

## **A framework for integrated assessment modelling**

Nadège Blond, C. Carnevale, J. Douros, G. Finzi, G. Guariso, S. Janssen, G. Maffei, A. Martilli, E. Pisoni, Elsa Real, et al.

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# Chapter 2

## A Framework for Integrated Assessment Modelling

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### 2.1 Introduction

“Air quality plans” according to Air Quality Directive 2008/50/EC Art. 23 are the strategic element to be developed, with the aim to reliably meet ambient air quality standards in a cost-effective way. This chapter provides a general framework to develop and assess such plans along the lines of the European Commission’s basic

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ideas to implement effective emission reduction measures at local, regional, and national level. This methodological point of view also allows to analyse the existing integrated approaches.

### ***2.1.1 The DPSIR Framework Concept***

To comply with the above aims requires the key elements of an Integrated Assessment Modelling (IAM) approach to be carefully defined. These elements will be derived by the general EEA DPSIR scheme (EEA 2012) and a holistic approach. The overall framework should:

- Be structured in a modular way, with data flows connecting each building block;
- Be interconnected to higher decision levels (i.e. national and European scales);
- Consider the approaches available to evaluate IAM variability (taking into account both the concept of “uncertainty”, that is related to “variables/model results” that can be compared with real data, and the concept of “indefiniteness”, related to the impacts of future policy decisions)
- Be sufficiently general to include the current experiences/approaches (presented in the next chapter) and,
- Show, for each module of the framework, different “levels of implementation complexity”.

The last two points are quite important. The idea is that, looking at the different “levels of complexity” defined for each DPSIR block, one should be able to grasp in which “direction” to move to improve the detail (and, hopefully, the quality) of his own IAM implementation. This should translate into the possibility to assess the pros and cons for enhancing the level of detail of the description of each block in a given IAM implementation, and thus compare possible improvement with the related effort. The final idea is to be able to classify existing European plans and projects, with the aim not to provide an assessment value of the plans themselves, but to show possible “directions” of improvement, for each building block of each plan.

In the next section, at first, a general overview of the proposed framework will be provided. Then, each building block will be described in detail, focusing on input, functionality, output, synergies among scales, and uncertainty and defining three possible tiers of different complexity.

## **2.2 A General Overview of the IAM Framework**

The DPSIR analytical concept (Fig. 2.1) is the causal framework for describing the interactions between society and environment, adopted by the European Environment Agency. The building blocks of this scheme are:

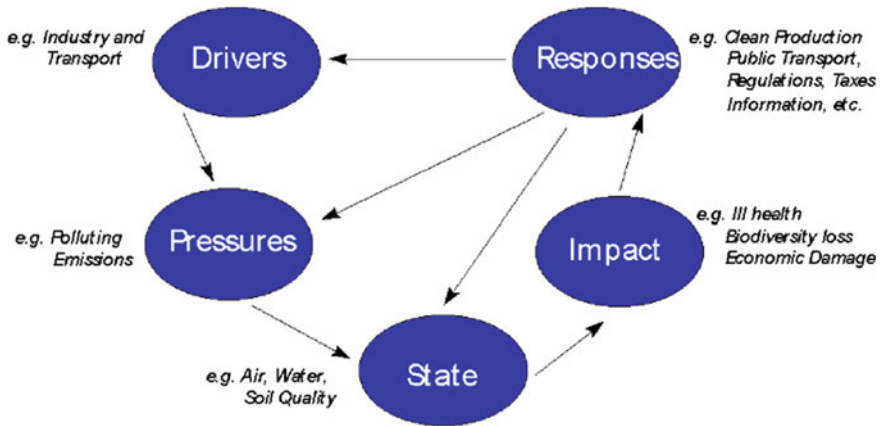


Fig. 2.1 The general DPSIR scheme (source <http://www.eea.europa.eu/>)

- DRIVING FORCES,
- PRESSURES,
- STATE,
- IMPACT,
- RESPONSES,

and represent an extension of the PSR model developed by OECD (definitions from *EEA glossary*, available at <http://glossary.eea.europa.eu>).

The DPSIR scheme helps “to structure thinking about the interplay between the environment and socioeconomic activities”, and “support in designing assessments, identifying indicators, and communicating results” (EEA 2012). Furthermore, a set of DPSIR indicators has been proposed, that helps to reduce efforts for collecting data and information by focusing on a few elements, and to make data comparable between institutions and countries. Starting from these definitions and features, it has been decided to adapt the DPSIR scheme to IAM at regional/local scale (considering with this definition domains of few hundreds kilometres). So the DPSIR scheme shown in Fig. 2.1 has been translated into the framework illustrated in Fig. 2.2.

In particular, in the scheme in Fig. 2.2, the meaning of each block is as follows (quoting again from *EEA glossary*):

- **DRIVERS**: this block describes the “actions resulting from or influenced by human/natural activity or intervention”. Here we refer to variables (often called “activity levels”) describing traffic, industries, residential heating, etc.
- **PRESSURES** (Emissions): this block describes the “discharge of pollutants into the atmosphere from stationary sources such as smokestacks, and from surface areas of commercial or industrial facilities and mobile sources, for example, motor vehicles, locomotives and aircrafts.” PRESSURES depend on DRIVERS, and are computed as function of the activity levels and the quantity of pollution emitted per activity unit (emission factor).

