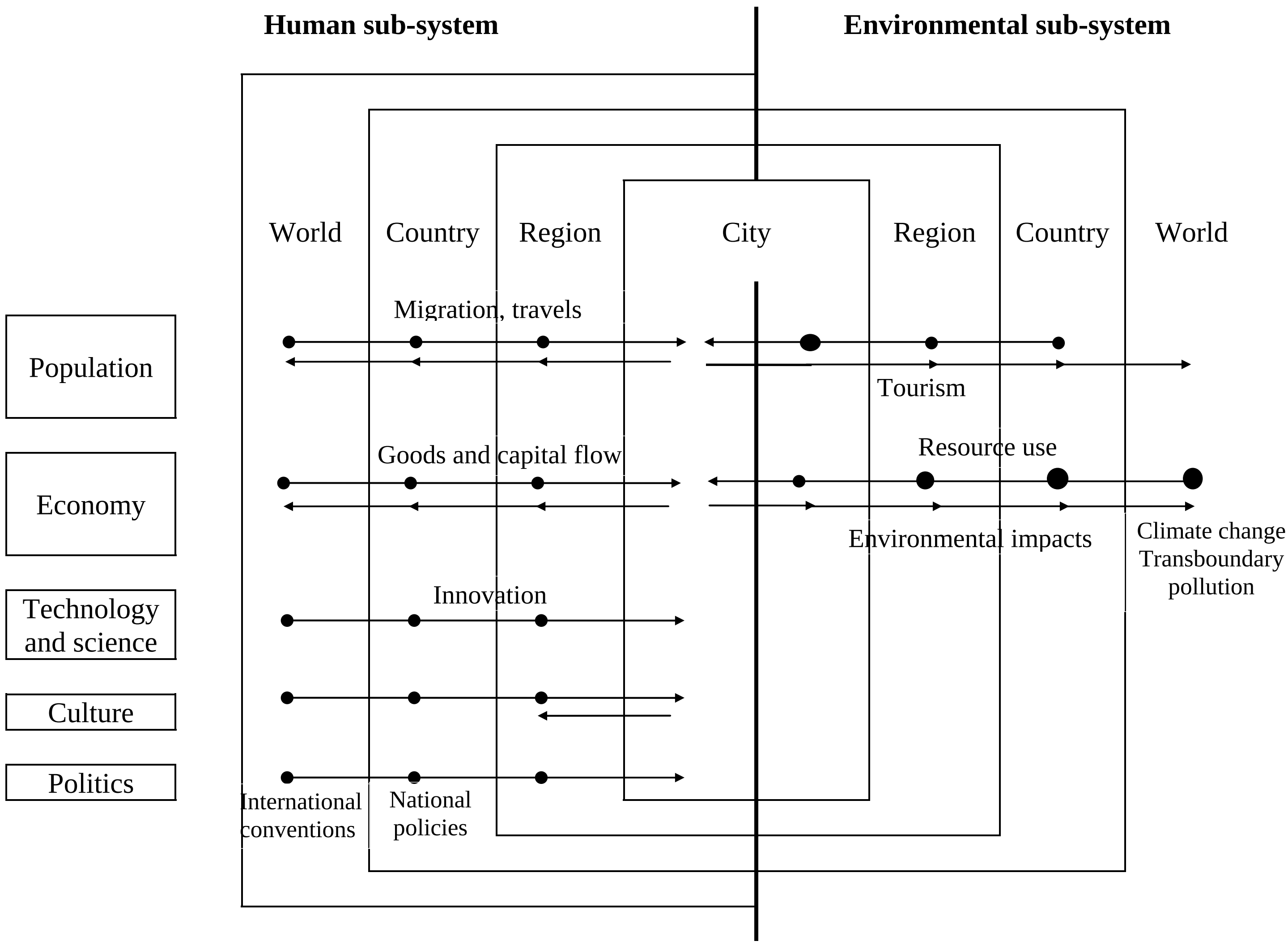
There is a number of possible approaches to sustainability modelling and the choice of approach to be adopted depends on the aims of the model.

Possible approaches to sustainability modelling include:

1. Cross-sector approach, based on the sustainability goal (columns in Table A-5)
    a) Resource-oriented

       One tracks flows of a selected resource, e.g. use of water or energy by various economic sectors (including households), in order to evaluate total current use of the resource and predict its future use. One evaluates existing stocks and compares supply with demand.

Figure A-5. Geographical scale of influences and impacts relevant to city sustainability.



(b) Pollution (or other harmful side effects) - oriented

One selects a particular environmental sector, e.g. water or air, and tracks down all sources of pollutants contributing to the decrease of its quality or performance. To do so one has to approach specific pollutants or groups of pollutants (e.g. in modelling ozone concentrations in the troposphere it is important to prepare an emission inventory of volatile organic compounds).

2. Based on activities (rows of Table A-5)

One selects a particular human activity and looks at all possible aspects of its influence on sustainability.

The approach based on activities is the one to be chosen by practitioners. For example, it can be used to optimise a policy mix to adopt in a given sector in order to promote sustainability. The approach based on sustainability goals is adopted by researchers, e.g. when predicting global CO_2 emissions, or forecasting for how long known oil resources will last.

Table A-5. Approaches to sustainability modelling (see an explanation in the text above).

Impacts / Activities	Resource use / consumption			Pollution			Quality of life		
	Water	Energy	…	Water	Air	…	(1)	(2)	…
…									
Mining industry									
Printing industry									
…									
Transport									
Health service									
…									

A.5 <u>Bibliography</u>

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B. Existing operational models for demography, land-use, transport and air pollution modelling.

Based on the conceptual model presented in Part A one can identify the following groups of existing models that should be considered for inclusion in the integrated urban sustainability model:

(i) Demographic models.

(ii)Economic models (e.g. input-output models of the economy, "green accounting" natural resources).

(iii)Land use and transport models.

(iv)Environmental models concerning interaction between selected human activities and the environment.

(v)Models of various processes in the natural environment involving inanimate nature, e.g. atmospheric processes.

(vi)Ecological models concerning fauna and flora.

(vii)Epidemiological models concerning human response to pollutants.

To review operational models existing in all above groups would be a tremendous task. In this report we have focused on transport and air pollution models. For both, we have given fundamental information about existing models and their classification and we have collected information on specific models in tabular form. The tables gives such information as:

(i) Model's name, author and owner, platform, operating system, programming language;

(ii) Purpose and brief description;

(iii) Input and output variables;

(iv) Availability of the model; References and/or the contact address.

Extensive bibliographic lists are also included.

Similar tables and bibliographic lists have been given for land use models, integrated land-use/transport models and comprehensive urban models, although the information is less detailed. Demographic models have been covered only very selectively.

Within all considered modelling sectors, except demographic, a number of models performing similar functions have been identified. It has not been possible to point to a single best model: the choice depends on such factors as modelling aims, availability of funding and computing resources, and compatibility other modelling software.

B.1 Demographic models

Urban sustainability modelling requires information on population changes, including changes in spatial distribution, and changes of demographic and social structure. Such information can be provided by multiregional multistate models. Modelling is performed in discrete time intervals *u* (usually in one year or five year periods), and takes into account births, deaths, and inward and outward migrations. Population is grouped into cohorts, which are groups of people born in the same time period of duration *u*. Population $P^{\cdot i}_{ag}(t+u)$ of the region *i*, sex *g* (*g* = male or female), in the cohort *a* at time $t + u$ at the end of the projection time interval is calculated using the following set of equations (Rees 1989):

$$P^{\cdot i}_{ag}(t+u) = \Sigma_j S^{ji}_{ag} P^{j\cdot}_{ag}(t),\ a \geq 1,$$
$$P^{\cdot i}_{0g}(t+u) = \Sigma_j S^{ji}_{0g} B^{j}_{g}\ ,$$

where $P^{j\cdot}_{ag}(t)$ are cohort populations at time t at the start of the projection time interval, B^{j}_{g} are the births in region *i* of gender *g* and S^{ji}_{ag} are the transition rates at which persons in cohort *a*, gender *g*, region *i* at the start of the time interval survive in region *j* at the end of the time interval. The transition rates expres the probability of migration and survival if $j \neq i$, or the probability of staying in the same region and survival, if $j = i$.

