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Urban environmental management: monitoring, GIS, and modeling

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Abstract

Urban environmental management must integrate the spatial, structural features of a city, typically captured in geographical information systems (GIS), and the dynamics of environmental quality indicators that can be obtained by monitoring. To provide decision-relevant information supporting planning and management, these components are integrated in models for scenario analysis and optimisation tasks. The paper describes some results from an environmental Telematics project (ECOSIM) and two Esprit projects (HITERM, SIMTRAP), as well as a EUREKA EUROENVIRON project (AIDAIR), and applications in cities such as Vienna, Berlin, Geneva, Basel, Milano, Athens, Gdansk, and Izmir. Strategies for the integration of monitoring, GIS, and modeling are presented, that use a common client–server architecture, an object-oriented design, embedded expert systems technology, and a multi-media user interface to support easy access, and easy use of complex analytical tools for urban environmental management.

Keywords: Urban environmental management; Monitoring; GIS; Modeling; Air quality; Decision support

1. Introduction

Urban environmental management addresses problems that are spatially distributed as well as dynamic.

The two basic methods or paradigms addressing these dimensions are data bases and geographical information systems (GIS) on the one hand, and dynamic simulation models on the other. In both cases, the integration with monitoring data as a third element, that is both spatially referenced and at the same time dynamic and with a real-time nature, adds an additional dimension that needs to be integrated into any comprehensive set of tools.

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Most urban environmental problems do have an obvious spatial dimension that can be addressed by GIS; GIS are tools to capture, manipulate, process, and display spatial or geo-referenced data. They contain both geometry data (coordinates and topological information) and attribute data, i.e. information describing the properties of geometrical spatial objects such as points, lines, and areas. With the map, albeit in an electronic and thus more versatile and analytical form, their basic paradigm is static.

Within the domain of environmental modeling the spatial dimensions is addressed by spatially distributed models that describe environmental phenomena in one (e.g. in river models), two (land, atmospheric and aquatic systems), and three dimensions (atmosphere and water).

In GIS, the basic concept is one of location, of spatial distribution and relationship, basic elements are spatial objects. In environmental modeling, by contrast, the basic concept is one of state, expressed in terms of numbers, mass, or energy, of interaction and dynamics; the basic elements are *species*, which may be biological, chemical, and environmental media such as air, water, or sediment.

2. The regulatory framework

EU regulations, e.g. the Air Quality framework Directive (92/62/EC), define criteria based on population size as well as density for the applicability of monitoring and reporting requirements, e.g. urban conglomerates of more than 250,000 inhabitants. This specific directive also explicitly refers to modeling as a technique to support monitoring in the context of air quality assessment.

The Directive defines assessment as any method to measure, calculate, predict, or estimate the level of a pollutant in ambient air. The Directive also states that for assessment, the measures provided for may be supplemented by modeling techniques to provide an adequate level of information.

Another example of explicit spatial references can be found in the area of technological risk assessment and management: most emergency management manuals include the concept of initial, substance-specific exclusion zones or a safety radius around the center of an incident.

Within the framework of the Seveso II Directive (96/82/EC) on the control of major-accident hazards involving dangerous substances, a number of specific classification criteria are defined for the reporting of accidents to the Commission. In addition to the substances involved, health and economic criteria, these include explicit spatial criteria such as the area contaminated for different types of land use or habitats.

Mandatory assessment and reporting, explicit spatial analysis, and modeling as part of data analysis are new tasks that call for new approaches and tools. Modern information technology and, in particular, the integration of monitoring and data base management systems, GIS, simulation modeling, and expert systems offers many possibilities to support environmental data and information management tasks with a new level of efficiency and effectiveness.

At the same time, the easy and direct access to, and dissemination of, information on the environment held by public authorities (as required by the Directive 90/313/

EEC on the freedom of access to information on the environment) and the exceedance of alert thresholds for air quality, in particular, can be realised efficiently by multimedia technologies and the use of the Internet as the medium of publication and access.

3. Setting the scene...

This paper is based on a number of European research projects that address aspects of environmental information management, the interactions between technology, and its impact on human living conditions. With a common technological and urban focus, the projects address different aspects of urban environmental management problems.

The ECOSIM environmental telematics project is designing an urban environmental management information system, integrating on-line monitoring with simulation modeling for both strategic planning and operational management questions; the environmental domains include air quality including photochemical smog (ozone; e.g. Mieth, Unger & Sydow, 1994), coastal water quality, and groundwater quality. ECOSIM has application sites in Berlin, Germany; Athens, Greece; and Gdansk, Poland.