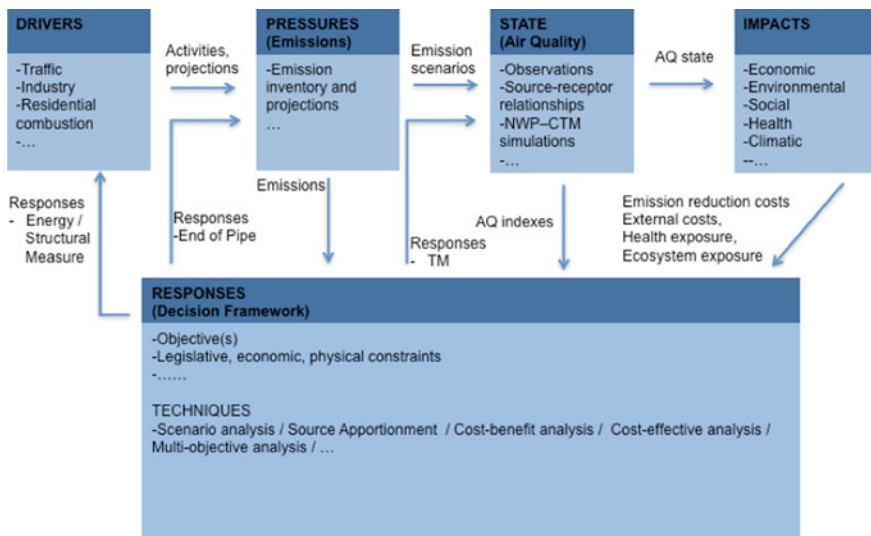


Fig. 2.2 The DPSIR scheme adapted to IAM of air quality at regional/local scale

- **STATE** (Air quality): this block describes the “condition of different environmental compartments and systems“. Here, we refer to STATE as the concentrations of air pollutants resulting from the PRESSURES defined in the previous block. In IAM implementations, STATE can sometimes be directly measured, but more often it is computed using some kind of air quality model.
- **IMPACT**: this block describes “any alteration of environmental conditions or creation of a new set of environmental conditions, adverse or beneficial, caused or induced by the action or set of actions under consideration“. In the proposed framework, we refer to IMPACT on human health, vegetation, ecosystem, etc. derived by a modification of the STATE. Again the calculation of the IMPACT may be based on some measure, but normally requires a set of models (e.g. health impacts are often evaluated using dose-response functions).
- **RESPONSES**: this block describes the “attempts to prevent, compensate, ameliorate or adapt to changes in the state of the environment“. In our framework, this block describes all the measures that could be applied, at a regional/local scale, to improve the STATE and reduce IMPACT.

It is worthwhile to note that the scheme in Fig. 2.2 is integrated with “higher” decision levels. This means that for each block some information is provided by “external” (not described in the scheme) components. For instance, the variables under DRIVERS may depend on GDP growth, population dynamics, etc.; the STATE may also depend on pollution coming from other regions/states; or the RESPONSES may be constrained by economic factors. Each block can thus be seen as receiving external forcing inputs that are not shown explicitly in Fig. 2.2, since they cannot be influenced (or just marginally) by the actions under consideration.

More specifically, all regional and local plans are to be compatible with national and international policies. These “scale” issues are discussed in the next sections.

## 2.3 A Detailed Analysis of the IAM Framework Modules

In this section, all the five building blocks of the IAM framework will be discussed in detail, considering their “input”, “functionality”, “output”, “synergies among scales” and “uncertainty”. The “functionality” is the core part of the description, and defines the cause-effect relationship between input and output.

### 2.3.1 Drivers

The basic function of the DRIVERS block is to model the development of key driving activities (i.e. road traffic, off-road traffic and machinery, residential combustion, centralized energy production, industry, agriculture) over time (Amann et al. 2011). It thereby provides input to the PRESSURES block in the form of, e.g., road traffic kilometres driven, residential heating fuel consumption, etc. (dis)aggregated in such a way that it includes emission-wise relevant classification of sectors, sources and technologies.

To provide relevant information to the PRESSURES block, DRIVERS have to be quantified with specific measurable variables. For instance, special attention has been given in European plans to the sectors that are important for urban air quality (road traffic, residential heating, industry). The next Table 2.1 gives an overview of the most important activity parameters used to quantify each of these sectors.

#### Input

Input parameters are factors that represent causes of emission-wise essential activities. Important input parameters include general factors such as population, general economic activities (e.g. in the form of GDP), more specific activity factors (e.g. sector specific production intensities, transport demand, energy demand etc.) and technology change factors (e.g. vehicle stock structure, energy efficiency of buildings etc.) that may be driven by international, national or local requirements or “natural”, non-forced development.

**Table 2.1** Parameters commonly used to quantify relevant urban activities

Sector	Key activity parameters
Road traffic	Kilometres driven, fuel consumption
Off-road and machinery	Fuel consumption
Residential combustion	Fuel consumption, heat production
Energy production and industry	Fuel consumption, energy/industrial production

## Functionality

The functionality expresses the cause-effect relationship (or model) between the input and the output, e.g. considering how transport demand of goods and people translates into kilometres driven and/or fuels used in different types of vehicles. While for some “base” period (often a past year for which a fairly complete set of data exists) an inventory is often adequate to attain directly the output of the DRIVERS block (e.g. transport kilometres driven or fuel used), for projections into the future the input-functionality-output chain needs to respond to the assumed future changes in economic activities, technology developments, etc. This chain can be implemented at different levels of complexity, from simple calculation of cause-effect relationships to detailed traffic, housing and energy system models. City or regional level assessments can be implemented using local information (bottom-up), or derived from national level models (top-down), or as a combination of both approaches. Models with dynamic spatial capabilities are desirable to be able to assess changes in spatial patterns of activities.

In general, for the DRIVERS block implementation, the following three-level classification can be adopted:

- **LEVEL 1:** when a top-down approach is applied, using coarse spatial and temporal allocation schemes;
- **LEVEL 2:** when a bottom-up approach with generic (i.e. national/aggregated) assumptions is applied, using realistic spatial and temporal allocation schemes;
- **LEVEL 3:** when a bottom-up approach with specific (i.e. local/detailed) assumptions is applied, using local spatial and temporal allocation schemes.

In the following sections, a more detailed description of the DRIVERS block implementation will be provided, focusing on two important aspects of DRIVERS, that is to say:

- Base year inventory and projections;
- Spatial and temporal assessment.

## Base Year Inventory and Projections

The inventory of activities and emission-wise relevant technologies can be based on the data collected or modelled from the respective city area or region (bottom-up approach), or on statistics of a wider area (typically a country) of which the share of the respective city area or region is defined using weighting surrogates (top-down approach).

In some cases it might be difficult to attain reliable, representative collected data from certain areas. For instance, technology stock inventory at sub-national level is often not practical, and national level data have to be used. In case of a top-down approach, the reliability of the activity estimate depends on the representativeness of the weighting surrogates used.

For future projections, it is particularly important that the changes in time of the input of the DRIVERS block (e.g. changes in population, economical activities, transport needs etc.) realistically translate into output (i.e. activities and

technologies). Therefore the assessment of future developments of the DRIVERS block typically requires a more sophisticated framework than what would be needed for the base year inventory.

In the following, the main emission source sectors are discussed in addition to the general three-level approach presented above.