In order to calculate the transition rates S^{ji}_{ag}, population $P^{\cdot i}_{ag}(t+u)$ may be expressed using mortality rates d^{i}_{ag} and migration rates m^{ij}_{ag}:

$$P^{\cdot i}_{ag}(t+u) = P^{\cdot i}_{ag}(t) - d^{i}_{ag} PAR^{i}_{ag} - \Sigma_{j\neq i} m^{ij}_{ag} PAR^{i}_{ag} + \Sigma_{j\neq i} m^{ji}_{ag} PAR^{i}_{ag}$$

where the third term describes the outward migrations, the last one describes the inward migrations, and PAR^{i}_{ag} is the population at risk, assumed to be the average population during the time interval:

$$PAR^{i}_{ag} = 0.5\,(P^{\,i.}_{ag}(t) + P^{\,.i}_{ag}\,(t+u)).$$

Births $B^{\,j}_{g}$ are estimated by applying fertility rates $f^{\,i}_{a}$ to the population and risks:

$$B^{\,j}_{g} = x_{g}\,\Sigma_{\mathrm{a}}\,f^{\,i}_{a}\,PAR^{i}_{ag}$$

where x_g give the proportion of births of gender g.

When modelling the population of a small area, for example the population of a city, the main difficulty lies in estimating values of migration, fertility and mortality rates for the regions (wards), because of the relatively small number of events involved. Usually, five-year age groups must be used to obtain reliable estimates. Modelling integral migrations is particularly difficult. Rees (1994a, 1994b) has approached the problem by using a spatial interaction model for projecting aggregated internal migrations, and then applying age profiles (uniform across all wards) to the obtained flows.

Table B-1 lists examples of population models. The West-Yorkshire population model is recommended as a prototype of an urban scale model.

Table B-1. Population models.

Model Name/Author/Owner/ Platform/Language/Type	**Purpose/Brief description** **Inputs and Outputs**	**References** **Comments**
West-Yorkshire Phil Rees, School of Geography, University of Leeds/GMAP/West Yorkshire authorities PC/DOS/FORTRAN Hybrid model: multiregional cohort survival model combined with spatial interaction models.	Forecasting the population of urban communities within the cities of West Yorkshire in fine time, age and gender detail; Estimating small-area populations between censuses; Developing scenarios of demographic change and housing development. Inputs ***Base population data*:** *Census data* on population by ward and sex in one-year age groups. *Inter-censal data*: Electoral register data on ward totals of the population aged 18 and over; Ward total population below electoral age; District population by single age and gender (estimate produced by the district authorities or by the OPCS); Mortality, fertility, emigration, immigration - ward totals and national age-specific rates. *Population scenarios*: Assumptions about the future development of the population components. ***Migration data:*** Census data on migration flows between wards and districts. National Health Service Central Register data on flows between Family Health Service Authority areas. Internal migration rates by age and gender. Migration scenarios. ***Data for spatial interaction models:*** Within-district migration rate per ward (from the SMS of the Census). Distances between the wards. Census data on observed total in-migration to the destination ward (for fitting distance friction parameter). The 1981 and 1991 Census data on ward total populations (for evaluating wards attractiveness factors). Census data on number of people per household in wards. Projected number of new housing units per ward per year. Projected number of demolished housing units per ward per year. Propensities of populations in wards to migrate Outputs Projected population by ward and sex in one-year age groups (up to 2015).	Rees (1994) The model has been applied to Bradford, Calderdale, Kirklees, Leeds and Wakefield.

Table B-1 (cont.). Population models.

Model Name/Author/Owner Platform/Language/Type	**Purpose/Brief description** **Inputs and Outputs**	**References** **Comments**
Office of Population and Censuses (OPCS) forecasts, Welsh Office forecasts; and General Register Office for Scotland forecasts	Official subnational population projections for England, Wales and Scotland OPCS carries out projections for 108 local areas in England. Welsh Office produces projections for the eight counties of Wales. General Register Office for Scotland produces projections for the twelve Scottish Regions and Island Areas.	OPCS (1991) General Register Office for Scotland (1991)
Lipro Version 2.0 and 3.0 NIDI (Netherlands Interdisciplinary Demographic Institute) PC/DOS Multistate, multiregional population model.	Multidimensional demographic projection and analysis: multiregional models; marital-status models; household-position models.	van Imhoff (1994) (includes a floppy disk with software) NIDI P.O. Box 11650 2502 AR The Hague The Netherlands

B.1.1 Bibliography of demographic models

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B.2 Urban land use models. Integrated land use/transport models. Comprehensive urban models.

Urban land use models aim to model the location of residential and/or industrial activities, based on the information on land availability, prices and accessibility. Accessibility, expressed in terms of transport costs, is usually exogenous to the model. In the integrated land-use/ transport models, the information on the location of activities obtained from the land-use sub-model is used to produce data on the demand for transport, needed by the transport sub-model. The role of the transport sub-model is to evaluate the performance of the transportation system, and to calculate transport costs, which are fed back to the land-use submodel.

Land-use and transport sub-models are the main components of all comprehensive urban models. Differences between various comprehensive urban models lie in the range of urban sub-systems included, underlying modelling theories and computing techniques. In the review of operational urban models Wegener (1994) lists the following sub-systems that can be included in urban models: land use, housing, workplaces, population, employment, travel, goods transport, transport network. In composite models various sub-systems are modeled in separate, loosely coupled sub-models, while in unified models there is a strong integration of all the elements.

A comparison of a number of land-use/transport models was performed in 1981-1991 by the International Study Group on Land-Use/Transport Interaction (ISGLUTI), that included eleven teams from eight countries (see for example Webster and Paulley 1990).

The literature review has shown that there are a lot of theoretical formulations of urban models and their implementations in single case studies, but it is difficult to find generic commercially available software. I have managed to identify only two commercially available comprehensive urban models: MEPLAN and TRANUS, both originating from the research at the Martin Centre of the University of Cambridge, and both requiring a substantial assistance from the model developers.

Even more importantly, the literature review has shown that while many models are very advanced from the mathematical and computational point of view, the understanding of human behaviour lags behind, which means that models are often based on arbitrary assumptions and not fully justified parametres. This is certainly one of the reasons for which land-use/transport models and urban models has not spread into the urban planning practice, but remained the domain of researchers.

Table B-2. Urban land-use models.

Model Name/Author/Owner/Type	**Purpose/Brief description** **Inputs and Outputs**	**References** **Comments**
DELTA David Simmonds Consultancy, Cambridge A dynamic land use model	Purpose: Estimation of the change in land use in response to changing accessibility and transport-related environmental effects. DELTA comprises following sub-models: Development (of building stock), Transition/growth (demographic and economic changes), Location (of households and business), Employment (changes in demand for labour and in employment status of households), Area quality. Inputs: Base-year planning data (such as: households, population, jobs, retail and residential floorspace by zone). Exogenous growth rates. Accessibility and environmental outputs calculated by a transport model. Outputs: Planning data for the next year.	David Simmonds Consultancy (1997) Applications developed for clients by David Simmonds Consultancy, 10 Jesus Lane, Cambridge CB5 8BA, UK Tel 44 1223 316098 Fax 44 1223 313893
IMREL C. Anderstig, L.-G. Mattson, Stockholm A static land use model	Purpose: Estimation of the change in the land use in response to changing accessibility Inputs: Travel characteristics by scenario, from EMME/2 transport model. Total population and total employment zonal bounds. Outputs: Residential and employment locations (no disaggregation).	Anderstig, and Mattson (1991)
SALOC L. Lundquist, Royal Institute of Technology, Stockholm	Optimising model Allocates a single category of population to the zones basing on employment location and travel characteristics to satisfy goals of accessibility, neighbourhood size, housing density. Maps out a range of possible locations.	Webster and Paulley (1990)
AMERSFOORT Utrecht	Uses a Lowry-type mechanism to allocate homes to different zones in relation to their accessibility to employment. Population disaggregated into three income groups.	Webster and Paulley (1990)
DRAM/EMPAL (land use components of ITLUP) S.H. Putman Simple spatial interaction models	Calculation of residential/employment location basing on land availability and accessibility to employment/population. Input: Regional forecasts of total employment, population and activity rates.	Putman (1995),Putman (1983) Putman (1991) Applications developed for clients by S.H. Putman Associates

