Evaluating Urban Sustainability Using Land-Use Transport Interaction Models

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The objective of the EU research project PROPOLIS (Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability) was to assess urban strategies and to demonstrate their long-term effects in European cities. To reach this goal, a comprehensive framework of methodologies including integrated land-use, transport and environmental models as well as indicator, evaluation and presentation systems was developed.

Sustainable development is viewed as comprising the environmental, socio-cultural and economic dimension. Thirty-five indicators were defined to measure the three dimensions of sustainability, such as air pollution, consumption of natural resources, quality of open space, population exposure to air pollution and noise, equity and opportunities and economic benefits from transport and land use.

Indicator values are derived from state-of-the-art urban land-use and transport models. A number of additional modules, including a justice evaluation module, an economic evaluation module and a GIS-based raster module, were developed and integrated to provide further indicator values. Both multicriteria and cost-benefit analysis methods are used to consistently evaluate the impacts of the policies. The environmental and social dimensions of sustainability are measured using multicriteria analysis for the evaluation of the indicators, whereas cost-benefit analysis is used for the economic dimension. The modelling and evaluation system was implemented in seven European urban regions: Bilbao (Spain), Brussels (Belgium), Dortmund (Germany), Helsinki (Finland), Inverness (Scotland), Naples (Italy) and Vicenza (Italy).

A large number of policies were tested with the modelling and evaluation system in the seven urban regions. Policies investigated are land use policies, transport infrastructure policies, transport regulation and pricing policies and combinations of these. Besides a common set of policies examined in all seven urban regions, also city-specific local policies were assessed in each urban region.

The first part of the paper introduces the methodology and the model system developed. A particular focus is on the development of indicators describing urban sustainability derived from different indicator modules in the modelling system. The second part presents selected aggregated results of the policy testing and evaluation for Dortmund as one of the seven urban regions. The paper concludes with recommendations on how successful strategies to enhance the long-term sustainability of urban regions should look like.

Keywords: Urban sustainability, land-use transport environmental modelling, policy evaluation

1. Introduction

The notion of each generation's duty to its successors is at the heart of the concept of sustainable development and was captured by the Brundtland Commission (WCED, 1987) in its report 'Our Common Future', which defined sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs". Many definitions have followed that of the Brundtland Commission. For example, Daly (1991) defines sustainable development as one that satisfies three basic conditions: (1) its rates of use of renewable resources do not exceed their rates of regeneration; (2) its rates of use of non-renewable resources do not exceed the rate at which sustainable renewable substitutes are developed; and (3) its rates of pollution do not exceed the assimilative capacity of the environment.

However, many definitions of sustainability are broader in concept and seek to extend the definition beyond environmental considerations and include issues of social equity and justice. Different weight is often also given to the importance of economic growth. For instance, the 'Charter of European Cities and Towns Towards Sustainability' (ICLEI, 1994) states that the main basis for sustainable development is "to achieve social justice, sustainable economies, and environmental sustainability. Social justice will necessarily have to be based on economic sustainability and equity, which require environmental sustainability."

In the sustainability discussion, often a distinction is drawn between major environmental threats to human life on the planet Earth on the one hand and local concerns, which are more amenable to trade-offs, on the other. In this discussion, cities and urban regions play an important role. Cities contribute to a large extent to global environmental problems, but at the same time people living in cities are confronted with environmental damage, pollution, health risks and social and economic problems.

Consequently, goals to make cities more sustainable have been formulated (e.g. European Environment Agency, 1995):

- minimising the consumption of space and natural resources,
- rationalising and efficiently managing urban flows,
- protecting the health of the urban population,
- ensuring equal access to resources and services,
- maintaining cultural and social diversity.

Also, different policies, including transport, land use, regulatory, investment, fiscal and pricing policies to improve the urban situation have been designed and partly implemented.

However, actual urban developments show that these policies have not been able to stop the decrease of sustainability of our cities. Even to maintain the existing level of sustainability will probably require the introduction of more radical policy measures. But such policies will not be implemented if their effects cannot be clearly demonstrated. Policies might have very different effects. Besides direct environmental, social or economic impacts many policy options may have negative side effects. Some policy options may work against each other, whereas some may reinforce each other. Some policy options may improve the situation in parts of the region, whereas in other parts the situation may get worse. Hence, the design of policies to improve urban sustainability is anything else than a straightforward task. Because the direct and indirect, the short-term and long-term effects have to be identified and measured in a transparent way, this calls for advanced methods of policy impact assessment and policy evaluation.

To develop and implement such a system was the objective of the EU research project PROPOLIS (Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability). The goal was to assess urban strategies and to demonstrate their long-term effects in European cities with respect to sustainability. To reach this goal, a comprehensive framework of methodologies including integrated land-use, transport and environmental modelling as well as indicator modules such as a GIS-based raster module, an economic indicator module and a justice indicator module as well as evaluation and presentation modules were developed.

The first part of this paper introduces the methodology and the model system developed. A particular focus is on the development of indicators describing urban sustainability derived from different models in the modelling system. The second part presents typical results of the policy testing and evaluation. The paper concludes with recommendations on how successful strategies to enhance the long-term sustainability of urban regions can be developed.

2. Indicatiors of Urban Sustainability

As definitions of sustainability have broadened in scope over time, the number of possible indicators has grown to an extent where virtually all aspects of life are covered. Consequently, a vast number of sustainability indicator systems are in use today.

In PROPOLIS, sustainable development is viewed as comprising the environmental, socio-cultural and economic dimension. For the three components, key indicators were identified using a set of criteria:

- Relevance. The indicator should be relevant for describing important aspects of sustainability.
- Representativeness. In order to keep the indicator system manageable, not each suitable indicator can be included; the focus is on key indicators representing different domains of sustainability.
- Policy sensitiveness. Only indicators that are likely to be sensitive to the policies investigated are of interest.
- Predictability. There exist a large number of indicators suitable for monitoring but, as the objective is to model future policy impacts, it is essential that the indicator values can be forecast into the future by the model system.