**Road traffic** activities and projections are typically relatively well known at city level because these data are of interest also for other bodies than environmental assessment. In addition to factors affecting tail-pipe emissions, non-exhaust road dust emissions are an important impairer of air quality. Important parameters for non-exhaust emission factors, in addition to vehicle types, are tire type, road surface type and climate conditions. Transport demand based modelling approaches enable also assessment of spatial changes.

The three tiers classification presented above may be represented, for instance, by:

1. Allocation of traffic activity data from national level (top-down). The allocation may be based on population data (in relation to national total);
2. Activities based on city level traffic counts or other estimate (bottom-up), and allocation of vehicle categories and technologies based on national average (top-down);
3. Activities based on city level traffic counts or other estimate, distinguished for each vehicle category and technology using city level survey data (bottom-up) or other local data (e.g. city level traffic model).

Availability of activity data for **off-road traffic and machinery** is variable. For sea vessels, trains and airplanes, activities often are relatively well known. On the other hand, activity data can be much more uncertain for construction and maintenance machinery activities derived from national level because of the lack of appropriate weighting surrogates. However, reliable estimate on the changes in vehicle stock age structure is essential especially for traffic and machinery because of remarkable differences in emissions factors of various EURO standard levels. The level of complexity might be similar to that of road traffic taking into account that for each specific category (rail traffic, aviation, marine, harbours, military, agriculture machinery, industry, construction, maintenance, etc....) different proxy variables must be used.

**Residential combustion** activities are often relatively uncertain. Especially for residential wood combustion, which is a major concern from air quality perspective in many European cities because of its high fine particle emissions, bottom-up approaches can rarely be based on sale statistics because a lot of wood fuel is used privately. For future changes, several factors should be taken into account: competitiveness of different heating systems, prospects of citizens' preferences, renewal of heating appliance stock and its effect on emission factors, changes in fuel qualities, legal requirements (e.g. Eco-Design Directive). The use of detailed housing and/or zoning models could enable the assessment of spatial changes in the future.



In case there is no reliable estimate of local level activity or practicable procedure for top-down allocation, source apportionment techniques might be considered to detect an initial order-of-magnitude evaluation of the residential combustion activities.

Once again, the three-level classification may be characterized by:

1. Allocation from national level values (top-down). The allocation may be based on surrogate data representing residential combustion activity in a coarse manner, e.g., number of residential houses or population data (in relation to national total);
2. Based on city level estimates about respective activity (e.g. local sales statistics of fuels or surveys about fuel use), or allocated from national data using surrogates that represent residential combustion activity more realistically (e.g. average fuel use per household for different types of houses). Projections can be based on city level residential combustion for each fuel/heating type (bottom-up);
3. Activities distinguished for each house type and/or combustion technology categories using city level survey data (bottom-up) or other locally specific data (e.g. city level building heating/cooling model).

For **large energy production and industrial plants**, activity and technology information can be sometimes attained even at individual plant or process level. For projections, factors such as new plant or technology investments, agreed plants shut-offs, local level goals and agreements on e.g. renewable energy, effects of national level prospects in energy production and industry, changes in legal requirements (e.g. IE Directive) etc. should be taken into account.

The three-level classification may be given by:

1. Allocation from national level of energy/industrial production activity for each fuel/industrial product (top-down). The allocation may be based on production capacity or annual production (in relation to national total) and information about national averages of production and emission control technologies;
2. Based on local level total energy/industrial production activity amounts for each fuel/industrial product and information about production and emission control technologies data at local level;
3. Based on individual plant data about energy/industrial production activity amounts as well as production and emission control technologies.

**Agriculture** emissions are often disregarded in urban assessments. However, at national level, agriculture is often the major source of ammonia emissions and can be relatively important in PM emissions. Base year data include animal numbers, use of different types of animal houses and their ventilation and air treatment technologies, different manure application methods etc. Projections typically include development of animal numbers following national agriculture policies and/or market prospects of agricultural products.

### **Spatial and Temporal Assessment**

To provide appropriate information to the PRESSURE block, it is important to know not only the quantity but also the physical location and temporal variation of emission releases. Therefore, in order to be able to resolve the emissions in space and time, the activities (i.e. the DRIVERS block) must be allocated to certain grid and temporal patterns. The spatial aspect is particularly important in city or local level assessments for local emissions may cause considerable impacts on human populations.

The spatial allocation of point sources simply implies the association of the geographical location and height of the stack with the corresponding grid cell and vertical layer of the atmospheric model, respectively. Area emissions, by contrast, must be spatially allocated using again weighting factors, i.e. surrogates. The choice of surrogate parameters for different source sectors depends on the availability of data that would represent the emission distribution in a given sector at the desired spatial resolution. The temporal variation for different sectors can be based on internationally, nationally or locally defined default variations or local data (e.g. questionnaires or observed data). The following provides a proposal for three levels of complexity in spatial and temporal assessment for different source sectors.

**Road traffic** network is typically available for spatial allocation. To distinguish between more or less busy roads and different driving conditions, availability of data may vary. Non-exhaust emissions vary highly in space and time depending also on other factors than driving amounts and conditions or vehicle technology (e.g. road surface type and condition, seasonal and hourly climate conditions). These factors might be difficult to take into account with a reasonable accuracy without specific road dust models.

A three-level classification might be:

1. Spatial assessment based on road network data with coarse traffic allocation scheme (e.g. using road type classification to distinguish more and less trafficked roads). Temporal variation based on general default variations.
2. Spatial assessment based on road network data with more realistic representation of traffic flows (e.g. actual traffic counts for each road segment). Temporal variation based on nationally or locally defined default variations.
3. Spatial assessment based on road network data with representation of district traffic flows for vehicle categories and/or driving conditions (e.g. based on a city level traffic model). Traffic demand based modelling approaches are desirable to assess spatial changes in future projections. Temporal variation should be based on locally observed data.

Data availability for spatial allocation of **off-road traffic and machinery** is variable. For some forms, the locations of activities are relatively well known, e.g. for sea vessels, trains and airplanes. For many forms of machinery, in contrast, the basis for spatial allocation can be much more complex.

Three-level classification:

1. Coarse spatial allocation scheme for each off-road and machinery sub-categories (e.g. gridding based on land use data about aviation, harbour, military, agricultural, industrial areas, population data, etc.). Temporal variation based on general national default variations.
2. Spatial allocation with more realistic representation of activity for each off-road and machinery sub-categories (e.g. gridding with estimate about the location of activity inside respective land-use classes). Temporal variation based on nationally or locally defined default variations.
3. Spatial allocation for each off-road and machinery sub-categories based on activity intensities in respective locations (e.g. based on train/aircraft/vessel movements, GPS data and/or activity model). Temporal variation based on locally observed data.