Table B-2 (cont.). Land-use models

Model Name/Author/Owner/Type	**Purpose/Brief description** **Inputs and Outputs**	**References** **Comments**
CUFM California Urban Futures Model J. Landis, Univ.of California, Berkeley successor of BASS	A disaggregated model of housing development; Utilizes GIS technology	Landis (1993)
POLIS Projective Optimization Land Use Information System P. Prastacos, San Francisco	Mathematical programming formulation of the Lowry Model, based on random utility	Prastacos (1986)
HUDS Harvard Urban Development Simulation J.F. Kain, W.C.Apgar, Cambridge, MA	Microsimulation model	Kain and Apgar (1985)
CPHMM Chicago Protoype Housing Market Model A. Anas, State University of New York, Buffalo	Dynamic microeconomic equilibrium model of urban housing market	Anas and Arnott (1991)
OSAKA K. Amano, University of Kyoto	Lowry-type model: Allocates population according to basic employment, and then service employment according to population location, using linear regression.	Webster and Paulley (1990)
RURBAN K. Miyamoto, Yokohama	Equilibrium market model	Miyamoto and Kitazume. (1989)

Table B-3. Land-use/transport models and comprehensive urban models

Model Name/Author/Owner/Type	**Purpose/Brief description** **Inputs and Outputs**	**References** **Comments**
LILT (Leeds Integrated Land-Use Transport Model) R.L. Mackett (model developed at the University of Leeds, further applications at the University College, London) A complex spatial interaction model	Forecasting land use. Integrates a Lowry-type land use model with a four-stage transport model. Exogenous forecasts of change in population, jobs and housing are allocated to zones on the basis of accessibility and attractivity using entropy-maximizing functions. Employment is disaggregated into 12 sectors in 3 categories; population is classified into three socio-economic groups. The model can handle demolition, overcrowding, vacancies, mismatch in employment. Car ownership is predicted within the model. Modal split includes walking.	Mackett (1983) Mackett (1984) Mackett (1990b) Mackett (1991) Mackett (1993) Wegener *et al* (1991)
MEPLAN M. Echenique Martin Centre,Cambridge TRANUS de la Barra, Caracas (formerly Cambridge) Comprehensive spatial-economic models	Analysis of land-use and transport policies. Integrates an input-output model, a random utility model of location choice and a rent-density function based on the Alonso model. Calculates simultaneous equilibrium of all processes. MEPLAN and TRANUS differ mainly in details of their transport models Inputs: Location of activities in a previous time period, levels of employment in the basic sector transport costs for the previous time period; parameters for transforming functional flows into trips; network data; data for energy, economic and financial evaluation Outputs: Quantity and location of activities Use and rent of land Flow of labour from home to workplaces Consumption of services by households Flow of goods (only in some applications) Fuel consumption,; Socio-economic and financial indicators.	MEPLAN: Echenique (1994) Hunt and Simmonds (1993) Echenique *et al* (1990) Echenique (1983) Wegener *et al* (1991) Mackett (1993) Williams (1994) Available commercially from Marcial Echenique & Partners. Dominates in Europe. TRANUS: de la Barra (1989) de la Barra and Rickaby (1992) Rickaby (1991) Rickaby *et al* (1992) Available commercially from Modelistica. Dominates in Central and Southern America.

Table B-3 (cont.). Land-use/transport models and comprehensive urban models.

Model Name/Author/Owner/Type	**Purpose/Brief description** **Inputs and Outputs**	**References** **Comments**
IRPUD M. Wegener, Institute for Spatial Planning, University of Dortmund Dynamic, activity-based model	Purpose: Research on relationships between employment, population and housing, including the influence of transport. Different processes are modeled by independent sub-models. Locational decisions based on accessibility, attractiveness and price of the land. Transport model includes disaggregation into purposes, modes and income groups. Car ownership predicted using household budget. Inputs: Regional employment and population forecasts, transport policies, housing policies, stock of non-residential buildings, land use controls Outputs: Population forecasts by zone; Jobs and households location; Residential and non-residential construction; Work trips	Wegener (1982a) Wegener (1982b) Wegener (1985) Wegener *et al* (1991) Mackett (1993) IRPUD has been applied only to Dortmund and is not available as a software package.
MASTER R.L. Mackett Dynamic, activity-based model, using a micro-simulation technique	MASTER - Micro-Analytical Simulation of Transport, Employment and Residence.	Mackett (1985) Mackett (1990a) Mackett (1990c)
D. Boyce, Univ. of Illinois, Chicago	Combined models of location and travel choice	Boyce (1990) Boyce *et al* (1992)
T.J. Kim , J.H. Rhoy, Univ. of Illinois, Chicago	Combined models of transportation and location incorporating goods movements	Kim (1989) Rho and Kim (1989)
NYSIM (New York Area Simulation Model) A. Anas, State Univ. of New York, Buffalo	Static microeconomic equilibrium model	Anas (1992)
METROSIM, A. Anas		Anas (1994)

Table B-3 (cont.). Land-use/transport models and comprehensive urban models.

Model Name/Author/Owner	**Purpose/Brief description** **Inputs and Outputs**	**References** **Comments**
5-Stage Land-Use Transport Model F.J. Martinez, Santiago de Chile		Martinez (1992a) Martinez (1992b)
CALUTAS Computer-Aided Land-use Transport Analysis System H. Nakamura, K. Miyamoto, Tokyo	Basic industries located exogenously. Other workplaces allocated on the basis of accessibility to suppliers and markets and attractiveness of the area. Population allocated on the basis of accessibility, land price, and other attributes. Conventional transport model predicts travel times, costs, location utility and land prices.	Nakamura *et al* (1983) Mackett (1991b)
TOPAZ (Technique for Optimal Placement of Activities in Zones) Brotchie *et al*., Commonwealth Scientific and Industrial Research Organization, Melbourne	An optimising model for urban planning Allocates employment and housing to minimize a weighted sum of the costs of urban infrastructure and transport costs.	Brotchie *et al* (1980)

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B.3

Transport models

Transport models aim to simulate and forecast changes in transport demand (e.g. resulting from changed locational patterns or socio-demographic changes) and the impact of changes in transport demand and supply (e.g provision of new roads, changes in costs) on the traffic patterns and the level of service.

The modelled area is divided into zones. The demand modelling stage leads to the evaluation of the trip matrix ***T*** (also called O-D matrix), which gives the number of trips between pairs of zones, i.e. between origins and destinations (Table B-4). In further steps the trips are assigned to the road network.

Zones To / From	1	…	j	…	n	Trip productions $O_i = \Sigma_j T_{ij}$
1	T_{11}	…	T_{1j}	…	T_{1n}	O_1
i	T_{i1}	…	T_{ij}	…	T_{in}	O_i
n	T_{n1}	…	T_{nj}	…	T_{nn}	O_n
Trip attractions $D_j = \Sigma_i T_{ij}$	D_1		D_j		D_n	Total trips $T=\Sigma_{ij}T_{ij}$

Table B-4 . Origin-destination matrix.

One possible classification groups transport models according to the level of detail of network description. The main three groups are: strategic models, tactical models and micro models. Micro models are used to simulate traffic on a single junction. On the other end, strategic models are constructed for large geographical areas, with networks covering up to thousands of junctions. They usually include the demand modelling stage (trip origins and choice of destination and mode). Some strategic models have an extended demand modelling part (e.g. frequency of journey and time of day choice), in which case the transport supply part is usually simplified: the number of zones is reduced and there might be no conventional network at all. Tactical models assume that the demand (O-D matrix) is known and focus on the route choice and junction simulation for relatively smaller networks. We will consider only tactical and strategic models, because they are more important for sustainability modelling.

B.3.1 Strategic models

A conventional strategic transport model comprise four stages (Figure B-1). The trip generation stage aims to evaluate number of trips originating from and ending in each zone (O_i and D_j in Table B-4). In the distribution stage trips generated from a zone are allocated to various destination zones, thus giving components T_{ij} of the trip matrix. The modal split stage allocates trips *Tij* to different modes of transport. Finally, in the assignment stage trips are loaded onto the links of the private and/or public transport network. Various modifications of this general scheme are possible, for example the modal split and trip distribution stage might come in the reversed order, or all first three stages might be combined into a single step.

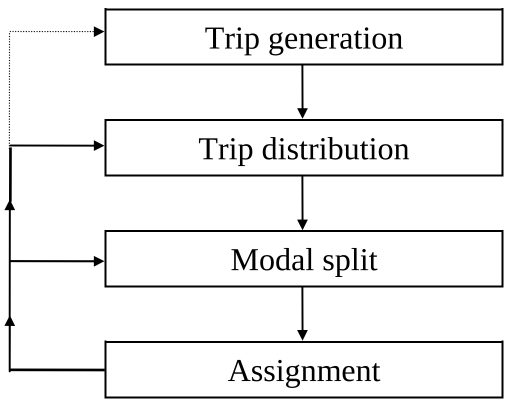

Figure B-1. A classic four-stage transport model.