AIDAIR, a EUREKA EUROENVIRON project, has similar aims, but concentrates on air quality assessment and management, with the new air quality framework Directive 96/62/EC as the guiding principle. Here, the emphasis is on the integration of different sources of air pollution: industry, domestic sources, and the transportation system, and the energy system as the general framework describing them. Linking models for energy planning and optimisation with air quality simulation for impact assessment is one of the objectives. Case studies include the cities Vienna, Geneva, and Izmir.

The Esprit project SIMTRAP concentrates on problems of urban transportation and air quality, linking dynamic traffic simulation models with 3D, dynamic photochemical air quality models. SIMTRAP application sites include Milano, Italy; Vienna, Austria; Berlin, Germany; and Maastricht, the Netherlands.

HITERM, and Esprit High Performance Computing and Networking (HPCN) project addresses technological risk management, primarily related to the chemical industry and the transportation of hazardous substances, with an obvious focus on urban population centers. HITERM involves various case studies, in Italy, Portugal, and Switzerland.

4. The technological framework

All the above examples address tough problems: they are complex, dynamic, and involve large volumes of data as well as spatially distributed 3D phenomena and models. They also involve problems of communicating difficult technical concepts and data to a largely non-technical audience, and of assisting non-technical users with complex analytical tools.

Despite the different application domains, different simulation models, and quite different user groups and their specific requirements, the three systems share some common technological framework and architecture. These elements include:

1. a flexible client–server implementation for distributed and decentralised use of information resources;
2. communication architecture based on the http protocol which is used to integrate real-time data acquisition from monitoring sites, as well as optional high-performance computing resources such as supercomputers or workstation clusters; primary consideration here is the scalability of applications over a wide range of performance requirements;
3. multi-media user interface design to support an intuitive understanding of results;
4. integration of GIS with data bases, monitoring results, and spatially explicit simulation modeling; and
5. embedded rule-based expert systems for logical modeling and user support; the expert system uses sets of IF-THEN rules to estimate model input parameters from easily available information, or can interpret model results for compliance within a given regulatory framework.

All of these features are designed to address difficult analytical problems with large volumes of data, and at the same time provide a convenient and easy to use intuitive user interface (Fedra, 1997).

5. Client–server implementation

To provide scientifically sound and decision-relevant information means tapping into a number of information resources. These are, in a typical urban situation, distributed physically, institutionally, and technically. They can include various data bases including GIS; monitoring data from observation networks; and a range of analytical tools. On the other hand, the users of this information may again be geographically and institutionally distributed.

To integrate the information resources, and reach distributed users, a distributed architecture for information management is needed. In the above examples, this is based on a client–server architecture that links conceptual servers with distributed clients. The connection between the different nodes is based on standard communications protocols (TCP/IP, http) and uses either the Internet or dedicated peer-to-peer connections, e.g. with ISDN (Integrated Servives Digital Network, digital telephone). Clients can either be local or on a high-bandwidth network using X11, or remote or on a low-bandwidth net, using Java for the user interface (Fig. 1).

5.1. Linking to monitoring data

Monitoring data are used for a number of tasks. They are required for basic state-of-the-environment reporting, e.g. for the assessment tasks mandated for urban

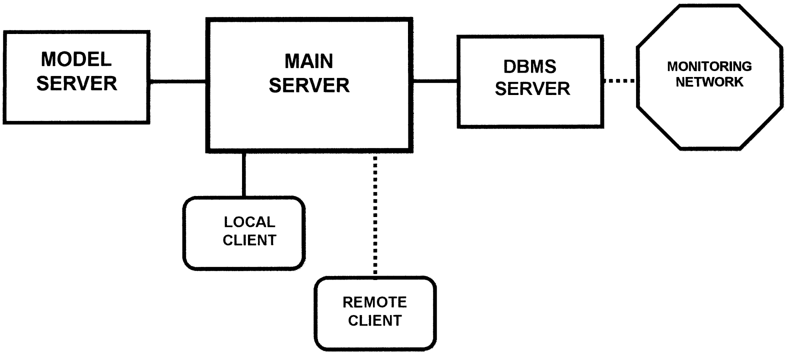


Fig. 1. A generic client–server architecture.

conglomerations above 250,000 inhabitants under the Directive 96/62/EC. They are also a necessary component of Environmental Impact Assessment studies (97/11/EC, 85/337/EEC) to provide the necessary baseline data.

