DECISION SUPPORT SYSTEMS FOR ENERGY, TRAFFIC, AND ENVIRONMENTAL MANAGEMENT

Kurt Fedra
Environmental Software & Service Group, GmbH, Advanced Computer Applications, Austria

Alain B. Haurie
Management Studies (SES-HEC), Faculty of Economics and Social Sciences, University of Geneva, Switzerland

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Content

1. Introduction

Air pollution in cities is mostly due to emissions related to traffic (usually dominant, contributing between 60 and 80 percent of the total pollution load in a typical urban environment) and energy uses (in industry and for space heating and air conditioning). Air pollution results from the dispersion and chemical transformation of these emissions (emission → immission process). Air pollution has negative impacts on the natural environment, materials and structures, and on public health, the latter depending on the exposure rates due to location and lifestyle of different social groups.

The urban air quality management problem is characterized by a dynamic structure with multiple time scales, and multiple objectives and criteria at different spatial and temporal scales for the different actors and the regulatory framework. The problem involves direct and indirect control on emission sources which include an energy sector that can be modeled as a large scale mathematical programming problem and a traffic sector that can be modeled as a network equilibrium process. Regulations and effective markets exist mainly at the sectoral level.

The design of a comprehensive air quality strategy for an urban region must consider the spatial distribution of emissions and impacts, the distribution of cost to the economic agents, and the role of constraints imposed by environmental laws and regulations. Some decisions are discrete and of a design type (e.g., traffic control strategies based on a redesign of the network, the setting of air quality standards), while others are amenable to a treatment via economic calculus based on comparing marginal costs.

Optimization models provide paradigms representing the *homo economicus* behavior. They permit the correct calculation of marginal costs and therefore the design of *rational* incentive schemes and market based instruments [5].

Two classes of optimization models have been successfully applied for policy design and assessment: energy activity analysis models (e.g. MARKAL [1,3,11,21,13]) and traffic equilibrium models (e.g. EMME/2 [12]). AIDAIR is designed to use scenarios provided by MARKAL and EMME/2 implementations or any other similar model.

In any representation of the economy / environment interactions in an urban context, the first challenge is to combine the spatial analysis with the optimization based activity analysis models. The second complicating factor in the representation of urban air quality is related to the different dynamics involved in: (i) the pollution dispersion or emission/immission process and (ii) the economic activities at the origin of these emissions. These dynamics have different time scales. The policy designer should therefore use some averaging techniques to aggregate the description of the fast moving dispersion process to the time scale of the economic decision process. Given a spatial representation of the activities and a description of the emission/immission process that has been lifted up to the appropriate time scale, the complex problem of allocating allowable emissions to the different economic agents arises. This leads to an approach based on ideas inspired from the theory of *resource-oriented* decomposition of large scale mathematical programs. However, due to the complexity of the underlying spatial equilibrium or optimization structure, the approach is only a “heuristic” one that could help in providing some insight.

Therefore, recognizing the overall complexity of the system to be controlled, it can be represented as a multi criterion decision analysis problem where quantitative criteria, like those resulting from activity analysis models, and more qualitative ones, like those related to health impact and equity, are combined in a search for a satisfying compromise.

This leads to a multi-tired iterative approach for the design of a strategy (Figure 1):

1. Obtain emission scenarios for different sectors (energy, transportation) through optimization models maintaining economic efficiency and meeting sectoral objectives and constraints. This is based on rational economic behavior of realistic agents at the sectoral level. The sectoral optimization approach is based on the use of models for energy, e.g., MARKAL optimizing an energy demand-supply balance for the city including bounds on pollution emissions, and for transportation, e.g., EMME/2 simulating traffic equilibria which again constitute an emission scenario.
2. Get a representation of the resulting ambient air quality as a function of these emissions for different averaging periods, relating to air quality standards through solving the dispersion equations with spatially distributed air quality models.
3. Obtain spatially distributed measures of environmental and public health impacts based on land use information and a population distribution, resulting in a spatially distributed measure of vulnerability or damage function, for different classes of pollutants.
4. Minimize this distributed impact function subject to economic constraints by distributing the maximum acceptable costs. Alternatively, subject to environmental quality constraints, allocate the maximum permissible emission levels to traffic and energy uses while maintaining economic efficiency. This global optimization takes emission scenarios (un-mitigated or sectorally optimized) as its starting point and is based on a source-receptor matrix computed by a long-term air quality model.
5. Use the permissible emission levels obtained as a constraint on the previous sectoral optimization. Feedback loops from the impact analysis and global optimization can help to redefine objectives and constraints of the sectoral models.
6. Repeat the above steps to obtain a number of (sectorally) optimal scenarios.
7. Use a discrete multi-criteria tool to find a preferred compromise solution that satisfies the objectives of all groups of actors.