Table 1. PROPOLIS Indicator System

	Theme	**Indicator**
Environmental indicators	Global climate change	Greenhouse gases from transport
	Air pollution	Acidifying gases from transport Volatile organic compounds from transport
	Consumption of natural resources	Consumption of mineral oil products, transport Land coverage Need for additional new construction
	Environmental quality	Fragmentation of open space Quality of open space
Social indicators	Health	Exposure to PM from transport in the living environment Exposure to NO_2 from transport in the living environment Exposure to traffic noise Traffic deaths Traffic injuries
	Equity	Justice of distribution of economic benefits Justice of exposure to PM Justice of exposure to NO_2 Justice of exposure to noise Segregation
	Opportunities	Housing standard Vitality of city centre Vitality of surrounding region Productivity gain from land use
	Accessibility and traffic	Total time spent in traffic Level of service of public transport and slow modes Accessibility to city centre Accessibility to services Accessibility to open space
Economic indicators	Total net benefit from transport	Transport investment costs Transport user benefits Transport operator benefits Government benefits from transport Transport external accident costs Transport external emissions costs Transport external greenhouse gases costs Transport external noise costs

The resulting PROPOLIS indicator system is presented in Table 1. To allow a structured evaluation, the three sustainability components are subdivided into themes. Then appropriate indicators are related to these themes.

Nine themes and thirty-five indicators were defined to measure the three dimensions of sustainability, such as greenhouse gas emissions, air pollution, consumption of natural resources, quality of open space, population exposure to air pollution and noise, equity and opportunities and economic benefits from transport. The present indicator list lacks indicators related to environmental impacts of land use, such as greenhouse gas emissions, air pollution, noise, energy use, or economic benefits. Some of these indicators were tested in individual case study cities, but it was outside the scope of PROPOLIS to implement these indicators in all case study cities.

3. PROPOLIS Methodology

This chapter briefly presents the PROPOLIS model system and introduces its main components such as the land-use transport models and the indicator modules, presents in more detail one of the new elements in land-use transport modelling, the raster module, and finally shows how the policy testing and evaluation process was organised.

3.1 The PROPOLIS Model System

For a systematic evaluation of policies with respect to their long-term impacts on urban sustainability, a model system was designed in which different models and tools are integrated. Figure 1 illustrates the main components and data flows of the model system from input through behaviour and impact modelling to output in the form of indicators and their evaluation and presentation.

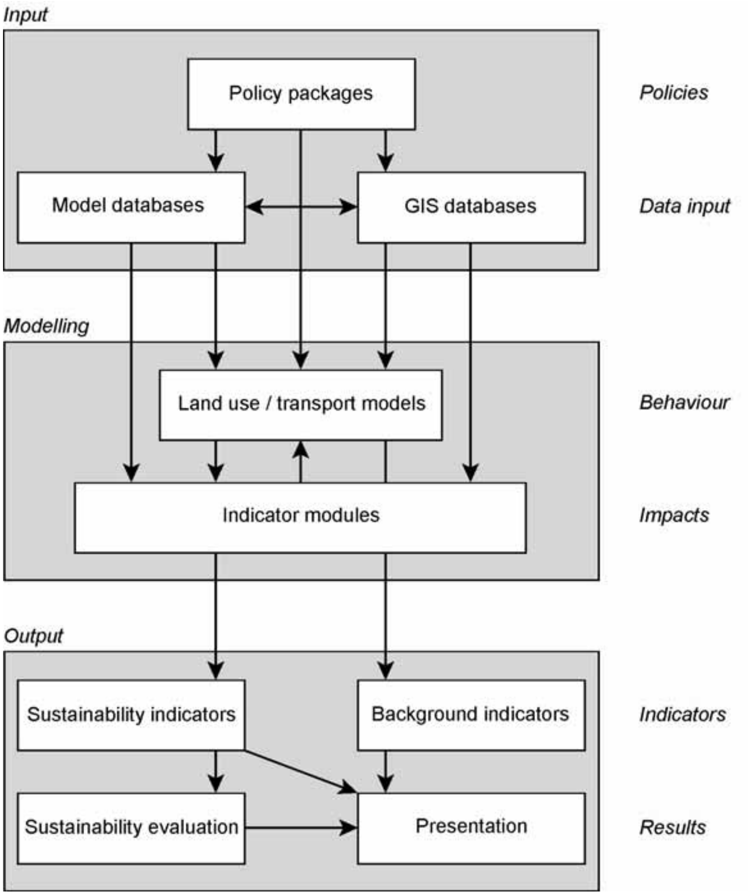

Figure 1. The PROPOLIS model system

The *input data* include policy packages, GIS databases and model databases. Policy packages to be tested are transformed to 'model language' by changing some of the model parameters or model data. GIS databases contain georeferenced data of zone boundaries, transport networks, land use categories etc. in a geographic information system (GIS). All land-use transport models used are fully GIS-integrated, i.e. each model zone or model network link is represented in the GIS database.

In the *modelling part* the land-use transport models are the driving engines of the system. They have been previously calibrated to correspond to the observed behaviour in the test cities. The land-use transport models simulate the effects of policies on zonal activities, such as population or employment, and on mobility patterns, such as modal shares and link flows. The indicator modules receive the outputs of the land-use transport models and calculate the sustainability indicators.

The *output part* consists of sustainability indicator values which are further processed in the sustainability evaluation module. Other information that helps to understand the behaviour of the system is stored as background variables. Examples for background variables are zonal population and employment, modal shares, car-km travelled etc. Background variables are not directly used in the evaluation of sustainability, because the sustainability indicators follow as far as possible the impact chain, e.g. environmental damage of car use is represented in the evaluation by emissions and exposure to emissions and traffic noise rather than by car-km travelled. A web-based presentation tool shows the results of each policy in a standard form for comparisons between policies and between cities.

The Land-Use Transport Models

The PROPOLIS model system was implemented in seven European urban regions: Bilbao (Spain), Brussels (Belgium), Dortmund (Germany), Helsinki (Finland), Inverness (United Kingdom), Naples (Italy) and Vicenza (Italy). For each region an operational land-use transport model existed before the project. Table 2 presents the seven urban regions, their land-use transport models and their zoning systems.

The seven case study regions differ in many respects. Their sizes range from 130,000 to over three million inhabitants. Some have experienced strong growth while others are old declining cities, sometimes in the process of restructuring. Some have high, some very low unemployment rates. Income per person and car ownership differ considerably. The spatial structures range from highly compact and centralised to dispersed or polycentric patterns. With different conditions of transport supply, the modal shares vary significantly, however, car travel is always dominant.

The models applied belong to three different types of urban land-use transport model: the MEPLAN model (Hunt, 1994; Martino and Maffii, 1999; Williams, 1994) was implemented in four urban regions, the TRANUS model (de la Barra, 1989) in two and the IRPUD model (Wegener, 1996; 1998; 1999) in one. The models simulate the effects of policies on the location behaviour of households and firms and on the resulting mobility patterns in the case study regions. Common base year of the models is 2001, the final forecast year is 2021.