In the **trip generation** stage, trips are often divided into several categories, and then each category is modeled separately. Possible classifications of passenger trips include:

- By Time of Day: a.m. peak, p.m. peak, and off-peak trips;

- By Trip Origin: home-based trips and non-home-based trips (non-home-based trips are mostly made from work for business purposes).
- By Trip Purpose: trips to work, education trips, trips to shopping and services, and social and recreational trips.

Factors influencing the demand and taken into account in the generation stage might include:

- Number of households in each zone and their socio-economic characteristics (car ownership or availability, income, household size and age structure, number of persons employed), needed to model trip productions;
- Number of jobs, school places or shopping floorspace in each zone, needed to model trip attractions.

Information about the number of trips made by each household category is usually collected through home interview surveys.

Modelling freight trip productions and attractions must be done separately for each product type, considering such factors as: number of employees per zone, number of sales, floorspace, season etc.

The main techniques used in the trip generation stage are:

(i) Multiple regression analysis, where socio-demographic and economic variables are used as explanatory variables. Modelling may be zone-based or household-based;

(ii)Growth factor method;

(iii)For the freight trip generation modelling, macroeconomic models (e.g. an input-output model) might be used.

In the growth-factor technique, the number of trips in the future year (O_i and D_j) is obtained by multiplying the productions (o_i) and attractions (d_j) in the base year by appropriate factors (F^o_i and F^d_j)that might depend for example on household growth for origin trip ends and on employment growth for destination trip ends:

$$O_i = F^o_i \, o_i$$

$$D_j = F^d_j \, d_j \, .$$

The **trip distribution model** aims to evaluate number of trips T_{ij} originating in the zone i and ending in the zone j. The main techniques used in the distribution modelling are growth factor methods and gravity models. All growth factor methods start with the trip matrix (t_{ij}) for a base year, and there are three variants for the matrix factorisation. In the most simple variant on assumes a uniform growth factor F for all the trips:

$$T_{ij} = F\, t_{ij}\,.$$

In the singly constrained growth factor methods one uses origin- or destination-specific growth factors, depending on the information availability:

$$T_{ij} = F^o{}_i\, t_{ij}\,,$$

or

$$T_{ij} = F^d{}_j\, t_{ij}\,.$$

Finally, the doubly constrained models are used when the future trip matrix row and column totals O_i and D_i are known from the trip generation stage. Growth factors $F_{ij} = a_i b_j$ for each matrix element are then found numerically using an iterative process to satisfy the conditions:

$$\Sigma_j\, a_i\, b_j\, t_{ij} = O_i$$

and

$$\Sigma_i\, a_i\, b_j\, t_{ij} = D_j\,.$$

Another popular technique used in distribution modelling are gravity models. Originally, they have been constructed as an analogy to the gravitation law formulated by Newton and referring to the attraction force F between two bodies of masses m_i and m_j, in the distance d_{ij} from each other:

$$F = G\frac{m_i m_j}{d_{ij}^2}\,,$$

where G is a gravitational constant. In transport applications, masses might be replaced for example by zone populations or employment figures, and d_{ij} would denote the distance between two zones. The gravity model was later generalised to allow for other then inverse squared power functional dependence on the distance. Also, the generalised travel cost c_{ij} between the zones is used instead of the distance. The generalised gravity distribution model has the form:

$$T_{ij} = \alpha O_i D_j f(c_{ij})$$

Most often used forms of the function $f(c_{ij})$ are an exponential function ($f(c_{ij}) = \exp(-\beta c_{ij})$) and a power function ($f(c_{ij}) = c_{ij}^{-k}$). Models based on these functions have been derived by Wilson using an entropy-maximising method (Wilson 1970).

The generalised travel cost is a linear combination of monetary costs and the cost of time spent traveling. The value of time might depend on the trip stage, for example for trips by public transport it might be different for the walking time, the waiting time and the in-vehicle time. Also, the value of time might be different for business trips than for private trips. For car trips the generalised travel cost might be defined as:

$$c_{ij} = a_1 t_{ij} + a_2 d_{ij} + c_j ,$$

where t_{ij} is the travel time (including parking time), a_1 is the monetary value of a unit time, d_{ij} is the travel distance, used to estimate operating costs, a_2 is a cost of traveling a unit distance, and c_j is equal to the car parking charges in the zone j.

The **Modal split** stage aims to estimate the percentage of trips made by each transport mode. As noted above, the modal split is often modelled simultaneously with trip distribution. One might then use again the entropy maximizing approach, with generalized travel costs c_{ij}^k now depending on the mode. This would lead to the following proportionality relation for the number of trips by the mode k:

$$T_{ij}^k \propto \frac{\exp(-\lambda c_{ij}^k)}{\sum_k \exp(-\lambda c_{ij}^k)} .$$

The same functional form (a logit model) is obtained from the **discrete choice modelling** approach, where modelling is performed not on the zone level, but on the household or individual level. In these models the probability that an individual *s* will travel by the mode *k* is given by the equation:

$$P_{sk} = \frac{\exp(\beta\ U^{sk})}{\sum_k \exp(\beta U^{sk})},$$

where U^{sk} is a utility function depending (usually linearly) on the characteristics of the mode k and on the socio-economic characteristics of the individual *s*.

An **assignment model** aims to evaluate the traffic volume on each link of the road network for a given trip matrix, assuming that each driver would follow the least generalised cost path available. In strategic models this stage is relatively simple, and usually does not include modelling of turning flows at junctions that is present in tactical models. Calculations of travel time for each link is based on fixed speed-flow functions, that ignore how many cars are turning left, right, or if there is an opposing traffic. However, the strategic models have the advantage of having a feedback mechanism from the assignment stage to the previous stages, thus allowing for modelling impact of traffic patterns on the O-D matrix.

There are several possible algorithms used for traffic assignment. The simplest one is the “all-or-nothing” technique, where all trips between two zones are assigned to a single minimum cost route. Here, the cost of each route is fixed and does not depend on the traffic flow. This method would be appropriate only for uncongested networks. In the congested networks one has to use a capacity restraint model, in which the cost of travel on a link is a function of flow. Trips between two zones are assigned to several possible routes in such a way, that the resulting travel costs on each used route are the same and minimum, while all other routes have greater or equal costs. The above rule is known as Wardrop’s equilibrium principle.

In strategic models that do not include conventional networks the route choice stage is limited (e.g. for each urban zone trips might be split into radial inward, radial outward and orbital).

B.3.2 Tactical models

Tactical models concentrate on the assignment stage with a fixed trip matrix on input, i.e. they assume that changes in the network do not influence the matrix. The O-D matrix, is usually expressed in terms of passenger car units (PCU). PCU is defined as equal one for cars and light duty vehicles, 0.5 for motorcycles, and 2 for buses and heavy duty vehicles. Unlike the strategic models, tactical models do not assume that the speed-flow curve is fixed for each link. Instead, they include sophisticated simulation sub-models, with a very detailed representation of the road network, which allows travel times on each path to be related to the delays occurring at the junctions. The assignment and the simulation stage of a tactical model are run iteratively, i.e. the demand flows generated by the assignment sub-model are fed into the simulation sub-model that calculates the delays occurring at junctions, taking into account junction characteristics and the currently assigned flows. The delays will usually be different for each turning movement. The estimated travel times are fed back into the assignment sub-model to calculate new demand flows, etc. The actual flows are obtained when the iterative process converges.

Tactical models have very high requirements for the input data relating to the road network, in particular for the data on the road intersections. Several types of junctions are distinguished, e.g. roundabouts, priority, and signaled junctions, and a different set of parameters must be specified for each junction type. The node, link and turn parameters might include: number of links at the node, number of entry lanes for each link, traffic signals data (number of stages, duration of each stage, turning movements allowed at each stage), minimum gap for give-way turns at priority junctions and roundabouts, free-flow speed on the link, link length, saturation flow for each turn.

Tactical models are extensively used in urban transport planning to predict the impact of traffic management schemes on traffic flows in the network. For example, they can be used to evaluate the impact of the introduction of bus-only lanes, changes in junction design, pedestranisation schemes etc. While strategic models are important for sustainability modelling to estimate changes in traffic volumes resulting from changes in demand, tactical models are needed for more precise modelling of traffic distribution on the network, which is important for modelling urban air quality.