**Residential combustion** activities are often poorly registered, because in many countries/cities individual household level heating systems do not need licenses. Therefore spatial allocation has to be based on some more general household level data, e.g. building registers.

Three-level classification:

1. Coarse spatial allocation scheme for each residential heating fuels and/or main heating sub-categories (e.g. gridding based GIS data on number of residential houses or population data). Temporal variation based on general default variations.
2. Spatial allocation with more realistic representation of activity for each residential heating fuels and/or main heating sub-categories (e.g. gridding based on GIS data on number or floor area of different types of buildings or other relevant information that distinguishes residential fuel use intensities in different building types). Temporal variation based on nationally or locally defined default variations.
3. Spatial allocation for each relevant fuels and heating sub-categories with gridding based on information that distinguishes residential fuel use intensities on building-by-building basis (e.g. gridding based on GIS data on heating/cooling technologies in use and/or energy efficiency of buildings or city level building heating/cooling model with GIS capabilities). Housing and/or zoning modelling approaches are desirable to assess spatial changes in future projections. Temporal variation based on locally observed data.

**Centralized energy production and industrial plants** can often be dealt with as point sources, i.e. attain both location and activity and relevant technology data directly from the individual plant (level 3). However, sometimes such plant data are not available, and the spatial assessment of activities/technologies must be based on a surrogate type of approach. This means that the classification of complexity may again follow the three levels outlined above.

For **agriculture**, the requirements for its spatial resolution are not as high as for urban emission sources. Horizontal resolution of approx.  $10 \times 10 \text{ km}^2$  is often practical. In case detailed farm registers are available, activity estimates farm-by-farm basis (bottom-up) might be possible. However, at national level assessments, top-down allocation based on agricultural field areas or animal numbers might be sufficient.

### **Output**

The output of the DRIVERS block is used as an input to PRESSURES. Therefore it needs to contain all relevant activity information for emission calculation. Activities used in the emission calculation typically include fuel use amounts, production intensities and kilometres driven aggregated in such a way to include emission-wise relevant classification of sectors, sources and technologies. Technological changes over time are important parameters for emission calculation, and are taken into account in the PRESSURE block. Especially for city level assessments, spatial patterns of activities and their change over time are essential.

### **Synergies among scales**

Activity changes in the form of fuel switching and industrial production changes are affected largely at international (e.g. global markets) and national (e.g. national taxation) scale. On the other hand, population, housing and transport demand changes are affected largely at city (e.g. city taxation policies, general “attractiveness” of the city) and sub-city (e.g. traffic planning, zoning policies) scales.

Technological changes that are mainly of interest for the PRESSURE block are also affected at different scales. Many of the emission-related (e.g. traffic EURO standards, IE Directive) and climate-related (e.g. RE Directive) legislations that influence technological developments are defined at EU level. National level decisions may have a great impact as well (e.g. consumption or emission based vehicle taxation). At city level, it is possible to influence local problem spots (e.g. low emission zones, prohibitions of residential wood combustion) and set more general goals (city climate strategies) that influence technological developments.

### **Uncertainty**

A short summary of the main challenges for the above emission source sectors is given in the following.

- **Road traffic:** Traffic models and/or detailed road segment specific traffic information are relatively commonly available. Technological parameters are relatively well known at least at national level. Parameters required for reliable non-exhaust emission assessment (e.g. road surface type and condition) can be a considerable source of uncertainty.
- **Non-road traffic and machinery:** For some forms of non-road activities, e.g. sea vessels, trains and airplanes, activities and spatial patterns are often relatively well known. For many other forms of machinery, in contrast, the activity data can be much more uncertain.
- **Residential combustion:** Residential wood combustion activities and technology information are often uncertain because a lot of the wood fuel is used from

private stock directly, and household level heating system stock is poorly known. Furthermore, spatial assessment (i.e. gridding) of residential combustion activities is often uncertain because of the lack of building registers for residential heating appliances.

### 2.3.2 Pressures

Air pollutant emissions act as pressures on the environment. Thus, the block PRESSURES of the IAM corresponds to the computation of the quantity of pollutants emitted into the atmosphere from stationary sources (such as smokestacks), surface areas (commercial or industrial facilities), and mobile sources (for example, road vehicles, locomotives, aircrafts, ships, etc.). The emission of a pollutant can in general be measured (as in large point sources) or estimated. These are generally calculated as the product of the activity of the emitter times an emission factor, that is the quantity of pollutant emitted per unit of activity.

Other possible pressures that affect air pollution concentrations are related to change of urban structures (new buildings, parks, etc.) that can modify the dispersion of the pollutants and so the concentrations. Similarly, strategies to mitigate Urban Heat Island (white or green roofs, etc.) may also have an impact on concentrations without modifying the emissions. These structural modifications in the city-level emission patterns are relevant, but at the moment very complex to be incorporated into a IAM scheme, and so will not be considered in the following descriptions.

#### Input

An emission is computed for a specific pollutant, an emission source, a spatial and temporal resolution. An emission inventory is a database combining emissions with a specific geographical area and time period (usually yearly-based) containing:

- The activity of the emission sources. For instance: the volume and the type of fuel burned, the number of kilometres travelled by the vehicles, etc. The activity data could be derived from (economic) statistics, including energy statistics and balances, economic production rates, population data, etc.;
- The amount of pollutant emitted by these sources per unit of activity, i.e. the emission factors.

The emission inventory may have different level of details depending on the availability of the data and their uncertainties. Data could be given per each activity sector, technology and fuel. For application of IAMs, information on costs and rates of application of technologies has to be integrated (normally with the assumption that costs remain linear with respect to rates of application).

The methodology used to estimate emissions depends on the objective of the study, the availability of the data and their uncertainty. In case of lack of detailed activity data or/and emission factors, it is necessary to collect such data at higher

levels (national socioeconomic statistics, for example) to allow indirect calculations/estimations of the emission sources (Ponche 2002). Two main types of approaches are again distinguished:

- The top-down approach: used when, for a given area, there is lack of detailed data and to obtain the required emission resolution (scale) it is necessary to disaggregate the emissions calculated for a larger area. This approach computes the total amount of aggregated emission using for example data like total fuel consumption for the whole city or the whole country during a full year. This total is then distributed in time and space using the distribution of parameters linked with the activity responsible of the emissions (like population, road network, etc.).
- The bottom-up approach: used when for a given area numerous data at small scales can be collected and must be aggregated to higher scales. In the bottom-up approach, the emissions are directly computed from activity values in time and space.