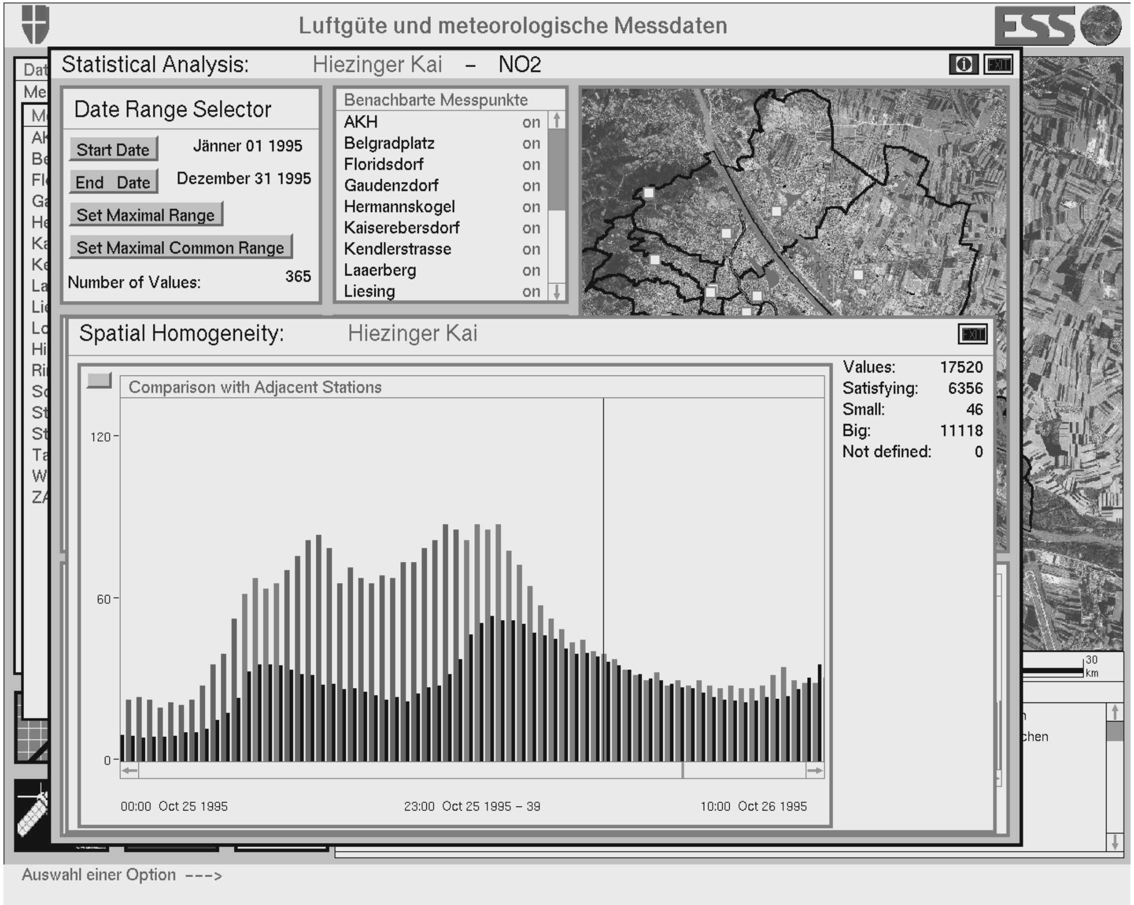
For more complex analyses, they provide the initial and boundary conditions for simulation and forecasting. Finally, by comparing monitoring data and modeling results, they can be used to validate and calibrate simulation models (Figs. 2 and 3).

The same basic architecture that integrates various information resources into one common framework can be used to link the spatial and dynamic analysis to on-line monitoring. An example is BLUME, the air quality monitoring network for the City of Berlin, and its integration in the ECOSIM project. The network consists of measurement equipment placed in containers which are positioned in a 4-km grid.

Additional measurements are performed in streets and residential areas with high pollution levels. The same measuring devices are on top of Berlin-Frohnau's telephone tower at 324 m to determine the background concentration. All measuring devices are connected via telephone to the central computer, which controls the complete network and at the same time serves as the evaluation unit. In 1994, there were 45 containers with 147 measuring devices, among them 39 units for SO_2, 43 for suspended particulate matter, 29 for NO_x, 21 for CO, 10 for ozone, and five for hydrocarbons. A team of 20 technicians and scientists are responsible for the operation of the network and the evaluation of the data.

The data of ambient air monitoring are shown permanently on a public display. Every 30 min, values are transferred automatically to the Meteorological Institute of the Freie Universität Berlin. The Institute's on-line weather information includes a report on ambient air quality in Berlin and is updated hourly. These reports are broadcast regularly by several radio stations. From Monday through Friday, all 11:00 values and the maximum values of the last 24 h are reported daily in the press. The information is also accessible through the Internet.