B.3.3 Dynamic microsymulation models

The above presented models can be classified as static models describing what happens in the equilibrium conditions. A new class of models has emerged in the 1980s, that aims to simulate the dynamic effects, i.e. temporal variations of traffic patterns. Some coarse treatment of dynamic effects has been present in some traditional models as well. What is new in dynamic microsimulation models is that they exploit an increased power of computers to perform the simulation of behaviour of individual drivers, with each vehicle being explicitly represented in the model. Vehicles are moved through the network based on car-following, lane changing and gap-acceptance rules. Simulation is performed quasi-continuously, with vehicle positions usually updated every second.

Table B-5. Transport models.

Model Name/Author/Owner/Type Platform/Language	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
START **MVA Consultancy** Strategic, zone-based model	A tool for strategic transport planning used to evaluate impacts of integrated transport strategies	Zonal population forecasts, income growth forecasts; Trip rates per purpose, person type and car ownership; Zonal forecasts of employment, shopping floorspace etc.; Base year trip matrices by purpose, car ownership, mode and time of the day Link capacity (for the main directions of travel); Up to three possible routes between origin and destination with distances traveled on each link; Parking supply Bus service frequency, availability of bus lanes, density of stops, capacity of rail transport Transport service strategy (maintain level or quality of service)	Trip frequencies; Trip matrices by time of day, mode and route; Changes in generalised cost matrices; Net present value of a strategy, present value of finance; Changes in noise levels, CO_2 emissions, accidents and fuel consumption.	Bates *et al* (1991) Roberts and Simmonds (1997) Applications developed for clients by MVA Consultancy, MVA House, Victoria Way, Woking, Surrey GU21 1DD, UK Tel 44 1483 728051 Fax 44 1483 755207
EMME/2 **INRO Consultants Inc.** Coded in FORTRAN 77; Available for PCs (under MS DOS) and workstations (UNIX)	A multi-mode transportation planning system comprising modules for travel demand forecasting (trip distribution) and network analysis (assignment). Designed for interactive-graphic use.	Network data: nodes (co-ordinates), links (length, type, number of lanes, volume/delay function), turns, modes (type, cost and energy coefficients, car speed, transit vehicle capacity, fleet size), transit lines. Origin-destination matrix, or attractions and production vectors and either impedances (e.g. travel times) for pairs of zones or base year O-D matrix.	Origin-destination matrix of the resulting travel times; assigned flows and travel times on links and turns. Boardings and alightings at nodes and transit segments. Tabular and graphic outputs available.	Babin *et al* (1982) INRO Consultants (1991) Available commercially from INRO Consultants Inc., Montreal, Canada.

Table B-5 (cont.). Transport models.

Model Name/Author/Owner/Type Platform/Language	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
ASSIGN Scott Wilson Kirkpatrick and partners **HINET** Transportation Planning Associates **JAM** Wootton Jeffreys & Partners **TRIPS** MVA Systematica	Conventional assignment models used in the appraisal of traffic management schemes TRIPS includes a facility for dynamic modelling, allowing for modelling the changes in flows during the assignment period.	Network data: links characterised by speed/flow relationship; Up to 1000-1500 nodes, some of which may be defined as turn-delay nodes. Demand matrix Bus trips Dynamic modelling in TRIPS requires specification of the type of input flow profile, that gives the proportion of the total demand to be assigned in individual time segments.	Turning volumes at all nodes, traffic flows, delays and queues at turn delay nodes; link flows, speeds and junction delays.	Scott Wilson Kirkpatrick and partners (1986) Transportation Planning Associates (1981) Wootton Jeffreys & Partners (1980), Bishton and Miller (1990) MVA Systematica(1991) MVA Systematica, MVA House, Victoria Way, Woking, Surrey, GU21 1DD, UK. Tel 44 1483 728051 Fax 44 1483 755207 All four models are described in Thomas (1991)
CONTRAM	A time-dependent assignment model aimed to determine changes in the pattern of flows in the network during up to 24 hours	Network data (link based, with three possible link types: signal controlled, give-way and uncontrolled); Demand matrix Bus route data	Total journey time, time spent traveling and delayed, total distance traveled; fuel consumption; average speed and queue time per link	Leonard and Gower (1982) Leonard *et al* (1989) Taylor (1990)

Table B-5 (cont.). Transport models.

Model Name/Author/Owner/Type Platform/Language	**Purpose/ Brief description**	**Inputs**	**Outputs**	**References Comments**
SATURN (Simulation and Assignment of Traffic in Urban Road Environment) Institute for Transport Studies, University of Leeds/ WS Atkins Planning Consultants PC DOS, Sun FORTRAN (Salford compiler)	Combined traffic simulation and assignment for the analysis of traffic management schemes for networks with 100-200 nodes; Traffic assignment for large networks (up to 500 junctions and 6000 links); Simulation of individual junctions. The period modelled may be divided into segments	Origin-destination (O-D) trip matrix for the period of interest, for a very fine zoning system. This matrix may be estimated from traffic counts using ME2 model. Network data (mostly intersection-based): junction type (roundabout, priority junction, traffic signal, Pelican crossing); travel distances and times (or speeds) from the previous junction for each entry arm, number of lanes on each entry arm, the lanes used and the saturation flow for each permitted turn; phase structure of traffic signals: cycle times, offsets, green splits between different turns, etc. Bus route data	Traffic flows on each link; Performance indicators for each intersection: delays for each turn, queue profiles; Network-wide indices (e.g. total vehicle-hours); Travel times for each O-D pair. Fuel consumption and pollutant emissions	Hall *et al* (1980) Van Vliet (1982) Dirck Van Vliet, Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, Uk Tel 44 113 2335338 Fax 44 113 2335334 WS Atkins Planning Consultants, Woodcote Grove, Ashley Road, Epsom, Surrey KT18 5BW Tel 44 372 726 140 Fax 44 372 740055
ME2 (Matrix Estimation from Maximum Entropy) L.G. Willumsen, Leeds/ University College London	Estimation of O-D trip matrix from traffic counts	Traffic counts from a survey. Optional: an old trip matrix or a trip matrix for another period (a.m. peak/p.m. peak)	Origin - destination trip matrix	ME2 is integrated with SATURN as SATME2
POLYDROM (Switzerland)	Supply, demand and assignment modelling. Includes calculation of noise, accidents and pollutant emissions			de Rham (1993) SYSTEM CONSULT Habsurgstr. 12, CH-3006 Bern Tel 41 31 352 03 63 Fax 41 31 351 0908

Table B-5 (cont.). Transport models.

Model Name/Author/Owner/Type Platform/Language	**Purpose/ Brief description**	**Inputs**	**Outputs**	**References Comments**
TRANSYT (UK) **VISEM/VISUM (Germany)** **PHEDRE (France)** **PREDICT** **INTEGRATION**				Robertson (1969) PTV System GmbH, Karlsruhe For references see Watling, D. (1994)
NETSIM (UK) **NEMIS (Italy)** **SIMNET (Germany)** **SITRA-B (UK)** **MICSIM (UK)** **AIMSUN (Spain)** **FLEXSYT (Netherlands)**	Microsimulation models. Detailed modelling of the movement of individual vehicles through the network based on car-following, lane changing and gap acceptance rules.			For references see Watling (1994)
TRAFFICQ (UK)	A less detailed microsimulation model			Logie (1979) MVA Systematica (1987)
DRACULA Model under development by ITS, Leeds PC-based, written in C.	A microscopic model for the dynamic simulation of movements of individual vehicles in the network	Network data: node geometry, type and number of arms, link length, number of lanes, permitted turns; Signal data; Gap-acceptance and car-following parameters; Vehicle/user characteristics (vehicle type, length, max. acceleration and deceleration rates, driver's desired speed and his normal acceleration rate); Demand flow along each fixed route.	Animated graphics representing movements of vehicles within the network (updated every second). Statistical measures of system performance (travel times and distances, average speeds, delays, number of stops, queue lengths etc.).	Liu (1994)

Table B-5 (cont.). Transport models.