Output of the land-use transport models is provided in a common data format for a pre-defined set of variables. Because the models are implemented in very different ways, harmonisation of the model outputs is necessary. The harmonisation is performed by aggregation to the 'lowest common denominator'. This means that the land-use transport models work with as much detail as they were implemented and that subsequent stages of the model system work with less detail but with a common set of variables in order to allow comparisons between cities. Socio-economic groups are aggregated to three types, employment sectors to four types, land and floorspace to three types, trips to five types, transport modes to five types and transport links to ten types.

Table 2. Case city regions and land-use transport models

Case city	Bilbao	Brussels	Dortmund	Helsinki	Inverness	Naples	Vicenza
Area (km²)	2,217	4,332	2,014	764	4,152	1,171	2,722
Population (1,000)	1,140	2,841	2,516	946	132	3,099	787
Density (inh/km²)	514	656	1,249	1,238	32	2,647	289
Average household size	3.2	2.7	2.1	2.1	2.8	3.1	2.7
Unemployment rate (%)	25.0	11.0	12.6	6.0	8.1	27.8	2.8
Income/inh/month (Euro)	750	713	1,570	1,100	n.a.	695	1,079
Cars/1,000 inh	418	461	492	345	332	526	591
Land-use transport model	MEPLAN	TRANUS	IRPUD	MEPLAN	TRANUS	MEPLAN	MEPLAN
Land use zones	111	152	246	173	153	179	102
Transport zones	111	152	246	173	153	39	27

The Indicator Modules

The indicator modules calculate the sustainability indicators. They post-process the output of the land-use transport models. Four indicator modules are implemented in the system: the *Raster Module*, the *Economic Indicator Module*, the *Justice Indicator Module* and the *Other Sustainability Indicator Module*. The output of the indicator modules are values of the sustainability indicators listed in Table 1.

The *Raster Module* calculates indicators for which a disaggregate treatment of space is required. The land-use transport models are not directly capable of capturing important aspects of urban sustainability because their zone-based spatial resolution is too coarse to represent other environmental phenomena than total resource use, total energy consumption or total CO_2 emissions. In particular emission-concentration algorithms such as air dispersion, noise propagation, but also land coverage, landscape fragmentation or the exposure of population to pollutants and noise, require a much higher spatial resolution than large zones. In all cases, the information needed is configurational. This implies that not only the attributes of the components of the modelled system such as quantity or cost are of interest but also their physical *micro locations*. This is where the Raster Module comes into play. It maintains the zonal organisation of the aggregate land-use transport model but complements it by a disaggregate representation of space in 100 x 100 m raster cells for the calculation of local environmental and social impacts of policies (Spiekermann, 1999; 2003; Spiekermann and Wegener, 1999; 2000). The Raster Module calculates most environmental indicators, the exposure indicators and an indicator of accessibility to open space. In addition the Raster Module feeds the Economic Indicator Module with information on emission and noise exposure and the Justice Indicator Module with information on exposure of different socio-economic groups to air pollution and noise (see Section 3.2 for more details).

The *Economic Indicator Module* performs a cost benefit analysis of the transport sector. Single indicators address transport investment costs, user, operator and governmental benefits as well as external costs of transport (noise, pollution and accidents). Indicators are summed up in a synthetic economic index that shows the overall economic impact.

The *Justice Indicator Module* addresses equity implications of the investigated policies. It translates the percent of people of different socio-economic groups who are exposed to air pollution and traffic noise into equity indicators. Four different theories of justice are incorporated in the module: the equal-shares principle, the utilitarian principle, the egalitarian principle and the Rawlsian difference principle.

The *Other Sustainability Indicator Module* calculates a small set of indicators which is not covered by the previous modules but may of general interest for understanding the behaviour of the urban system, such as zonal population and employment, modal shares and car-km travelled.

The Evaluation and Presentation Modules

Finally, the indicators are evaluated by a multicriteria evaluation tool and analysed and presented in a harmonised way for comparisons between policies and between cities.

The multicriteria evaluation tool *USE-IT* determines the sustainability of policies with respect to environmental, social and economic sustainability. It calculates the contribution of each indicator to sustainability and aggregates them to the sustainability themes and components defined in Table 1.

Value functions are used to transform the indicator values to a scale from zero to one by taking target values agreed within the project group into account. Indicators are given weights for aggregation to indices. The weights are the outcome of an internal expert survey performed to determine a common set of weights for all case study cities. In addition, local value systems are explored to determine weights in the local contexts. Indices are formed as weighted averages of the evaluated indicators. Aggregation is performed separately for the environmental, social and economic components of sustainability. A single index aggregating the three components is not calculated to avoid double-counting, because some aspects are considered in more than one component, i.e. are treated from different viewpoints.

An Internet-based *Analysis and Presentation Tool* presents the results of the policy testing for all cities in a standardised format. The tool analyses and displays sustainability indicators and background variables for comparison between policies and between cities. The Internet tool is designed to be used by planners and policy makers in the case study regions to make it easier for them to understand the impacts of policy decisions and so aid them in the process of selecting the most appropriate policy measures.

3.2 The Working of the Raster Module

This section presents one of the indicator modules, the Raster Module, in more detail. The task of the Raster Module is to calculate micro-scale indicators meaningful for urban sustainability such as land coverage, biodiversity, air pollution or exposure to air pollution that cannot be calculated by the aggregate urban models. The Raster Module is a new element in land-use transport modelling as it introduces a disaggregate representation of the study area. By doing this it maintains the zonal organisation of the land-use transport models and adds a raster-based representation of space for environmental and social impact submodels (Spiekermann, 2003).

As the Raster Module is based on the outputs of the aggregate urban models, several steps have to be undertaken to arrive from the polygon representation of model zones and the line representation of networks to raster-based environmental and social indicators.

There are two main sources of input for the Raster Module. On the one hand there is a spatial database containing zone boundaries and land use categories coded as polygons and the network links coded as vectors. On the other hand there are the policy-dependent forecasts by the land-use transport models for the location of population by socio-economic group, employment and floorspace in the zones and the traffic flows on the links of the network.

This information is converted to raster cells of 100 x 100 m in size. The main assumption concerning the disaggregation of activity locations is that population and employment are not equally distributed over the territory of a zone but that there are differences in density. The assumption of intra-zonal differentiation is reflected by weights assigned to the raster cells based on typical densities of land use categories (e.g. Bosserhof, 2000). These weights are converted to probabilities by dividing them by the zonal total of weights. This gives a probability distribution of population in a zone. Cumulating the weights over the cells of a zone one gets a range of numbers associated with each cell. Using a random number generator for each person a cell is selected as the person's location. The allocation of persons takes account of different weighting schemes for three socio-economic groups. If the land-use transport models forecast an increase in zonal floor space for residential purposes the module is extending the housing areas by looking at neighbourhood relationships, i.e. an appropriate number of additional raster cells next to already occupied raster cells are used for new development. The disaggregation of employment follows the same procedure but with different weights (for details, see Spiekermann and Wegener, 2000).