The display and analysis of the monitoring data includes the display of individual time-series data, basic statistical analysis, comparison with neighboring stations (spatial homogeneity), comparison with standards and analysis of compliance for



Luftgüte und meteorologische Messdaten

Statistical Analysis: Hiezinger Kai – NO2

Date Range Selector

Start Date: Jänner 01 1995

End Date: Dezember 31 1995

Number of Values: 365

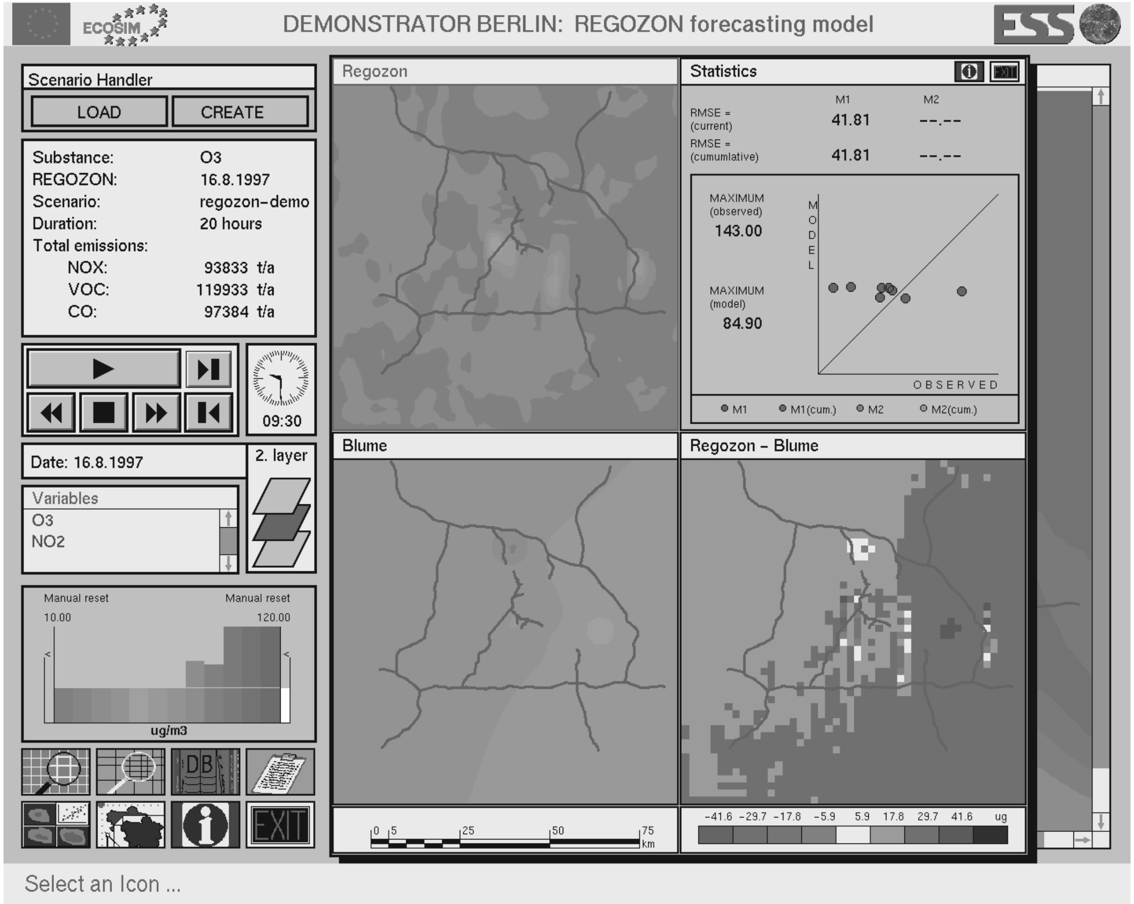
Benachbarte Messpunkte	
AKH	on
Belgradplatz	on
Floridsdorf	on
Gaudenzdorf	on
Hermannskogel	on
Kaiserebersdorf	on
Kendlerstrasse	on
Laaerberg	on
Liesing	on

Spatial Homogeneity: Hiezinger Kai

Values:	17520
Satisfying:	6356
Small:	46
Big:	11118
Not defined:	0

Auswahl einer Option --->

Fig. 2. Monitoring data analysis.



DEMONSTRATOR BERLIN: REGOZON forecasting model

Scenario Handler

Substance: O3
REGOZON: 16.8.1997
Scenario: regozon–demo
Duration: 20 hours
Total emissions:
NOX: 93833 t/a
VOC: 119933 t/a
CO: 97384 t/a

09:30

Date: 16.8.1997

Variables
O3
NO2

Statistics

	M1	M2
RMSE = (current)	41.81	--.--
RMSE = (cumumlative)	41.81	--.--

MAXIMUM (observed) 143.00
MAXIMUM (model) 84.90

Select an Icon ...