Model Name/Author/Owner/Type	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
Metropolis Model under development by de Palma *et al*	Dynamic traffic simulator in which drivers select their route as well as their departure time. May be used to evaluate the impact of traveler information systems.	In addition to input data required for static assignment models (network data, O-D matrices, parameter defining travel costs), METROPOLIS scenario requires data on the desired arrival interval for each user and schedule delay costs.		de Palma *et al* (1995) http://www.ceic.com:8104/
COPERT 90 CORINAIR Working Group on Emissions Factors for Calculating 1990 Emissions from Road Traffic	Calculation of emissions from road traffic. Includes hot emissions, cold-start emissions and evaporative emissions.	Fuel consumption per fuel type and vehicle category; Vehicle park: number of vehicles per vehicle category (passenger cars, light duty vehicles, heavy duty vehicles, two wheelers, off-road vehicles) and age distribution; Driving conditions: annual mileage per vehicle class (hot and cold), annual mileage per road class; and average speed; Emission factors per vehicle class, production year and road class (vehicle speed) Climatic conditions	Annual emissions of NOx, N_2O, SO_x, VOC, CH_4, CO, CO_2, NH_3, particulate matter and lead from all CARINAIR road traffic source categories at all defined territorial units (has been applied to NUTS regions) and road classes.	Samaras *et al* (1991) Eggleston *et al* (1992)
COBA Dept. of Transport, London	Cost-benefit analysis of trunk road schemes			DoT(1989)
URICA2 Dept. of Transport, London	Economic appraisal of urban road schemes			
SURI 8 **S**ATURN TO **UR**ECA **I**NTERFACE **P**ROGRAM WS Atkins Planning Consultants	SURI 8 allows the results from a SATURN 8 assignment run to be prepared for input to URECA2			WS Atkins Planning Consultantsd, Woodcote Grove, Ashley Road, Epsom, Surrey KT18 5BW Tel 44 372 726 140 Fax 44 372 740055

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B.4

Air pollution models

The main types of air pollution models are: stochastic, receptor and dispersion models (Milford and Russel 1993, Zannetti 1993). Stochastic models use statistical methods to describe and forecast temporal changes in air quality. Dispersion or source oriented models aim to evaluate concentrations of pollutants in space from information on emissions, meteorology, topography and atmospheric chemistry. Dispersion models are deterministic models and describe the fate of pollutants on their way between a source and a receptor using mathematical equations. Receptor models use information on measured air pollutant concentrations and possibly on source profiles (the typical composition of emissions from a given source) to apportion contributions from various sources. They usually use statistical methods, without describing actual processes leading to observed concentrations.

Usually, dispersion modelling is more difficult than receptor modelling, mainly because of the high requirements for input data, an incomplete understanding of physical and chemical processes and problems with numerical calculations. However, only dispersion models are suitable for forecasting purposes, while receptor models can be used only to evaluate an existing situation. Receptor models are also not suitable to model secondary pollutants. For example, photochemical models (dispersion model including description of photochemical processes) are the only solution to model concentrations of ozone.

Dispersion models are the most suitable for inclusion into an integrated model of urban sustainability, because they may be used to predict changes in urban air quality in response to changes in emission levels, thus permitting the impact of various policies and scenarios to be evaluated in air quality terms.

There are also models of atmospheric processes referring to scales much larger than urban or regional. They were not included in this review, but might be useful in some sustainability modelling applications. These models include for instance acid rain models, models of processes in the stratosphere (e.g. ozone depletion), and importantly models of global warming (global circulation models).

B.4.1 Dispersion models

Dispersion models have to take into account all atmospheric processes affecting polluting species after an emission from a source (Figure B-1) (Seinfeld 1975). These are: transport of air masses by the wind (advection); diffusion; chemical and photochemical reactions; and physical processes such as dry (gravitational) and wet deposition. These processes take place in the boundary layer, the lower part of the troposphere. The mixing height, above which there is free troposphere, depends on the time of the day, meteorological conditions, and on the latitude, and is from 0.5 to 1.5 km. Diffusion is responsible for mixing of pollutants with the remaining components of the atmosphere, while the wind transports pollutants far away from the source. Typically, pollutants can travel several tens of kilometers within several hours and thousands of kilometers within several days, crossing countries boundaries. During temperature inversion and calm weather conditions, dispersion is greatly reduced and one observes cumulation of pollutants near the sources.

Dispersion of pollutants is also affected by source characteristics. Building high chimneya allows reduction in concentrations near the source, but causes an increase of concentrations at larger distances.

Eulerian models

There are two main types of dispersion models: Eulerian models (McRae *et al* 1982, Russel *et al* 1988, Scheffe and Morris 1993) and Lagrangian models (Derwent and Jenkin 1991, Seinfeld 1975). Eulerian models are based on a fixed co-ordinate system. Changes of concentrations of a pollutant in the point $\bar{x}=(x,y,z)$ at the time t are described by the equation:

$$\frac{\partial c_i(\bar{x},t)}{\partial t} = -\frac{\partial(u_x c_i)}{\partial x} - \frac{\partial(u_y c_i)}{\partial y} - \frac{\partial(u_z c_i)}{\partial z} + \frac{\partial}{\partial x}\left[k_H \frac{\partial c_i}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_H \frac{\partial c_i}{\partial y}\right] + \frac{\partial}{\partial z}\left[k_V \frac{\partial c_i}{\partial z}\right]$$
$$+ R_i(c_1,\ldots,c_n) + S_i(\bar{x},t) + L_i$$

The first three terms in this equation describe the advection; u_x, u_y, u_z are the components of the wind velocity. The three next terms describe the diffusion, k_H and k_V are the

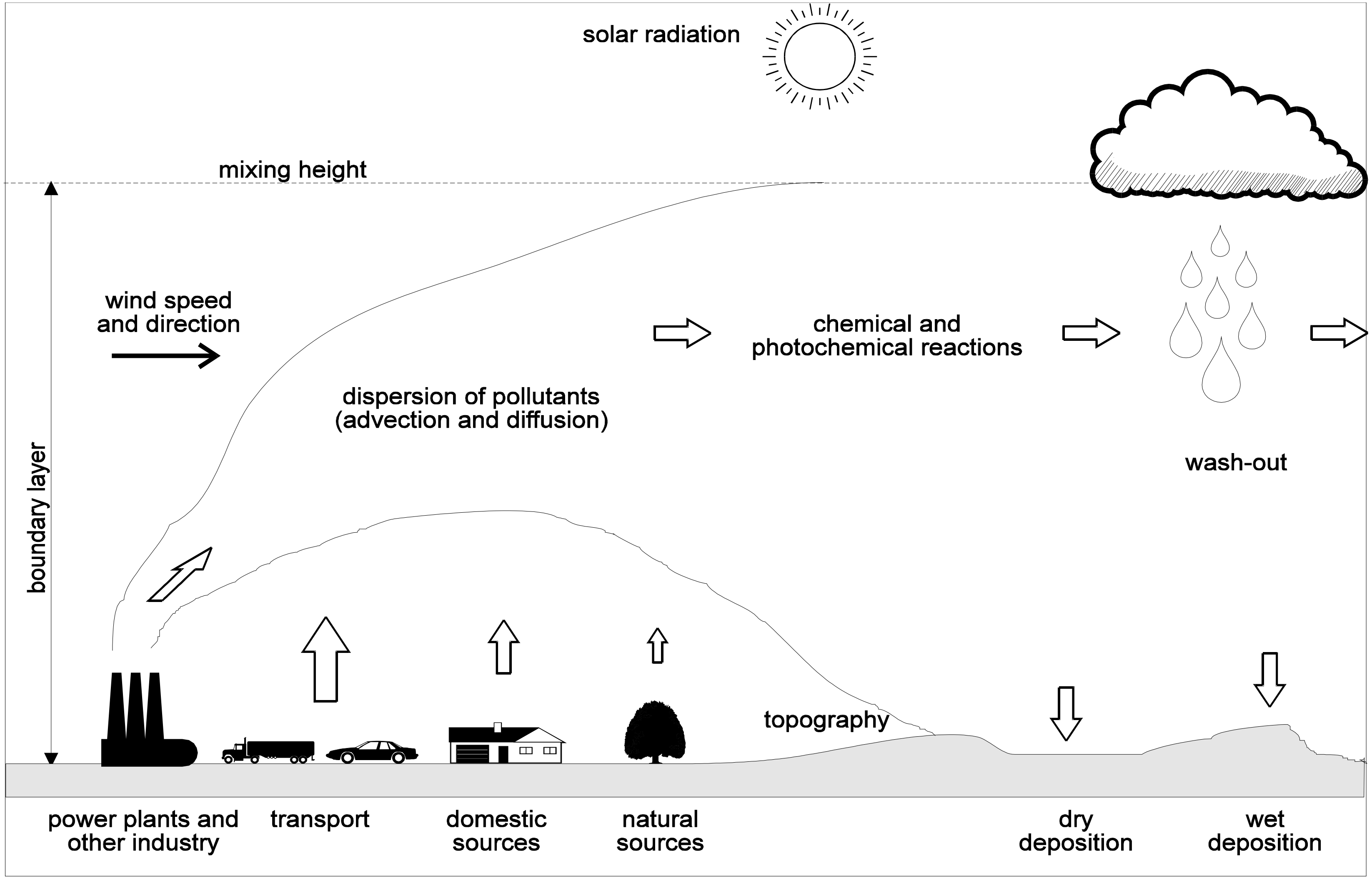

Figure B-2. Main processes responsible for emission and dispersion of pollutants.

horizontal and vertical diffusion coefficients. R_i gives the rate of production (or destruction) of the pollutant in chemical reactions (this rate depends on the concentrations of other species $c_1, \dots, c_n$); S_i is the rate of emission from the sources (time and space dependent). Finally, the last term reflects the rate of removal of the pollutant in the result of the deposition processes. Wind velocity and diffusion coefficients are not constant in space, therefore a meteorological model describing the movements of air masses is often used as a starting point to dispersion modelling, in order to evaluate the wind field and the strength of turbulences.