The result of the population and employment disaggregation are artificial micro data that are controlled by zonal totals and of which the intrazonal allocation follows empirical observed patterns and additional information such as land use. The raster representation of three socio-economic population groups and employment is used for the localisation of intrazonal and access trips and the calculation of land coverage. In addition, the raster representation serves as a proxy for barriers in the dispersion models, where the population is also considered as recipient of pollutants and noise.

Raster disaggregation is also applied to the network data. The transport flows forecast by the transport model (number of cars, trucks and buses, speed by link) is related to the information in the GIS database which contains the alignment of each link. Because the transport models consider network links as straight lines between nodes, the alignment is required to localise the emission points for subsequent environmental modelling more accurately. The rasterisation of the networks is straightforward: The raster grid is overlaid over the network.

Each raster cell traversed by a network link receives the information assigned to the link, i.e. the number of cars, trucks and buses and the average speed on the link. The results of the network disaggregation are five raster layers representing urban traffic: three of them contain the number of cars, trucks and buses, the other contain the dominant link type and the average speed in each raster cell.

Using this information, environmental and social impact submodels are used to assess emissions, air quality for several pollutants and noise levels, population exposure, environmental quality and accessibility in each raster cell:

- The *emission submodel* relates the information on traffic flows with up-to date emission functions (Hickman et al., 1999, Journad, 1999). Whereas the transport models forecast only the number of basic vehicle types (cars, lorries, buses) on a road link, the emission submodel disaggregates these numbers into about 85 different vehicle types with different emission characteristics according to the overall composition of the vehicle fleet in that urban region. Future technological developments and foreseeable environmental regulations are taken into account by changing the composition of the vehicle fleet over time. The emission submodel calculates also the consumption of mineral oil products by transport (based on Ntziachristos and Samaras, 2000).
- The *air pollution and exposure submodel* models the chain from emissions to exposure for the whole study area by applying a Gaussian air dispersion model to the emissions and by relating the resulting concentration to the living places of population. The raster cells are considered point sources of emissions. The air dispersion model is applied sequentially to all emission cells. The concentrations in a receptor raster cell received from all emission raster cells are added up and related to population following European guidelines for air quality.
- The *noise submodel* models the sequence from noise generation via noise propagation to noise levels for all raster cells. It is based on the German guidelines for noise protection measures along roads, the so-called RLS-90 (BMV, 1990). For the implementation of this model in a raster framework some modifications and simplifications had to be made with respect to road surface, slope, meteorological conditions and intersections. The result is a raster layer that contains for each cell the traffic noise level in dB(A) which is then related to the population living in those cells.
- The *environmental quality submodel* calculates land coverage and two indicators related to open space. Open space is defined as raster cells without transport links, population and employment. A fragmentation index is calculated as the average size of contiguous open space areas, based on the rationale that a less fragmented urban region provides a potentially better living environment for rare species than areas with higher degrees of fragmentation. For assessing the quality of open space, the noise level is taken into account. High-quality open space is calculated as the area not disturbed by traffic noise.
- The *accessibility to open space submodel* assesses the living environment in terms of open space usable by the inhabitants. For this a potential accessibility indicator was developed in which the attraction term is open space and the impedance is walking distance.

The output of the *Raster Module* consists of eleven of the PROPOLIS sustainability indicators. In addition, the Raster Module generates graphical presentations in form of maps showing air quality, noise levels, environmental quality and accessibility (see examples in

Section.4). The Raster Module provides also input for the Economic Indicator Module and the Justice Indicator Module (see Section 3.1).

3.3 Implementation and Policy Testing

Figure 2 shows how the system is used to define strategies that increase urban sustainability. The model system is the core of the policy analysis. First single policies are defined and introduced into the system. Policies include land use, transport, pricing and regulatory and investment policies. The evaluation of policies and the comparison between policies and between cities may lead to a reformulation of policies ('Replanning'). Replanning includes the refinement of policies, e.g. finding an optimal level of a pricing policy, but also experimenting with policy combinations to improve the results. The final output of the systematic policy tests are general and city-specific recommendations which policies or combinations of policies are likely to contribute most to sustainable development.

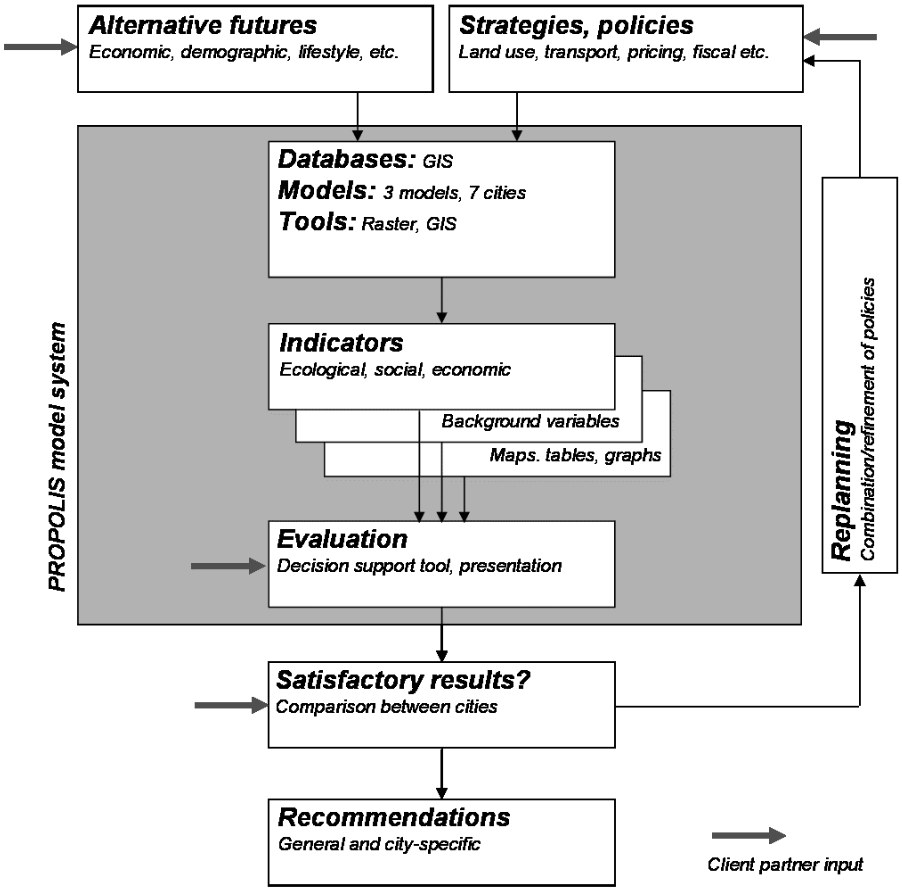

Figure 2. Policy testing process

The PROPOLIS system offers various points at which planners and policy makers in the case study regions may intervene and introduce their ideas and values into the modelling and evaluation process. They may contribute to the formulation of the assumptions about external developments for the models, such as assumptions about the likely overall economic development of the region or about migration flows across the regions' borders. Or they may want to test the impacts of alternative assumptions about external developments. An important task of the local partners is to contribute to the formulation of strategies and policies common for all case study cities or specific to their regions. Finally, the local experts are asked to indicate their values, i.e. enter their own weights into the evaluation system.