Fig. 3. Comparing the interpolated data from the Berlin BLUME network with the results from a dynamic ozone simulation model.

different aggregation periods, and spatial interpolation that results in a topical map of urban air quality.

5.2. Linking to model-based forecasts

To initiate control measures under the ozone regulations, however, a forecast of air quality is required. This can be derived from monitoring data directly, i.e. by time-series analysis methods. It can, however, also be based on simulation modeling. In the latter case, we also have the opportunity to evaluate the effectiveness of any proposed intervention strategy such as restricting traffic or industrial emissions.

The simulation of spatially distributed photochemical air pollution, i.e. ozone and its precursors, is computationally very demanding due to the complex chemistry involved on top of the basic physics of the dispersion processes. At the same time, the spatial element is of crucial importance, since the pollution problem is usually observed away from the major emission zones. Ozone is not directly emitted, by the results of photochemical transformations, so that its peak concentrations are usually observed downwind of major cities rather than in their centers.

The principle design of the model REGOZON includes a wind field model that is coupled with a dispersion model and a chemical module. Initial meteorological input, obtained from the monitoring network and meteorological stations includes vertical soundings (potential temperature profile), geostrophic wind, cloud cover, humidity, and surface water temperature.

For the computation of meteorological values and the dispersion, an Eulerian grid model is used. It is based on the conservation laws for impulse, mass, energy and passive. A hydrostatically stratified atmosphere is assumed, which is dry and incompressible. The model equations are expressed in three vertical layers. The first (surface layer) follows the ground level and has a fixed vertical thickness of 50 m above ground. It is turbulently mixed and its physical behavior is strongly coupled with the surface characteristics.

Emissions from traffic, from households and from industrial sources with low emission heights are introduced into the surface layer. The second layer (mixed layer) reaches from the upper level of the surface layer to the upper level of the atmospheric boundary layer, up to the mixing height. This layer is also turbulently mixed and shows the characteristic diurnal variation of the thickness of the atmospheric boundary layer. Emissions from higher emission sources, e.g. high stacks from power stations, enter the mixed layer. The third layer (temporary layer) is located above the mixed layer. It is assumed to be free of turbulence. Dry deposition velocities and biogenic emissions are computed as a function of land use. For a detailed description of the model and its application in Berlin see Mieth et al. (1994).

5.3. Impact assessment

Simulation modeling cannot only be used for operational forecasting, they can also answer WHAT-IF questions related to new projects or policies. A very large, but static data set is used in an environmental impact study for a new power plant with co-generation for district heating in Vienna. The modeling compares the air quality situation with and without the district heating scheme and the associated power plant. The basic simulations use data from more than 7000 housing blocks and their energy consumption, heating system, and resulting emissions.

The model first calculates, based on the frequency distribution of meteorological data for the heating period, the air quality or immission situation for unmitigated domestic emissions. It then calculates the values based on the emission reduction due to the district heating scheme, and adds to that the new emissions from the power plant. Finally, these two scenarios are compared and the difference is shown together with the base scenarios as a set of thematic maps. The levels of air pollution are shown as color-coded map overlays, and the difference between scenarios is displayed in the same way (Figs. 4 and 5).