The level of aggregation of the input data needed to apply these two types of methods is different. Usually, the bottom-up approach is preferred and also recommended to develop spatialized emission inventories (SEIs) and can reduce uncertainties. Nevertheless, the top-down approach is also generally used to control and correct the emission estimates. Applications show that in most cases the top-down and bottom-up approaches do not give the same results.

In order to harmonize European emission inventories, EMEP/EEA (2009a, b) proposed a guidebook with basic principles on how to construct an emissions inventory, the specific estimation methods and emission factors. In this guidebook, one key issue is the classification of the emission sources.

### **Classification of Emission Sources**

The emission sources are usually at first classified in two classes depending on the emission process: natural sources and anthropogenic sources. They are also classified in three categories depending on their geographic characteristics, location and type:

- point sources, that are precisely located and often concern industrial sites, where large amount of atmospheric pollutant are emitted from very a small area (compared to the space resolution of the emission inventory);
- line sources, that correspond to main transportation infrastructures. If the traffic (road, air, railway, ship) on these routes is dense enough (relatively to the time and space resolutions of the emission inventory), they can be considered as continuous emission lines;
- area sources, that include all other sources as residential areas, industrial areas, etc., where numerous small emitters are spread/diffused.

In order to categorize the anthropogenic sources, several classifications in terms of activity, sectors and fuel use were proposed. At European level, SNAP97 (Selected Nomenclature for Air Pollution) is a reference classification proposed by

EEA, while in the EMEP/EEA (2009a, b) guidebook, NFR (Nomenclature for Reporting) classification developed under the Convention on Long-range Transboundary Air Pollution is used. This classification is completed by the list NAPFUE (Nomenclature for Air Pollution of FUEls), which allows to take into account all kinds of fuels used in the emission processes. For specific national, regional or local circumstances or needs, activities may be detailed based on more resolved categories. To help this work with the SNAP classification, EMEP/EEA (2009a, b) proposes a methodology to identify the major pollutants involved from all anthropogenic and natural emission processes. This handbook of default emission factors is especially useful in case of lack of specific knowledge of the processes used in the investigation area.

### **Spatialized Emissions Inventories (SEIs), Scenarios and Projections**

Emission inventories are usually spatialized on a regular grid: the result is called spatialized emission inventory (SEI). The resulting SEI is used as input in the AQ part of an IAM to simulate the STATE, and is generally used as basis to simulate emission scenarios and projections.

Emission scenarios could be produced in several ways (EMEP/EEA 2009a, b) depending of the objectives of the studies:

- By modifying the activity index or data, as described in DRIVERS section.
- By modifying the emission factors of the emission generation processes. This includes new technologies or technological improvement, industrial processes, changes in fuel types or characteristics, energy saving (in terms of efficiency), composition of the vehicle fleet, etc.

The level of detail of the scenario is highly dependent on the level of classification of the sources and the data available for each category: in other words, the emission scenarios may be very simple and derived from the application of an emission reduction rate directly on the SEI; or they may be the results of assumptions on the future projections of the activities and the emission factors. Future emission factors should reflect technological advances, environmental regulations, deterioration in operating conditions and any expected changes in fuel formulations.

### **Functionality**

The functionality of the PRESSURES box of an IAM aims at producing emission data or/and emission projections. The PRESSURES can be estimated through three different levels of complexity, depending on their further uses and the available data:

- **LEVEL 1:** emissions are estimated for rough sectors on a coarse grid (spatialization), using a top-down methodology. Uncertainties are not necessarily estimated. This level does not allow to perform detailed emissions projections.
- **LEVEL 2:** a combination of bottom-up and top-down methodology is used to calculate the emissions with the SNAP—NAPFUE classifications. Emissions factors and activity data representative of the area of study are used when available. Uncertainties are not necessarily estimated.

- **LEVEL 3:** emissions are calculated with the finest space and time resolution available, with the bottom-up method with all the SNAP-NAPFUE classifications details. Emission factors and activity data have to correspond to the specific activities of the studied area. The processes have to be detailed so that it is possible to attribute the most representative emissions. In case of lack of data, the top-down approach can be used but with the help of complementary data to take into account the regional specificities. The uncertainties may be quantitatively calculated, e.g. by a Monte Carlo method, whenever possible. This level is the best one to allow the generation of all kinds of scenarios provided that the emission changes are higher enough compared to the uncertainties of the SEI emission values.

Emission scenarios may be built directly from the SEIs by reducing the total emissions per grid box. These scenarios are then used in the STATE block to give general indications of the possible evolution of the air quality, or identify simplified equations that represent the links between emissions and concentrations in a complex IAM.

EMEP/EEA (2009a, b) classifies the methodologies to compute the emission projections:

- **LEVEL 1** projection methods can be applied to non-key categories and sources not expected to be modified by future measures. Level 1 projections will only assume generic or zero growth rates and simply projected or latest year's historic emission factors.
- **LEVEL 2** projections would be expected to take account of future activity changes for the sector, based on national activity projections and, where appropriate, take into account future changes in emission factors. It is necessary to have a detailed description of the source category in order to apply the appropriate new technologies or control factors to sub-sectors.
- **LEVEL 3** projections use detailed models to provide emission projections, considering additional variables and parameters. However, these models have to use input data that are consistent with national economic, energy and activity projections used elsewhere in the projected emissions estimates.

## Output

A first output is an emission inventory that gives the total amount of different pollutants released into the atmosphere by all the different sources. These sources are classified using the processes producing the pollution (biogenic, industrial, transport-related, agricultural, etc.) and their type and spatial characteristics and distribution: point sources (industries, power plants, etc.), line sources (road transport) and area sources (biogenic, diffuse industries, residential areas, and small road sources).

A second output is a SEI that represents the amount of different pollutants released in each cell of a mesh. To get this SEI, the spatial information about the distribution of the sources (point, line and area) has to be projected on the mesh (normally a matrix of square cells). Then, the contribution of each source category



for each pollutant is simply added. On the one hand, this resulting SEI can directly be used by an air pollution model. But, on the other hand, some information concerning the distribution of source categories as well as the accuracy of the source locations may be lost.