4. Results for the Dortmund Urban Region

In this section selected results of the modelling work for the Dortmund case study region are presented (for results for all case studies see Lautso et al., 2004). The first part presents examples of results produced by the Raster Module for the Dortmund urban region, the second part presents the evaluated results for the case study region.

The Dortmund case study region is the urban region of Dortmund consisting of the city of Dortmund and 25 surrounding municipalities. The region is subdivided into 246 statistical areas or zones (Figure 3). However, as it was explained in Section 3.2, the spatial resolution of zones is not sufficient for the simulation of environmental impacts, such as air quality and traffic noise. Therefore the zone-based and link-based results of the land-use transport model are disaggregated to raster cells by the *Raster Module* (see Section 3.1.2). In the Dortmund case study, raster cells of 100 x 100 m size are used to model environmental impacts. In total, about 207,000 raster cells cover the study area.

Figure 3. The Dortmund case study region

4.1 Environmental Indicators

The land-use transport models predict long term changes in the urban land use and transport system. The Raster Module (see Figure 1) uses the output of the land-use transport models (zone data and link flows), disaggregates it to raster cells using GIS information and produce some of the sustainability indicators. Figures 4 and 5 show examples of raster-based output of environmental indicators in the Dortmund urban region.

Figure 4 (top) shows exposure to traffic noise for the current situation in the Dortmund urban region. Based on the transport model output of number, type and speed of vehicles on the links of the road network, noise emission and propagation are calculated (see Section 3.2). To take into account that buildings along the roadways act as noise barriers, assumptions about the reduction of noise propagation in areas of higher density are made. As also population by socio-economic group is disaggregated to raster cells, it is possible to calculate how many people in each neighbourhood and in each socio-economic group are exposed to which level of traffic noise. This information is used for the health and equity indicators in the system of indicators (see Table 1). Figure 4 (bottom) displays changes in noise level for each raster cell between the current situation and the future reference scenario.

In Figure 5 (top) traffic noise corridors as presented in Figure 4 are overlaid with open space. It is assumed that only those parts of open space which are not disturbed by traffic noise of more than 45 dB(A) are of value for recreation and wildlife and can therefore serve as an indicator of the quality of open space. Figure 5 (bottom) shows another indicator related to open space: walking accessibility to open space (see Section 3.2).

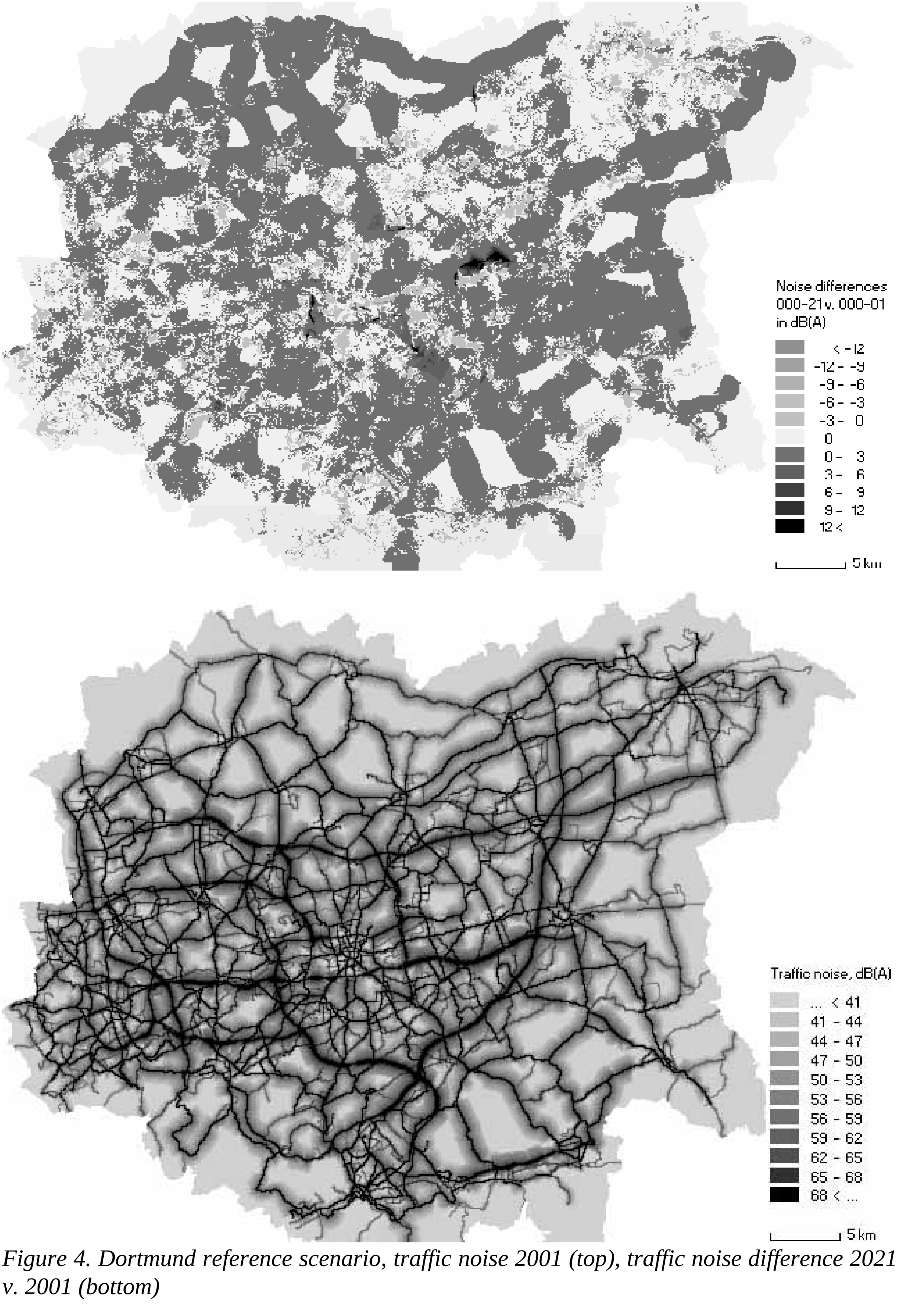

Figure 4. Dortmund reference scenario, traffic noise 2001 (top), traffic noise difference 2021 v. 2001 (bottom)