6. Traffic and air quality

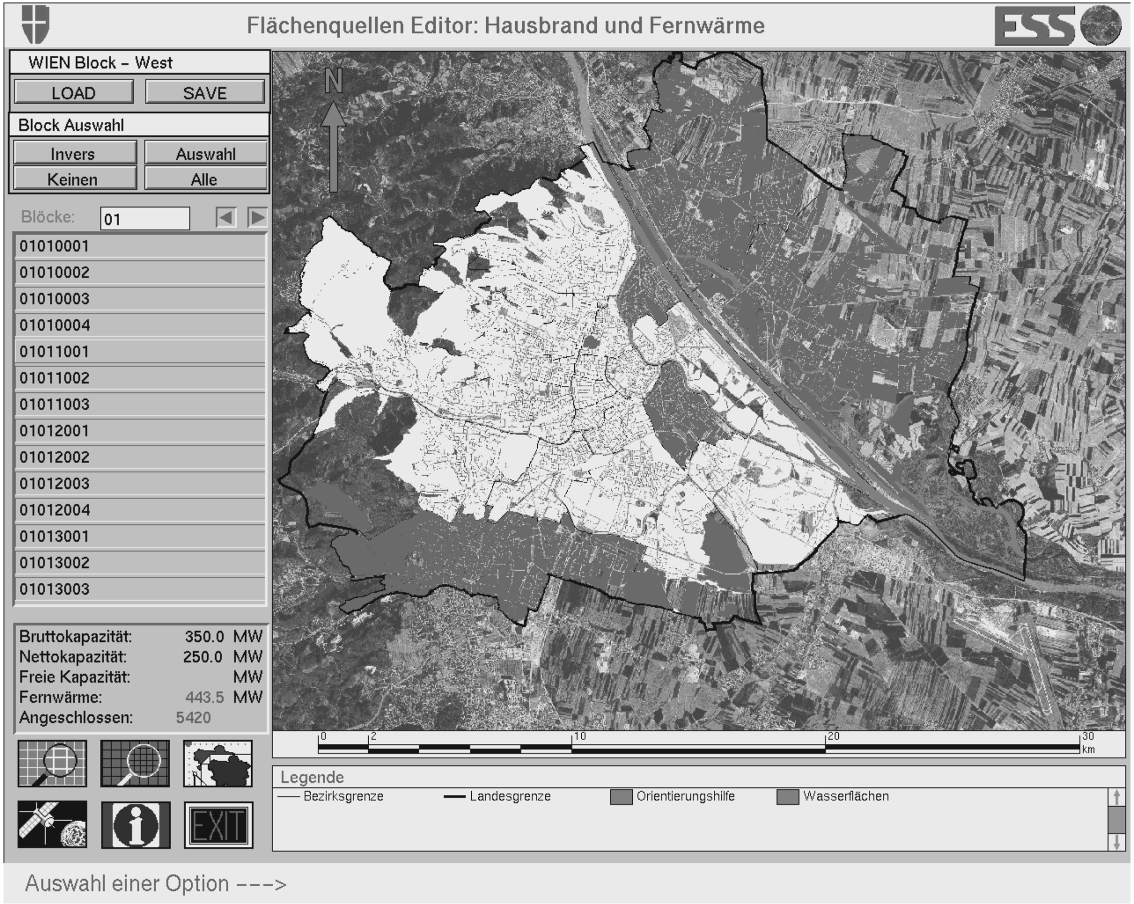
Another example of integrating models with GIS and large volumes of data is the analysis of traffic-generated pollutants (e.g. Fedra et al., 1996). Here, detailed street-network data are required for the simulation of traffic flows, the emission from traffic, and finally the resulting air quality. Using a static equilibrium traffic model, or a computationally much more demanding dynamic model, average or time variable traffic frequencies are obtained for different periods of the day and various scenarios of traffic planning and control.

These scenarios can involve different street networks, fleet composition, speed limits, one-way systems, outright closure of certain streets and areas, or the simulation of short-term events such as road construction, special events such as a major sports event, or accidents. The resulting data are stored on a street-network graph, and converted to emissions based on fleet composition, average speed, and trip durations. For each street segment of 20–50 m as an emission source scaled according to the traffic density in the segment, a dispersion model is used to estimate the resulting immissions. Repeating the exercise for the tens of thousands of segments in an average city results in an overall picture of traffic-generated air pollution (Figs. 6 and 7).

7. From research to application

Urban data management must ultimately provide useful, i.e. decision-relevant, information (Fedra, 1997). The potential users for the environmental management information and decision support systems described above includes both public institutions (such as larger cities subject to the Air Quality Framework Directive [96/62/EC] or the competent authorities of the Seveso Directive [96/82/EC]), environmental consultants, and industry, in particular hazardous installations or the waste management and transportation sector.

To turn the results of research projects into potentially useful products for these users involves several steps: first, a marketable product version of the project results