### **Synergies among scales**

In theory, it is possible to use the spatial characteristics and locations of the emission sources in order to project the data on any kind of grid domain.

In practice, it is very difficult to manage, or even to find, a detailed and complete description of all the sources over large areas (scale of a continent or large countries). It follows that the first output of the large scale SEIs is based more on area than point and line sources in comparison to small scale SEIs. The sources of large scale SEIs are calculated using more top-down than bottom-up approaches. Consequently, the locations of the sources in large scale SEIs are not accurate and the projections of such SEIs on fine resolution grid lead to an overestimation of the sources dilution. It becomes then necessary to “re-concentrate” the sources using different earth surface characteristics defined at smaller scale. For example, the emission can be redistributed according to the land use (emissions release over the ground only and no emissions over water surfaces), the density of population (more emissions over dense population areas), the road network (road transport emissions only in cells crossed by roads), etc. Apart from simple redistribution proportional to these supplementary characteristics, which is typically done using linear regression, also more advanced approaches can be applied, e.g. using geostatistical methods, like kriging (Singh et al. 2011).

When using AQ models, it often happens that an accurate detailed emission inventory is available only on a part of the grid domain on which the study has to be performed. It is therefore necessary to combine data provided by different scale SEIs. In this situation, the best procedure is, first, to project all the SEI outputs on the same grid (using “re-concentration” when necessary) and then, to keep on each cell the data provided by the most accurate SEI. Even if there is a risk of inconsistency between the different SEIs because they have been produced using different methodologies (top-down or bottom-up for example) this procedure is a good compromise between consistency and accuracy.

### **Uncertainty**

The uncertainties associated to emissions inventories (Werner 2009) are directly related to accuracy. This accuracy can be split into two main contributions:

- Structural inaccuracy, which is due to the structure of the inventory;
- Inaccuracy on the input data (i.e. activity data, emission factors).

The structural accuracy estimates the inventory structure ability to calculate as precisely as possible the real emissions. This uncertainty can be split into three contributions: inaccuracy due to aggregations (the emissions are calculated on defined spatial and time scales that may lack the information on the emission processes or on the variability of the real emissions); incompleteness (an emission inventory may be inaccurate due to the absence of emission sources); inaccurate

mathematical formulation and calculation errors (the mathematical formulation used is generally highly simplified, and assumes, for example, that the relation between emission and activity is linear).

The uncertainties on the input data are mainly due to the lack of information on the different parameters used to estimate the emissions of an inventory. These emissions result mainly in the combination of input data like activity values and emission factors. The uncertainty on the values of input data can be due to simplification hypotheses, for example in the case of a large number of similar sources, supposed to have an average behaviour. They can be divided into four categories: extrapolation errors (when lacking emission factors or specific data related to some emissions sources, the corresponding values are extrapolated from other available data); measurement errors (they can lead to inaccurate activity data or emission factors); errors of copy (errors made during the reporting of values); errors in case of unknown evolution (future emission scenarios are associated to probability factors which can be seen as uncertainty or indefiniteness).

It is obvious that some relations exist between these different types of uncertainties and it is sometimes difficult to distinguish them.

The uncertainties of an emission inventory can be evaluated in a qualitative or quantitative way. The qualitative evaluation is mainly performed by experts (IPCC 2000; EPA 1996), while the quantitative one is based on error propagation methods and Monte Carlo methods. There is also a semi-quantitative method that can be used to evaluate the uncertainties, which consists in the rating of the data quality. Some numerical or alphabetical scores are attributed by experts to emission factors and activity data to describe the uncertainties of these data. There are two main classifications for these methods (see: EPA 1996): (1) the DARS method (Data Attribute Rating System) that attributes to each dataset a score ranging between 1 and 10 (the most accurate); (2) the AP-42 emission factor rate system that is the main reference in the USA but only for emission factors evaluation. The scores range from A (most accurate) to E. Both methods attribute scores, which are general indications on the reliability and the robustness of the data.

### 2.3.3 *State*

In the DPSIR approach, STATE is defined as the “environmental conditions of a natural system”. In the case of air quality, it describes the ambient concentrations of targeted pollutant (in specific applications also pollutant’s deposition). AQ state can be described as gridded concentrations/depositions over the studied area, or as local concentrations/depositions on receptor sites, depending on the objectives of the IAM and on the available tools. In addition to the spatial dimension, the AQ state also has a temporal dimension, considering that a pollutant can be monitored/ modelled with a temporal resolution of hours/days, etc. Once concentrations/ depositions are evaluated in space and time with the different available approaches, AQ indicators are usually calculated, such as aggregation of the initial AQ data to

provide the number of PM10 daily exceedances on a cell, the annual mean of NO<sub>2</sub> aggregated over a domain, etc.

In the following, we focus on concentrations only as a state indicator, but the content would be basically the same for deposition.

It can be noticed that sometimes the PRESSURES block may be seen as acting directly on the IMPACT block, if simplifying the scheme and assuming a direct relationship between emissions and effects, with no evaluation of the STATE conditions.

### **Input**

In IAM, the AQ state is described as the joint responses to pressures, constituting driving forces on which society can act at the spatial scale of the study, and external conditions, such as meteorology and pollution coming from the larger scale. Depending on the method chosen to perform an IAM, these forcing can be treated explicitly (this is the case when using a numerical model including meteorological and boundary conditions data), or act implicitly on other data. In certain cases, when AQ models are used for state evaluation, AQ observations can also be considered as input data, when these are used for model validation, data assimilation, or as initial or boundary conditions for models.