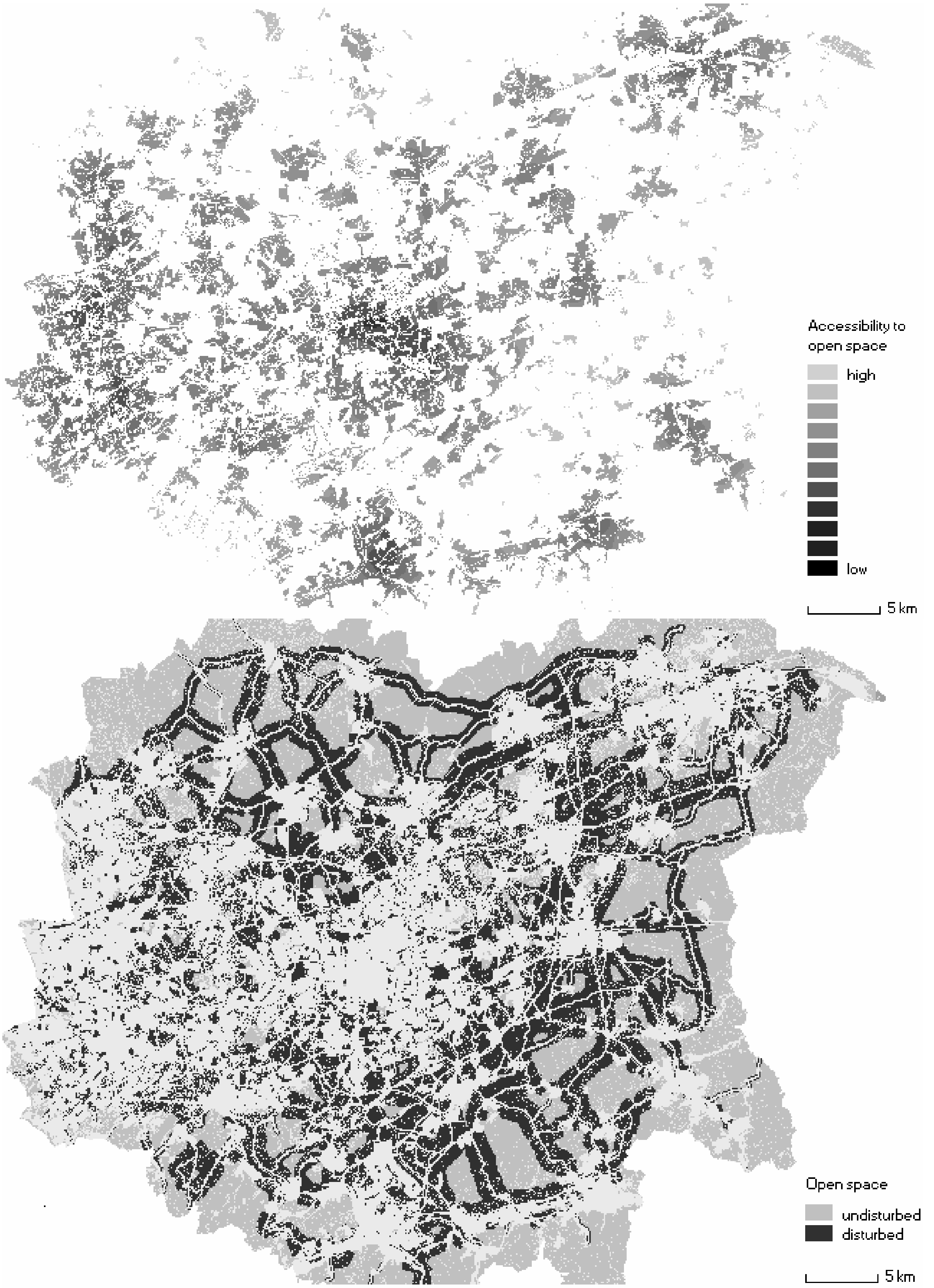

Figure 5. Quality of open space (top) and accessibility to open space (bottom) in the Dortmund region

4.2 Sustainability Evaluation

For policy evaluation with the PROPOLIS system in the Dortmund urban region, a set of 24 policies were defined of which 20 policies are common to all PROPOLIS case studies and four are specific policies for Dortmund. Table 3 lists the policies and indicates the year in which the policy was assumed to be implemented. There were two policies with city-specific investment programmes (policies 111 and 112), nine pricing policies addressing car operating costs, parking prices and cordon pricing in the inner city (211 - 232), two regulation policies reducing maximum speeds on the road network (311 and 321), three public transport policies reducing travel times or fares (411 - 421), three land use policies that concentrate development in selected areas within the urban region (511 - 541) and eventually four combination policies linking selected policies of the previous categories (711 - 719).

As it was explained in Section 3.1.3, the indicators calculated by the indicator modules are evaluated by the multicriteria evaluation tool *USE-IT*. Figure 6 shows output of USE-IT at the highest level of aggregation for the comparison between policies, i.e. the environmental and social indices for all tested policies and also the assessment of the base and mid-year of the reference scenario as well as the contribution of each theme to the total indicator value (for detailed results for Dortmund and the other case study regions, see Lautso et al., 2004).

- *Environmental evaluation*. The environmental evaluation shows that, like in the other case study cities, the environmental quality in Dortmund in the reference scenario decreases between 2001 and 2021. The assessment yields that only policies or policy combinations in which car travel is made more expensive, make a significant contribution to sustainable urban development, and that this contribution increases with the level of car pricing. Policy 219, which assumes the strongest increase of fuel tax, scores best on the environmental index for all policies. The combination policies are always better then their policy components; policy combination 713, which includes accompanying land use policies, and policy combination 719, which in addition includes the high fuel tax increase of policy 219, score best.