Flächenquellen Editor: Hausbrand und Fernwärme

WIEN Block – West

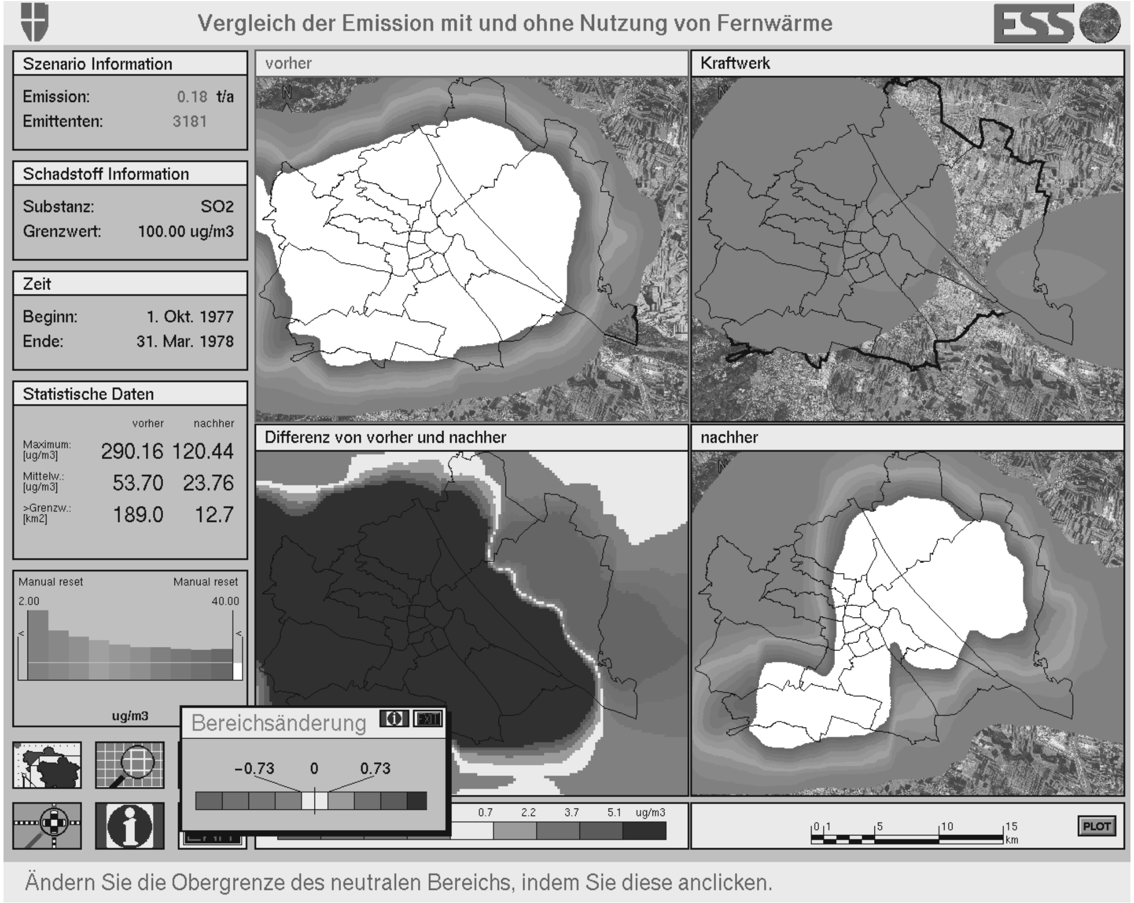
Blöcke: 01

01010001
01010002
01010003
01010004
01011001
01011002
01011003
01012001
01012002
01012003
01012004
01013001
01013002
01013003

Bruttokapazität: 350.0 MW
Nettokapazität: 250.0 MW
Freie Kapazität: MW
Fernwärme: 443.5 MW
Angeschlossen: 5420

Auswahl einer Option --->

Fig. 4. District heating scenario showing blocks connected in white.



Vergleich der Emission mit und ohne Nutzung von Fernwärme

Szenario Information

Emission: 0.18 t/a
Emittenten: 3181

Schadstoff Information

Substanz: SO2
Grenzwert: 100.00 ug/m3

Zeit

Beginn: 1. Okt. 1977
Ende: 31. Mar. 1978

Statistische Daten

	vorher	nachher
Maximum: [ug/m3]	290.16	120.44
Mittelw.: [ug/m3]	53.70	23.76
>Grenzw.: [km2]	189.0	12.7

Ändern Sie die Obergrenze des neutralen Bereichs, indem Sie diese anclicken.

Fig. 5. Comparative analysis of the model results with and without a possible district heating scheme.