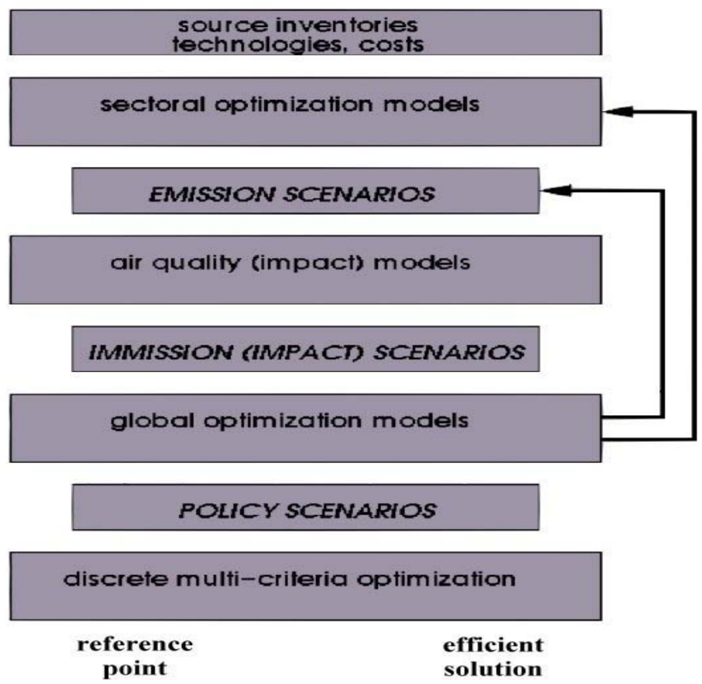

Figure 1: The AIDAIR iterative approach

2. Spatial analysis and optimization models

Optimization models are designed to explore the efficient behavior of complex systems. Typically the optimization models we consider in order to capture the fundamental elements of Energy-Traffic-Environment interactions are the following:

Traffic equilibrium: given a set of trips by the users who seek to minimize their travel time (or cost), find the equilibrium load on the various arcs of a transportation network of a city. EMME/2 [12] is a widely used model performing this task to help traffic planners in many cities.

Energy supply-demand equilibrium: given a set of useful demands (the energy services like space heating, cooking, lighting, etc..) and a set of available technologies, find a minimum cost organization of the global energy system for a region. MARKAL [1,3,11,21,13] is a widely used model performing this task to help energy planners in different countries or regions in the world. The model can also be used, given a set of environmental constraints, *e.g.* on air quality, to find the emission taxes, or tradeable emission right prices that would lead rational economic agents to achieve, globally, the required standard.

In addition to these sectoral optimization models one has to include physico-chemical models describing the spatial and temporal distribution of (air) pollutants in the region under consideration. These are typically, for screening and planning purposes, Gaussian (steady-state) models, or dynamic models of an Eulerian or Lagrangian type. Chemical processes play an important role in photochemical smog (ozone) problems, and can be represented in (geometrically) simple box models or complex, often nested-grid Eulerian three-dimensional and dynamic codes.

Coupling GIS and optimization models we may answer more complex "What if" questions, such as how to design a strategy for air quality in an urban environment? However this coupling is not straightforward as the paradigms of GIS and optimization models are often very different. In optimization theory, the spatial distribution of activities has been represented via two approaches:

network optimization: typically used in Operations Research (OR) for the analysis of transportation problems; the topology of the network representing the (logical) spatial structure of the transportation system however, does not require a true georeferencing.

distributed parameter systems: typically used in control system theory; the spatial diffusion operator, usually in the form of a partial differential equation, representing the structure that leads to the distribution of a process or activity.

The coupling of GIS functionality with spatially distributed simulation models and optimization models can exploit these two approaches in order to realize a set of hierarchical models based on decomposition techniques. The proposed implementation is based on the iteration between a layer that would deal with the complicating spatial allocation and assessment problems and a layer that will propose optimal organizations of the energy and transportation system subject to the constraints defined at the spatially explicit level. The problem of convergence or the lack thereof is addressed by a third layer of a discrete multi-criteria tool, that selects an efficient, preferred, and satisfying solution from the set of alternatives generated.

3. A dynamic multi-time scale system representation of the air quality management problem

The air pollution control problem can be formulated as a distributed parameter system. This will provide a conceptual basis from which different approximate modeling approaches can be derived.