Table 3. Policies evaluated in the Dortmund urban region

			2001	**2006**	**2011**	**2016**	**2021**
POLICY Type	Code	POLICY	*Base year*		*Intermediate year*		*Horizon year*
Base	000	Reference scenario					
Investment policies	111	Additional investments in public transport					
	112	Public transport infrastructure for the 'dortmund project'					
Pricing	211	Car operating costs +25%		25%	25%	25%	25%
	212	Car operating costs +50%		25%	50%	50%	50%
	213	Car operating costs +100%		25%	50%	100%	100%
	214	Car operating costs +75%		50%	75%	75%	75%
	219	Car operating costs +300%		25%	50%	200%	300%

	221	Parking price increase, + 20/10 minutes time value in/around city	X			
	222	Parking price increase, + 60/30 minutes time value in/around city	X			
	231	Cordon pricing, + 20 minutes time value	X			
	232	Cordon pricing, + 60 minutes time value	X			
Regulation	311	Max speed - 10% on all road network	X			
	321	Max speed -20% on other than motorway and main roads	X			
Public transport	411	PT travel time –10%	5%	10%	10%	10%
	412	PT travel time –5%	-2.5%	-5%	-5%	-5%
	421	PT fares –50%	-50%	-50%	-50%	-50%
Land use policies	511	Increase housing density in city centre	X			
	521	Concentrate the expansion of the residential/tertiary at rail stations	X			
	541	Concentrate the expansion of the residential/tertiary in Dortmund	X			

- *Social evaluation*. In the social evaluation, too the index declines in the reference scenario between 2001 and 2021, and only the car pricing policies or the policy combinations which include car pricing policies can halt or reverse this trend. It is interesting to note that higher fuel taxes score better and not worse in terms of opportunity and equity, in contrast to fears that they would discriminate low-income households. It is also interesting to note that the high scores of the car pricing polices are partly caused by positive effects in the health component, such as less air pollution, noise and accidents. It is surprising that policy combination 719 scores worse than policy 219, even though it provides additional incentives. The reason is the choice of accessibility indicator which awards suppressed mobility.

The results of the policy test for Dortmund are summarised in the correlation diagram of Figure 7. The diagram shows the 24 scenarios simulated for Dortmund in a two-dimensional space in which the score of the environmental index is presented on the horizontal axis and the score of the social index on the vertical axis. Each scenario is represented by a combination of environmental and social index scores. The score of the economic index is indicated by the colour and shape of the marker representing a scenario, where a green square indicates a positive and a red diamond a negative per-capita benefit. The three dark blue circles represent the reference scenario in the years 2001, 2011 and 2021. As already noted, in the reference scenario both environmental and social quality decrease over time.

The diagram shows that in general policies with a high score of the environmental index are also socially sustainable. This is an important result as usually a goal conflict between environmental and social objectives is assumed. There is one exception, policy combination 719, which contains 'pull' measures making public transport more attractive and strong 'push' measures making car travel less attractive and land use policies promoting higher-density

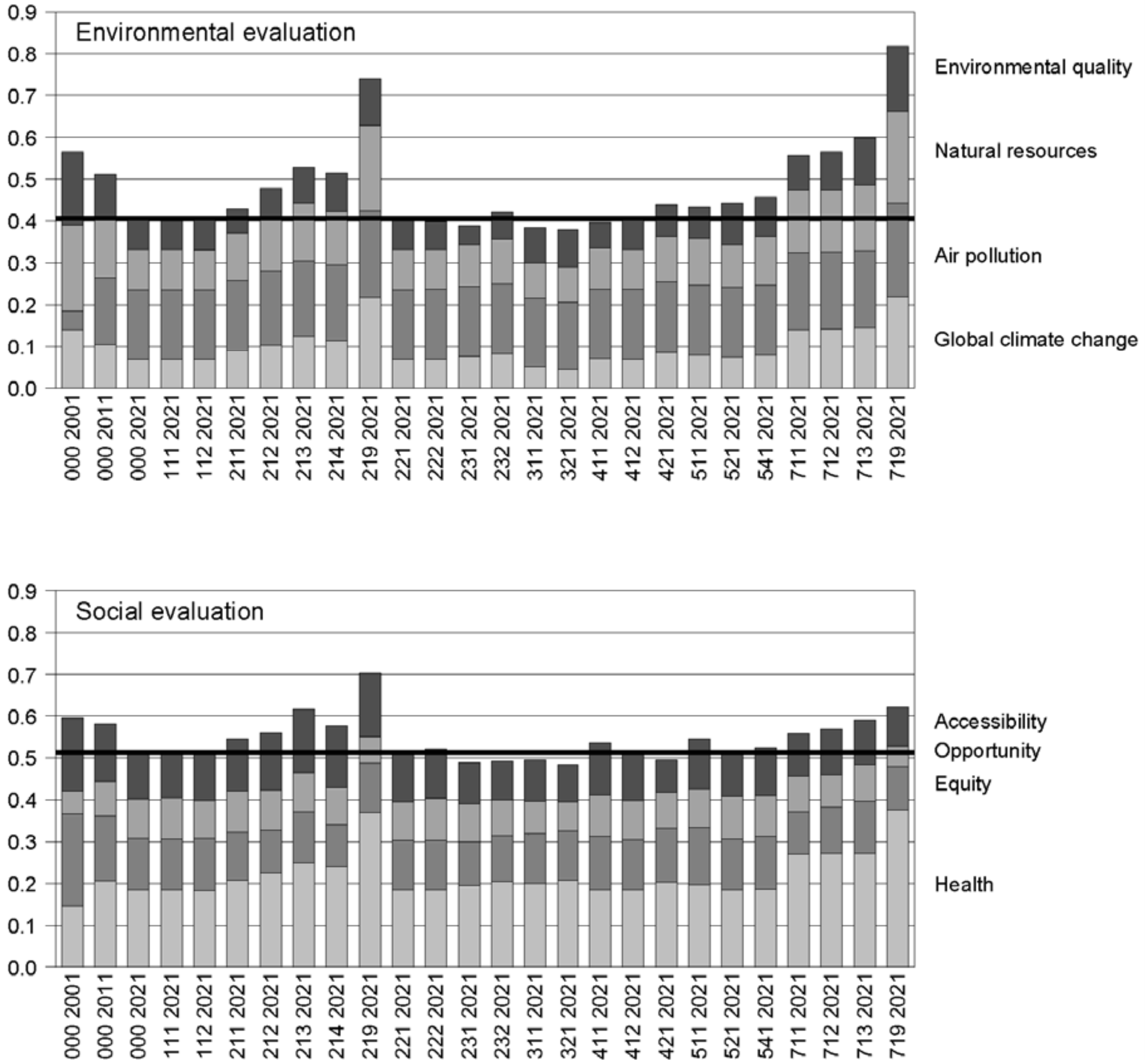

Figure 6. Dortmund policy evaluation: environmental and social indices

mixed land use. Scenario 719 scores very high in terms of environment but not equally high in terms of the social index (though still higher than any other scenario except scenario 219 which it includes). As explained earlier, this is due to the accessibility indicator used in the social evaluation, which fails to recognise the benefit of increased mobility in the scenario.