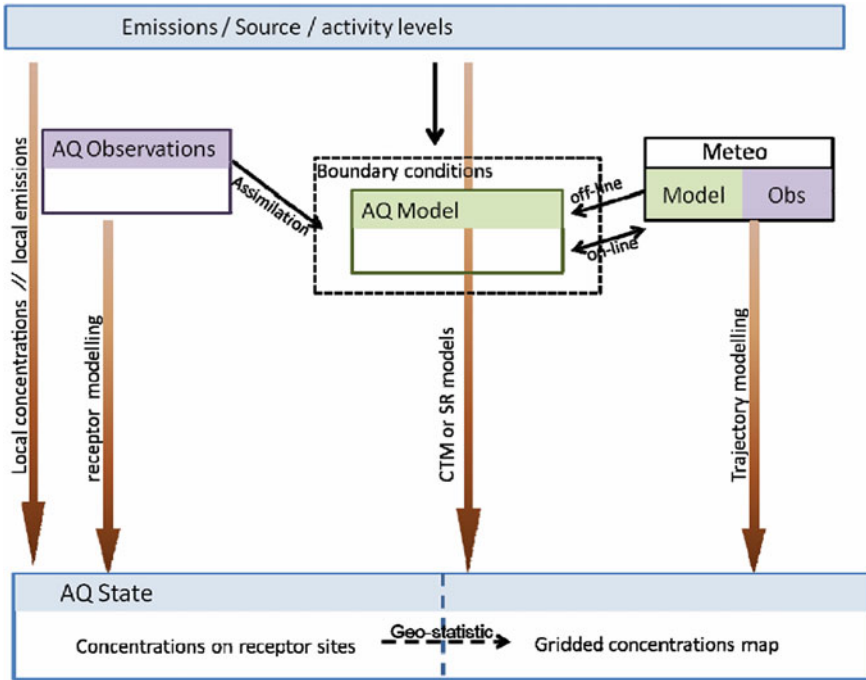
### **Functionality**

The different methods that can be used to evaluate the AQ state, i.e. pollutant concentrations, are summarized in Fig. 2.3 and will be described in the following paragraphs. In parallel to the method used to define pollutant concentrations, methods are also often defined to estimate the contribution of the different emissions to the concentration (source apportionment).

The STATE block three-level classification is as follows:

**LEVEL 1:** The simplest way to characterize AQ state is to use measurements taken routinely, or during a measurement campaign (together with a geostatistic interpolation method if the aim is to obtain a map of concentrations over a studied area). Some studies also use the strong and highly uncertain hypothesis that local concentrations are proportional to local emissions to estimate source contributions.

**LEVEL 2:** It is based on a characterization of the AQ state using one model, adapted to the studied spatial scale. This model should be validated over the studied area and should use emissions input data also adapted to this scale. Concentrations used as boundary conditions of the model can be either extrapolated from measurements or extracted from a larger scale model. Observed concentrations can be used to correct the model (data assimilation) at least for the reference year, often used as a starting point for IAM applications. If the IAM is a prospective study, aiming to evaluate future policy scenarios, a method could be used to correct the model. A possibility in this context is to estimate, through data assimilation (if observations are available), map of increments/bias (related to the base case) to be used to “correct” the concentrations of future alternative emission reduction scenarios. Another input to the model are meteorological data, which can be obtained from observations or from a meteorological model. Spatial and temporal



**Fig. 2.3** Schematic of the different methodologies to estimate AQ state and to relate it to source contribution

resolution of the meteorological model should be adapted to that of the AQ model. For prospective IAM, using meteorological data from a specific year raises the problem of their representativeness, as it does not permit to catch the inter-annual variability of the meteorological conditions. To tackle this issue, one option could be to simulate more years, or in some way to “filter” the effect of the inter-annual variability in meteorology.

The full deterministic AQ model can be used to estimate contribution of the main sources on each grid point concentration, for example by cutting-off these sources one at a time. This method assumes the possibility of “adding” effects in some way and is time-consuming, as one full model run has to be done for each estimation of source contributions. Therefore, such calculations are generally limited to estimate large emission contribution over an area (e.g., industry, traffic, etc.). For some RESPONSES module implementations (as in the case of optimization approaches) thousands of model runs would be required, for example to minimize the cost of emission reduction measures. In such cases, the AQ model may be substituted by a more computational efficient source/receptor model (also called *surrogate model* or *meta-model*) based on simplifications of the AQ model. This model directly links the activity levels or the emissions to an AQ index calculated from targeted pollutant concentrations. The level of complexity of the surrogate

model depends on the objectives of the IAM, on the nature of the pollutant (non-linearities, chemical reactivity, etc.) and, above all, on the output necessary for the subsequent IMPACT block (Carnevale et al. 2012b).

**LEVEL 3:** is based on a characterization of the AQ state using a downscaling models chain, both in term of AQ and meteorological models, from large scale (Europe, for example) to regional (country or regions) and local scale (city or street level). Using a downscaling model chain allows to take into consideration interactions between the various scales, such as transport of pollutant from large scale or interactions between mesoscale wind flows and local dynamics. Nesting between models can be one-way or two-ways, allowing local information to be passed to the larger scale model run. Sub-grid modelling approaches can also be used to combine different scales. The same model could be used for different parts of the chain, running the model itself at different resolutions; or different models could be applied at different scales, as local models (Gaussian models, for example) may use boundary conditions from a larger scale Eulerian model. Data assimilation and meteorological data representativeness issues are similar to those described for Level 2.

### Output

The output of the STATE block may go from spatially and temporally-resolved concentrations of the targeted pollutants, i.e. hourly/daily concentrations on receptor sites or in each grid of the studied domain, to aggregated AQ indexes calculated through spatial/temporal aggregations. Typical aggregated indexes are, for instance, the number of PM10 daily exceedances, or annual mean of NO<sub>2</sub> in few or all domain cells. Other variable describing the STATE could be related to pollution depositions and climate change indicators (CO<sub>2</sub> emissions, global warming potential, etc.). In general, the choice of the correct output is based, on one side, on those adopted by the EEA, on the other, on their use for the calculation of IMPACT.

### Synergies among scales

Using a downscaling model chain allows to take into consideration the interactions between different scales, both in terms of pollutant transport from large scale and in term of interactions between dynamic flows at various scale.

There is a close connection between climate change and air quality. Pollutant concentrations in the air are strongly influenced by changes in the weather (e.g., heat waves or droughts). At the same time, concentrations of pollutants such as O<sub>3</sub> and particles impact the climate through direct and indirect forcing. The first relation can be taken into account by using meteorological conditions from a climate model. However the relevance of using future climate meteorological conditions for short term studies (e.g., five years as in some cases in AQ plans) has not been demonstrated yet, as future meteorological conditions may not vary enough in 5 to 10 years. On the other way, estimating the impact of local changes in O<sub>3</sub> and particles on climate would require the use of meteorology-atmospheric chemistry coupled models at the regional scale. In this case, the STATE would not be the pollutant concentrations, but rather climate change related metrics, such as global warming potential or radiative forcing.

### **Uncertainty**

When the AQ state is evaluated through measurements only, uncertainties are related to the measurements themselves, to the geostatistical methods used to interpolate point measurements and to the representativeness of measurement sites to characterize the area under study.