3.1. Pollution Dispersion Dynamics

As a central component of the proposed approach, the pollution emission and dispersion process is represented as a distributed dynamic system. If we adopt the simplifying assumption of independent (non-reactive) pollutants we may write an equation for each type k of pollutant

$$\frac{\partial}{\partial t} P_k^n\left(t,\omega\right) = \mathcal{L}_k^{\mu^n(t)}(P_k^n(t,\omega), e_k(t,\omega), \sum_j E_k^{jn}(t))\,\delta(\omega^j;\omega)), \quad \omega \in \Omega, \tag{1}$$

where

$P_k^n(t,\omega)$: pollutant k concentration at period n, time t in location ω

n: time periods during the planning horizon $n = 1,\dots,N$ (typically a year)

k: pollutant type index $k = 1,\dots,K$

t: time index, $t \in [0,T]$ within each time period

ω: space index $\omega = (\omega_1,\omega_2) \in \Omega \subset \mathbb{R}^2$

$\mathcal{L}_k^{\mu^n(t)}$: is a local dispersion operator representing the transport and diffusion processes

$\mu^n(t)$: weather condition at time t of period n, $\mu^n(t)$ is a random jump process with a set of possible values $M = \{1,\dots,m,\dots,M\}$

$e_k^n(t,\omega)$: distributed emission rate at time t of period n and location ω of pollutant k

$E_k^j(t)$: emission rate of pollutant k at time t by polluter j

j: point source polluter (industry) index $j = 1,\dots,J$

ω^j: location of polluter j

$\delta(\omega^j;\omega)$: Dirac function $\delta(\omega^j;\omega) = \begin{cases} 0 & \text{if} \omega^j \neq \omega \\ \infty & \text{otherwise} \end{cases}$, $\int_\Omega \delta(\omega^j;\omega)\, d\omega = 1$.

Typically, the local operator $\mathcal{L}_k^{\mu^n(t)}$ would take the form

$$\mathcal{L}_k^{\mu^n(t)}(P_k^n(t,\omega), e_k(t,\omega) = -\eta^{\mu^n(t)} \frac{\partial}{\partial\omega} P_k^n(t,\omega) + \kappa^{\mu^n(t)} \frac{\partial^2}{\partial\omega^2} P_k^n(t,\omega) + e_k(t,\omega), \quad (2)$$

where $\mu^n(t)$ through the coefficients $\eta^{\mu^n(t)}$ and $\kappa^{\mu^n(t)}$ describe the speed of the transportation and the diffusion processes. Note that the operator is indexed over the time-variable weather conditions $\mu^n(t)$. The system also needs some boundary conditions on the domain frontier $\partial\Omega$, and an initial condition $P_k^0(0,\omega) = P_k^0(\omega), \omega \in \Omega$.

The simplifying assumption of independent substances would not hold for pollutants, like ozone that are not emitted but the result of complex photochemical transformations involving several different precursor emissions, primarily oxides of nitrogen and volatile organic compounds (VOC). In that case the system should be written as:

$$\frac{\partial}{\partial t} P^n(t,\omega) = \mathcal{LC}_k^{\mu^n(t)}(P^n(t,\omega), e(t,\omega), \sum_j E^{jn}(t))\delta(\omega^j;\omega)), \quad \omega \in \Omega, \qquad (3)$$

where $P^n(t,\omega)$ is the vector of all concentrations and $e(t,\omega), E^{jn}(t)$ the vectors of all emissions, and $\mathcal{LC}_k^{\mu^n(t)}$ represents the dispersion operator including chemical transformation.

In air quality modeling practice, we use either individual weather events (representing most common or extreme situations), interpolated time-series of observation data, or a frequency distribution of weather events representing an annual or seasoned period. The links between air pollution and distributed system theory are explored, for example, by [2,9,14,16,18].

3.2. Emissions Generation by Economic Activities

The emissions are the dynamic and spatially distributed forcing terms in the dispersion equations (1,3). We can distinguish emissions that are represented by an equivalent area source lumping several smaller point sources such as chimneys from buildings within a spatial element $d\omega$, the individual street segments of the transportation network, see *e.g.* Eq. (4), and those corresponding to single (major) point sources.

Emissions of classical pollutants (SOx, NOx), result primarily from combustion processes in traffic and buildings furnaces. If we consider ozone we also need to take into account VOCs (volatile organic compounds) which are not directly linked to energy use but rather to some industrial and commercial processes, domestic use of chemicals, the transportation (fuel) system, and natural biogenic sources, that are also distributed in the domain Ω. We can write

$$e_k^n(t,\omega) = \theta_k^n(t,\omega) + h_k^n(t,\omega), \quad \omega \in \Omega, \quad k = 1,\ldots,K \qquad (4)$$

where

$\theta_k^n(t,\omega)$: distributed emission rate due to traffic, at period n, time t and location ω of pollutant k,

$h_k^n(t,\omega)$: distributed emission rate due to heating furnaces, at period n, time t and location ω of pollutant k.

For the energy sector distributed activities have a location that will not change with t. They are essentially the furnaces used for space heating of buildings. The heating equipment has to satisfy a demand $d^n(t,\omega)$ at each time t of period n.