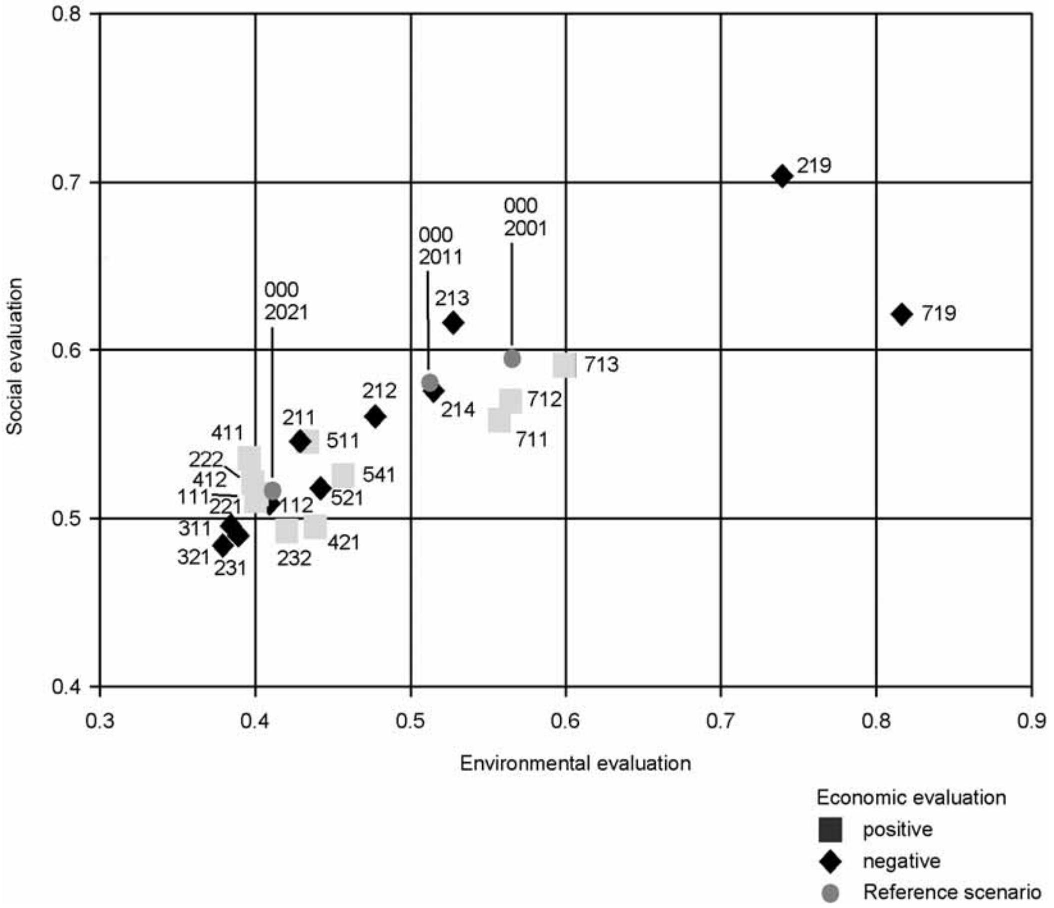

Figure 7. Dortmund policy evaluation: three indices correlated

Most policy scenarios are not able to reverse the declining trend of the reference scenario in both the environmental and social dimension. Only few policies and policy combinations come close to or exceed the scores of the base year of the reference scenario, and all of these are car pricing scenarios.

There is little correlation between the economic index and the other two indices. However, this may be due to the fact that not all government benefits such as taxes on ticket sales, could be fully accounted for, whereas parking charges in scenarios 221 and 222 were. With this caveat with respect to the economic index it can be concluded that policies making car travel moderately more expensive tend to be also economically viable. However, this result is tentative and points to the need for further research.

5. Conclusions

This paper presented a model system developed to simulate and evaluate the impacts of land use and transport policies on sustainability in seven European urban regions and selected results for one of the urban regions.

The PROPOLIS system of sustainability indicators differs from other sustainability indicator systems. Other systems are based on monitoring approaches in which the quantities in question are directly observed or measured, whereas in PROPOLIS the indicators are modelled, i.e. forecast. Another distinction is that the PROPOLIS indicators were chosen as near as possible to the tail-ends of causal chains. For example, vehicle kilometres or average travel times are not presented as indicators for sustainability but emissions or numbers of residents in the most polluted areas.

The land-use transport models implemented in PROPOLIS are integrated with geographic information systems. All model zones and network links have their direct correspondence in a GIS. Tools were developed to exchange information back and forth between the models and the GIS, such as tools for editing links and link attributes in the GIS and to load them into the models. In this way the land-use transport models follow the trend to link spatial models to georeferenced data (Fotheringham and Wegener, 2000). GIS integration is a precondition for linking land-use transport models with environmental impact modules.

The PROPOLIS model system is one of the first attempts to address the issue of urban sustainability in a comprehensive long-term forecasting framework. The model system moves from two-way land-use transport modelling towards three-way land-use transport environment modelling (LTE). The Raster Module is instrumental in overcoming the formerly separate modelling traditions. It makes the aggregate urban models more disaggregate in spatial terms by post-processing their zone and link-based output and linking it to the raster-based environmental and social impact models integrated in it. In this way, the PROPOLIS modelling system addresses several important indicators for sustainability not covered by other urban modelling approaches. However the feedback from environment to land use and transport, i.e. the way by which changes in environmental quality affect location decisions of investors, firms and households and so indirectly also influence activity and mobility patterns, has so far been only poorly developed (Spiekermann and Wegener, 2003),

The results for the Dortmund region have shown that most policy scenarios are not able to reverse the declining trend of the reference scenario in both the environmental and social dimension of sustainability. Only few policies and policy combinations come close to or exceed the scores of the base year of the reference scenario, and all of these are car pricing scenarios. Accordingly, a promising policy strategy to improve urban sustainability consists of coordinated elements that work together to produce cumulative long-term effects that attain a balanced set of environmental, social and economic goals. These elements include combinations of pricing policies mainly directed at car users, investment programmes supporting the changes in demand caused by the pricing policies and land use planning making it possible for the population to live near central areas or along well served public transport corridors to compensate for higher car operating costs. Such a policy line is likely, as demonstrated in all PROPOLIS case cities (Lautso et al., 2004), to improve all dimensions of urban sustainability in typical European cities compared with their reference scenarios and might even enhance the current level of sustainability.

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