The above equation, together with the equations describing the kinetics of chemical reactions, is solved numerically to produce values of concentrations of the polluting species on a three-dimensional, usually regular grid. The spatial resolution depends on the scale of the problem; for urban areas it might be for example 1-5 km, for regional models even up to 100 km.

Lagrangian models

Two groups of often used models belong to the Lagrangian model category: trajectory models and particle models. *Trajectory models* describe the behaviour of a parcel of polluted air which has a fixed volume. Pollutant concentrations are expressed in relation to the co-ordinate system moving with the air parcel. This parcel, while traveling according to the wind velocity, picks the pollutants emitted from various sources; at the same time, some pollutants are removed due to deposition. The path followed by an air parcel depends on the meteorological conditions, therefore a number of trajectories have to be investigated in order to analyze changes of pollutant concentrations in a given place. Trajectory models do not describe the horizontal diffusion properly, but lead to simplified equations allowing for better description of chemical processes. For example. the photochemical trajectory model developed by Derwent and Jenkin (1991) includes 384 chemical compounds and 684 chemical reactions.

In *particle models* the emitted pollutants are represented by a very large number of imaginary particles. The movement of each particle is simulated separately, and then averaged concentrations are calculated for each grid point. In each time step particles follow the trajectory defined by the local wind velocity, but a random displacement is also added to account for wind fluctuations and atmospheric diffusion.

Gaussian models

In some situations, concentrations of pollutants may be evaluated using much simpler models than presented above. In particular, Gaussian models are used when the following assumptions hold: (i) the wind field is homogenous (but the wind speed can not be close to zero); (ii) the emission rates, wind velocity and strength of turbulences are constant in time; (iii) pollutants are not subject to chemical reactions and deposition might be neglected.

In the case of a point source (e.g. a factory chimney) of height *h*, with the wind along the x axis and the wind speed *u*, the spatial variation of average pollutant concentrations around the source is expressed by the formula:

$$c(\overline{x}) = \frac{S}{2\pi\delta_y\delta_z u}\exp\left(-\frac{y^2}{2\delta_y^2}\right)\left[\exp\left(-\frac{(z-h)^2}{2\delta_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\delta_z^2}\right)\right],$$

where *S* is the emission rate. Parameters $\delta_y(x)$ and $\delta_z(x)$ denote standard deviations of distribution of pollutants in the plume in the horizontal and vertical directions.

Box model

A box model is the simplest of dispersion models. It is usually used for rough estimations of average concentrations of pollutants in cities. The air in the part of the boundary layer above a city is modelled as a box with a base covering the city area and the height equal to the mixing height. One assumes a homogenous distribution of pollutants in space and an instantaneous mixing. From the equilibrium between the pollutants emitted from urban sources and pollutants carried away from the city by the wind one gets the average concentration of pollutants in the city:

$$c = \frac{S\,l}{u\,h}$$

where S is the emission rate per unit area, l is the length of the box, h is the mixing height (time dependent), and u is the wind speed. Box models are often extended to include chemical transformations and deposition effects.

B.4.2 Receptor models

Receptor models are used when there is not enough information about the sources of pollution, about the transport and transportation processes, and/or about meteorological conditions, but one has data on measured concentrations of a number of pollutants. Information on the composition of emisssions from various sources is also exploited. Reviews of receptor models may be found in (Gordon 1988, Henry *et al* 1984, Hopke 1985, Hopke 1991).

Receptor models are based on the principle of mass conservation that can be expressed by the equation

$$c_{ij} = p_{i1} S_{1j} + p_{i2} S_{2j} + ... + p_{im} S_{mj}$$

where c_{ij} is the concentration of the species i in the sample j. Coefficients p_{ij}, known as source profiles or source fingerprints, describe the composition of each of m sources, i.e. they specify the percentage of the species i in the total mass of emissions from the source j. S_{ij} are the unknown emissions from the source j measured in the sample i, which relative contribution one tries to evaluate. Depending if the source profiles are known or not, one uses respectively either a Chemical Mass Balance model (O'Shea and Sheff 1988, Scheff and Wadden 1993) or a multivariate receptor model based on factor analysis. As mentioned above, receptor models are less useful for sustainability modelling, so they have been excluded from the detail review process.

Table B-6. Air pollution models.

Model Name/Author/Owner Platform/Language	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
The Meteorological Office Box Model (UK)	A box model is the simplest pollutant dispersion model assuming uniform distribution of emissions and perfect mixing.	Box (a city airshed) dimension along the wind direction, height of the mixing layer, wind speed, emission rate per unit area	Average concentration of a pollutant	Broad (1991)
Gaussian dispersion models				
***Breeze models (EPA approved)**, Trinity Consultants Inc., U.S.* PC/DOS/FORTRAN				Trinity Consultants Inc. 12081 N. Central Expwy. Suite 1200 Dallas, Texas 75243 Tel (214) 661-8100
SCREEN2	Predicting non-reactive pollutants concentrations from a single continuous point source	Source description -such as emission rate, stack height, stack gas temperature, stack gas velocity, stack diameter; Terrain information; Receptor locations; Dispersion coefficient (Pasquill Gifford or Briggs Urban); Meteorological data, e.g. wind speed and direction, Pasquill stability class; ISCST2 - averaging time for input meteorological data is from one hour to a month. ISCLT2 - averaging time for input meteorological data is from a month to a year. For calculating direction-specific building downwash with ISC2 models, output data from the BREEZE WAKE/BPIP model (direction-specific building dimensions) are required.	Tabular data indicating concentrations at the receptor points for the appropriate meteorological conditions	$640+$70(user guide)
ISCST2 (Industrial Source Complex short term model) **ISCLT2** (Industrial Source complex long term model)	Predicting non-reactive pollutants concentrations from multiple point and/or area sources, in simple terrain (terrain heights below stack height).			$1450+$150 (ISCST2) $1380+$150 (ISCLT2) $775 (BREEZE WAKE)
ATDM (All Terrain Dispersion Model)	Predicting non-reactive pollutants concentrations from multiple point and/or area sources, in simple, complex and intermediate terrain. For simple terrain the model uses the ISCST2 algorithm		Concentration values at each receptor location, accompanied by a terrain regime indicator.	£2000

Table B-6 (cont.). Air pollution models.

Model Name/Author/Owner Platform/Language	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
CALINE4	Assessing air quality impact near highways and arterial streets (at grade, elevated and depressed). Includes emission analysis of parking lots, intersections and street canyons	Traffic data; Site geometry; Meteorological data; Emission factors (e.g. from MOBILE5 model).	Tabular data showing the concentrations at various receptor points.	$605+$130
MOBILE5	Calculation of emission factors for hydrocarbons, carbon monoxide and oxides of nitrogen from gasoline and diesel fueled vehicles complying with US standards.	Geographical region (two options); Vehicle type (eight options); Ambient temperature, vehicle usage, speed, mileage. Gasoline volatility.	Emission factors for hydrocarbons (running and refueling loss), CO and NOx.	$1060+$120(MOBILE) Modification of the program is required for its use outside the US
Breeze Haz **SPILLS, DEGADIS, TRPUF**	A serious of hazardous toxic gas release models (for liquid and gaseous emissions)	Information on the type and size of the release, which chemical was released, receptor location, meteorological data	Tabular data indicating the concentration levels at specified receptor points.	$1000-$3000 for each model
Indic Airviro (Indic, Sweden) UNIX sever for modelling/ PC for data retrieving and presentation.	System for air quality management: air quality monitoring, data analysis, emission simulation, dispersion calculation. Airviro modules for data collection, presentation, analysis and distribution are used by the DoE Enhanced Urban Network. The Airviro dispersion simulation system includes Dynamic emission database, meteorology preprocessor and wind model, Gaussian plume model, Street canyon model, time-dependent grid point model and receptor (reverse dispersion) model.			£22500 for the Indic Basic Indico System (including hardware); £45000 for the Indic Airviro Basic Urban Planner ENVIRO Technology Services Plc., Environment House, Dudbridge Road, Stroud, Gloucestershire GL5 3EE, UK Tel (014530751641 Fax (01453) 757596

Table B-6 (cont.). Air pollution models.