Traffic can be understood as the result of equilibrium of individual users of the transportation network. Traffic load $\ell^n(t,a)$ is obtained on each arc a of the network as a result of the origin/destination demand matrix $O^n(t)$ and the network topology $(\mathrm{N},\mathrm{A},\gamma)^n(t)$ in period n and time t:

$$\ell^n(t,.) = \mathcal{E}[(\mathrm{N},\mathrm{A},\gamma)^n(t), O^n(t)], \qquad (5)$$

where

$\ell^n(t,a)$: traffic load per arc, including driving conditions like average speed etc.

$\mathcal{E}$: stands for traffic equilibrium,

$(\mathrm{N},\mathrm{A},\gamma(\cdot))^n(t)$: transportation network at period n and time t; N is the set of nodes, A the set of arcs, $\gamma(\cdot)$ is the function defining the travel cost on each arc as a function of the load on the arc.

Now emission $\in_k^n(t)(a)$ per unit of length on the arc a is a function of the load (subsuming driving conditions such as average speed) and of the technology mix characterizing the vehicle fleet $\Theta^n(t)$:

$$\in_k^n(t)(a) = f(\ell^n(t,a), \Theta^n(t)). \qquad (6)$$

Since the basic street network as used by a traffic simulation model like $\mathrm{EMME}/2$ uses a logical connectivity (topology) rather than true georeferencing, the emissions along each arc are translated into a spatially distributed set of emissions. With each elementary rectangle (grid cell) $d\omega$ an emission rate is associated, which amounts to a straight-forward rasterization of the transportation graph, which is a standard GIS function.

Major point sources of pollution are the industrial plants located in the domain Ω. Some of these plants may be combined heat-power plants distributing heat on a district heat network.

The emission rates $E_k^{jn}(t)$ are defined as a function of the activity levels

$$E_k^{jn}(t) = F_k^j(t, x^{jn}) \qquad (7)$$

where

$F_k^j(t, x^{jn})$: function relating the activity levels x^{jn} to substance specific emissions,

x^{jn}: activity level (capacity, investment, operation) of possible equipments at plant j.

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Biographical Sketches

Kurt Fedra obtained his Ph.D. from the University of Vienna in biology for his thesis on a computer simulation model of the ecology of the North Adriatic Sea. During 1971 - 1977 he studied at the University of Vienna (biology, chemistry, human ecology, philosophy; from 1976 through 1980 he also attended courses in computer sciences, physics, and mathematics, parallel enrolment at the Technical University of Vienna).

His professional career is as follows:

1989 - 1995 Manager, Computer Applications and Services at IIASA (International Institute for Applied Systems Analysis, Laxemburg, AUSTRIA), managing the computer resources for more than 100 scientific and administrative users.

1985 - 1995 Project Leader, Advanced Computer Applications Group at IIASA; design and development of information and decision support systems in the area of environmental management, development planning and risk analysis, for international governmental and industrial clients;

1982 - 1983 Postdoctoral Fellow at MIT, the Massachusetts Institute of Technology, Cambridge, MA, working at the Parsons Laboratory for Water Resources and Environmental Engineering on problems of environmental modeling.

1978 - 1982 Research Scholar, Resources and Environment Area at IIASA, working on several water resources and environmental modeling projects.

1979 - International Consultant and Lecturer on scientific computing and environmental systems analysis. Clients include: UN organizations, including UNESCO-MAB, UNESCO, SCOPE Paris, UNEP Nairobi, UNIDO, UNIDO/UNDP Vienna and New Delhi World Bank (ONIX project), EC Research Projects, EpiMan (IAH, UK); HYDRA (University of Trento, Italy), Council for Scientific and Industrial Research, (CSIR), Pretoria, RSA; Bharat Heavy Electricals, Hardware, India and others.

His Fields of Work and Special Experience include:

-*Teaching Experience*: Lecturer at the University of Trento, Italy (environmental decision support systems)and Joh. Kepler Univ., Linz (applied systems analysis and environmental systems analysis);

-*Applied Systems Analysis and Computer Technology*: research on information and decision support systems for large environmental and socio-technical systems, interactive simulation, visualization, GIS and AI applications, knowledge engineering, advanced programming skills, including simulation techniques, interactive graphics, multi-media design and content editing; management of large software development projects.

-*Environmental Systems Analysis*: environmental and ecological modeling, including air, surface and groundwater models; water quality, lake/watershed systems, coastal marine systems, rain-runoff and regional water resources management, nonpoint-source pollution; local and regional air quality simulation; risk analysis; state-of-the-environment and environmental impact assessment.

-*Ecology and Biological Sciences*: experimental ecology, biostatistics and biometrics; biological modeling, energy flow modeling.

He has more than 100 *publications* including international journal articles, conference papers, technical reports and documentation, and contributions to several books in the area of environmental systems analysis and related computer applications.