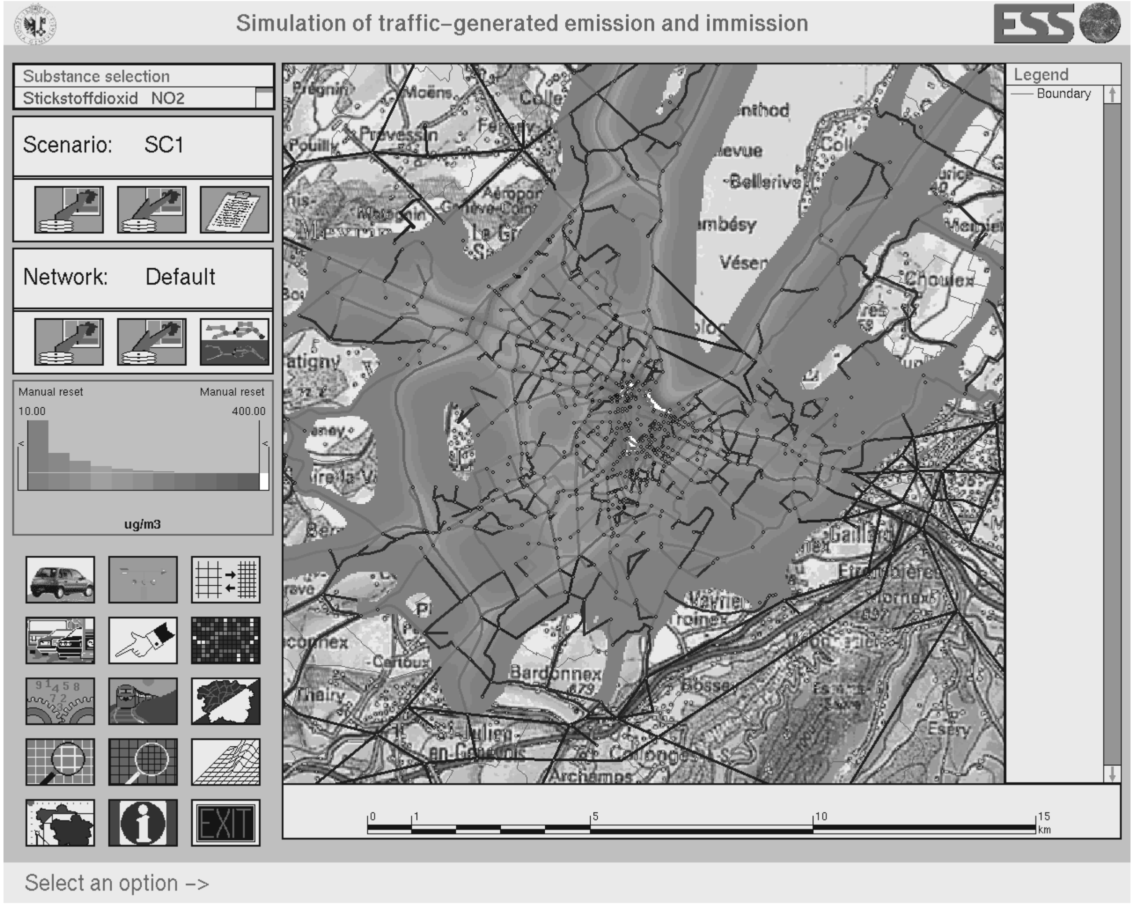
Color Desc Daily_av
Width Desc DATA0

From: ON570
To: ON572

Properties	
segment length	273.83 m
MOD	ab
road type	4.00
Nr of lanes	1.00
DATA0	4.00
Avg. speed	30.00 Km/h
DATA2	2400.00
Lane capacity	400.00 cars
LCMTO	133.00
LCTTO	380.00
LCSTO	170.00
Working day ATL	2400.00 vehi
Daily avg.traffic	2098.00 cars
LCMFR	0.00
LCTFR	29.00
LCSFR	10.00

Legend				
below 370 m	370 to 375 m	375 to 400 m	400 to 425 m	425 to 450 m
450 to 475 m	475 to 500 m	500 to 525 m	525 to 550 m	550 to 575 m

Fig. 6. Street-network data.



Substance selection
Stickstoffdioxid NO2

Scenario: SC1

Network: Default

Fig. 7. Traffic-generated air pollution (Geneva).

has to be developed. This requires additional investment, but is a necessary condition for marketing. These developments include:

1. quality assurance, converting research prototype software into a commercial product;
2. professional documentation, development of user support material;
3. national adaptations for target markets; and
4. porting to different hardware/software environments.

In all the above projects there is also the problem to adapt a high-tech product to a low-tech market. Since, however, the high-tech elements constitute the main innovation and the intrinsic value of the product this must be based on a flexible strategy of scalable implementation and a modular system with optional add-on components.

Scalability here refers to several related domains: systems must be available in a modular structure, with a low-cost entry level set of tools, that can be gradually expanded with optional components, e.g. starting with simple screening level models and moving (eventually) to full-featured 3D dynamic codes.

The same applies for hardware: offering low-cost entry-level hardware configurations with smooth upgrade paths for increasing computational performance that preserve customer investments is essential: this can be achieved through the use of cluster computing, where additional CPUs and thus computational resources can be integrated easily. And finally, a low-cost entry level must also be available in terms of data requirements. In many situations, data availability is the most expensive constraint on the efficient use of information technology-based solutions. Clearly, these three aspects of scalability are tightly related.

In parallel to the final product development, first marketing efforts are being based on direct contacts with the existing customer base, starting with broad mailing campaigns based on the prototype; presentations at conferences and trade fairs; publications in the technical and professional literature.

The product, in all three cases, bundles the software and related consultancy. This includes data acquisition and processing, installation, and training for the systems. As a special element of related services, the client–server implementation also supports the possibility of outsourcing of the more demanding computational tasks. In particular where high-performance computing resources are required the possibility to offer these as a service, on a pay-as-you-go basis, seems to be an attractive option for public institutions where investment in non-standard hardware or personnel for computer support are more difficult to include in shrinking budgets than external services.

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