Model Name/Author/Owner Platform/Language	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
ADMS 2 Atmospheric Dispersion Modelling System CERC (Cambridge Environmental Research Consultants) and the UK Meteorological Office PC/Windows	Dispersion modelling package based on methodology developed in 1980s. Takes into account changes in turbulence with height. Does not cover calm conditions	Source emissions data (up to 50 sources and 10 pollutant types); Topographical data (terrain elevation and surface roughness); Terrain elevation data may be loaded automatically from OS Landform Panorama^{TM} digitised terrain data (1:50,000); Dry deposition velocity (optional); Meteorological data (e.g. standard data sets provided by the UK Met Office); Standard data comprise categories of 12 wind directions, 6 wind speeds, 7 surface heat fluxes, 8 boundary layer heights, 3 precipitation rates.	Pollutants concentrations (numerical data, contour and x-y plots, link to the GIS ArcView); Wet and dry deposition fluxes of deposits; Plume geometry: dispersion coeffs and plume height.	£5,000 + £350 for Surfer for Widows used to draw contours. Cambridge Environmental Research Consultants Ltd., 3 King Parade, Cambridge CB2 1SJ, UK. Tel. (01223)357773 Fax (01223)357492
ADMS 2 Urban CERC PC/Windows (Interface written in Visual Basic; needs Arc/View GIS)	Air pollution model for the urban environment based on ADMS 2; Released in 1996.	Includes: Emission database form the Highways Agency Design Manual for Roads and Bridges, which converts traffic flow data to emissions of CO, CO_2, NO_x, hydrocarbons and particulates; Street canyon model; Chemistry model for prediction of ozone levels		Cambridge Environmental Research Consultants Ltd., 3 King Parade, Cambridge CB2 1SJ, UK. Tel. (01223)357773 Fax (01223)357492

Table B-6 (cont.). Air pollution models.

Model Name/Author/Owner Platform/Language	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
IIASA Urban/ Industrial Air Quality Management System International Institute for Applied System Analysis, Austria UNIX workstation/ C, FORTRAN, Xlib	Compilation of emission inventories with the help of a rule based expert system; Simulation of air quality for SO_2, SO_4, possibly NO_x and ozone for individual episodes and over longer periods; Includes dry and wet deposition considerations and chemical transformation of SO_2 into S4; Optimization of pollution abatement strategies	Computation domain: time horizon, geometry, topography (DEM on a regular grid), aerodynamic roughness of the terrain; Meteorological data: mixing height, geostrophic wind, atmospheric stability, precipitation intensity; Difference of temperatures between the urban area and its surroundings (or satellite imagery); Emission field (point and area sources), including emission strength, stack height and diameter, flue gas velocity and temperature; Physical transformation parameters (dry and wet deposition coefficients, chemical transformation rate); Initial and boundary conditions. Cost functions for emission reduction for each source (for all alternative technologies); Background maps; Air quality observation data;	Pollutants concentrations: maps overlayed over topical maps), isoline and pseudo 3D displays; Diurnal cycles of NO_x, ozone and related oxidants (from photochemical box model); Summary report with the scenario assumption and the basic results.	Software is free for qualified end-users (e.g. a City Council, Ministry for the Environment); Costs of implementing the software (including IIASA staff time, travels to and from IIASA and user training at IIASA): ~ $30000 Computer hardware: ~ $20000 Fedra, K. (1993) Dr K. Fedra, Advanced Computer Applications Group, International Institute for Applied System Analysis, A-2361 Laxenburg, Austria

Table B-6 (cont.). Air pollution models.

Model Name/Author/Owner Type/Platform/Language	**Purpose/ Brief description**	**Inputs**	**Outputs**	**References Comments**
Dispersion models including chemistry				
FLUIDYN-PANACHE Transoft, France	Probably the scientifically most advanced of commercially available dispersion models. Includes a range of modelling techniques, from Gaussian model to 3-D PDE solver. Option for replacing default modules (e.g. meteorological model, chemistry scheme) by user's own modules. Processes included: vehicular emissions dispersion, street canyons, urban area effects (high rise buildings, residential areas, anthropogenic heat); vegetation effects; traffic noise; particulate dispersion Features: User-friendly graphical interface, 3-D visualisation, dynamic display of results. Possibility of getting the source code.			£12000 £4800 for academic research Centre d'Affaires Integral 82, Rue de Paris 93804, Epinay/Seine Cedex Tel. (33-1) 42.35.30.30 Fax. (33-10 42.35.25.26
The Photochemical Box Model US EPA	Model based on the simple approach of the single box model (assuming uniform distribution of emissions and perfect mixing), and including photochemical transformations	Box (a city airshed) dimension along the wind direction, height of the mixing layer, wind speed, emission rates per unit area	Average concentrations of primary and secondary pollutants (e.g. ozone) within a city.	Schere and Demerjian (1984)
The Harwell Photochemical Trajectory Model Lagrangian Photochemical Model	Calculation of concentration of pollutants within an air parcel moving along a trajectory defined by the wind direction and speed. The chemical scheme contains 684 reactions and 384 species (69 hydrocarbons). The air parcel is split into two layers reflecting the diurnal variations of the boundary layer depth.	Meteorological data; Emission inventory of VOC, NO_x and SO_2 for 50 km x 50 km grid.	Ozone and PAN (peroxyacetylnitrate) concentrations along the air parcel trajectory.	Derwent and Jenkin (1990a, 1990b, 1991)

Table B-6 (cont.). Air pollution models.

Model Name/Author/Owner Type/Platform/Language	**Purpose/** **Brief description**	**Inputs**	**Outputs**	**References** **Comments**
UAM/EPA **Urban Airshed Model** Three-dimensional photochemical grid (Eulerian) model	Calculation of concentration of both inert and chemically reactive pollutants by simulating the physical and chemical processes in the atmosphere. In particular: simulation of advection and dispersion of NOx and VOC and formation of ozone within every grid cell of the modelling domain. Usually applied to an 8-72 hours period with adverse meteorological conditions.	Day-specific data: Three -dimensional wind field for each hour; Hourly estimates for the height of the mixed layer; Ambient temperature, water concentration, atmospheric pressure, solar radiation, cloud cover; Observed air quality data (to estimate the initial condition field for ozone, NOx and VOC); Hourly gridded emissions for NOx and VOC from anthropogenic and biogenic emission sources (5km x 5km grid); VOC emissions must be speciated or classified into the respective carbon-bond class.	Concentrations (instantaneous and averaged) of all species in all grid cells calculated at the time interval specified by the user (usually 1 hour).	Scheffe and Morris (1993) Free from the US EPA (Environmental Protection Agency).
EUMAC Zooming Model (EZM) (European Modelling of Atmospheric Constituents) EUROTRAC project/ Universitat Karlsruhe/ Aristotle University Thessaloniki	Simulation of wind flow and pollutant transport and transformation for urban air quality studies	Meteorological, topographical and emission data	Maps of diurnal variations of pollutants concentrations (NOx, CO, ozone, hydrocarbons)	Moussiopoulos (1994) Payment required for software implementation and training. EUROTRAC International Scientific Secretariat, Fraunhofer Institute, Kreuzeckbahnstr. 19, D-82467 Garmisch-Partenkirchen, Germany
RAINS 7.0 International Institute for Applied System Analysis, Austria PC/Windows	Integrated assessment tool for modelling transboundary air pollution. Sub-models: Pollution generation and control, including costs; Atmospheric transport and deposition; and Environmental impacts, including lake and soil acidification and impact on forests.			Amann (1993, 1995) Alcamo *et al* (1990) International Institute for Applied System Analysis, A-2361 Laxenburg, Austria

B.4.3 Bibliography of air pollution models

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