Uncertainties related to AQ numerical modelling have been widely discussed in the scientific literature. Intrinsic uncertainties of AQ modelling are mainly related to errors in the physical formulation of the model, and to uncertainties in the input data. An operational validation of the AQ model by comparison with measurements is required, opening the question of the representativeness of the chosen measurement sites in relation to the model scale. Evaluating the indefiniteness of prospective study is more challenging and would require the use of diagnostic evaluation (e.g., sensitivity tests) or probabilistic evaluation (e.g., errors propagation). Furthermore, as mentioned earlier, for prospective IAMs, estimating the AQ state over a relatively short temporal period (up to one year) introduces uncertainties on the representativeness of the estimated state itself.

### **2.3.4 Impact**

The IMPACT block describes the consequences of any alterations or modifications of environmental conditions, being either beneficial or adverse. Among the various impacts, we could distinguish between impacts on human health, on environment (vegetation and ecosystems), on social, economic aspects or on climate. Moreover some impact could be derived from another, such as economic consequences of human health or of ecosystem services changes.

The choice of IMPACT would primarily allow to support the selection of the RESPONSES that would eventually influence the complete DPSIR chain.

Special attention will be paid in the following to health issues, that are important for local and regional decision making and are, in many cases, the most relevant impact from the economic viewpoint.

### **Input**

Human health is a response to the exposure to a given air quality (STATE), and can be calculated using data that describe the air quality (such as level of concentration measured at a monitoring site, levels of concentration averaged for several monitoring stations or determined using an AQ model) and dose-response functions or concentration-response functions when available. In some case, the health impact can be calculated using data such as intake fractions computed after modelling the emissions to take into consideration (PRESSURES).

The choice of a pollutant to perform HIA (Health Impact Assessment) is often more restricted by the available knowledge on health effects and on the way to measure those effects, than by the input provided by the STATE block. The selection of input data depends in fact on the availability of a causal function to

derive health output. The level of needed details on the exposure data depends on the output chosen, its occurrence and the strength of the causal relationship. However in general, the following input are needed to compute impacts:

- Air pollution concentrations
- Population data
- Dose-response functions.

### **Functionality**

The input-functionality-output chain can be implemented at different levels of complexity. It depends on the strength and the robustness of the causal relationship between the exposure indicator (STATE or PRESSURES) and the health indicator chosen to support the decisions (RESPONSES) to be taken. The chosen approach to compute health impact (retrospective, prospective, counterfactual) does not restrict the level of complexity to be applied; it only demands more or less detailed data in the input-output chain.

- **LEVEL 1:** A coarse description of exposure provided either by measurement or modelling of AQ (e.g. average mean annual exposure for a city), a dose-response function or concentration-response function and a simple population description would give a rather coarse output. For examples: the number of hospital emergency visits related to increased ozone levels for a city or region.
- **LEVEL 2:** Similar to level 1, but with spatial details in the STATE description.
- **LEVEL 3:** A detailed temporal and spatial resolution for exposure and population data allows an accurate health analysis integrating, for instance, distance to roads, spatial distribution and vulnerable groups. For examples: The number of hospital emergency visits of those who live in greener or more trafficked areas of a city, related to local changes in ozone.

### **Output**

The choice of health indicators to support decisions has to be made to show the potential policy action or inaction impact. Outputs have different strength in supporting policies. The burden of disease related to air quality can be expressed as such or translated into YOLL, DALY (Disability-Adjusted Life Year), life expectancy related to changes in exposure. Other indicators such as morbidity or mortality rate, number of hospital visits related to exposure and exposure changes can be used with a known dose-response or concentration-response function. The output representativeness strongly depends on the level of detail of population data.

The temporal resolution is also of importance, decisions on short-term exposure or on long-term exposure should be addressed separately using related health data.

### **Synergies among scales**

Concerning the IMPACT and specially those on human health, the scale is strictly related to the level of uncertainties. The challenges of synergies encountered in

STATE and PRESSURES blocks will be emphasized in IMPACT with some more uncertainties and robustness issues. The description of the population data and their level of details will limit the potential of synergies among scales. As an example: Local scale IAM on one city will not show the same impact values than a larger scale IAM. Increasing coherence can be reached in computing a multiscale IAM with re-distribution to each local city of their own data.

### **Uncertainty**

As not everybody is affected in the same way by air quality exposure, the HIA presents large uncertainties. Dose-response functions or concentration-response functions are identified as the main source of uncertainty in IAM. Epidemiologists often report an underestimation of causality. Therefore the literature recommends to use the available most detailed exposure estimate in epidemiological studies (e.g. for pollutants with high spatial variability this can be based on personal activity-based modelling or personal dosimetry), to assess the health effects of air pollution.

### **2.3.5 Responses**

The RESPONSES block represent the Decision Framework, that is to say the set of techniques/approaches that are used to take decisions on emission reduction measures, or on activity changes, or on direct concentration reductions.

#### **Input**

Input required for this block may be:

- *Emissions*. They constitute the block input in those cases that do not use an explicit calculation of the STATE and of the IMPACT. Their spatial domain, discretization, and composition detail must be coherent with the detail of the possible actions;
- *Air Quality Indexes (AQIs)*. Evolving pollutant concentration at different sites (measured or produced by some model) can be summarized into one or more AQIs. This often happens when an evaluation of the IMPACT is not performed. These AQIs are directly compared and/or combined in the RESPONSES block.
- *Impact*. This is the case when the full chain is implemented. While AQIs and impacts can be computed from measured data, to support decisions it is essential to compute them through (deterministic or statistical) models, since their variation has to be linked to possible actions.

As external forcing of the RESPONSES block, one has mainly to consider the decision setting in which the IAM will be used. This means that the range of actions that the local/regional authority can consider is clearly defined and the connection with other plans/regulations are explicit.



## Functionality

The functionality of this block must suggest responses to the decision maker, to reduce precursor emissions (PRESSURES), or modify the DRIVERS, or directly act to improve the STATE (Vlachokostas et al. 2009).

The main components of this block are:

- *Control variables*: these represent the measures that can be applied by the regional/local Authority. They can be related to a macrosector or a pollutant level reduction (aggregated approach), or to a single technology acting on one or more pollutants (detailed approach). A further classification distinguishes between “end-of-pipe measures” (applied to reduce emissions at the “pipe” of an emitting activity) and “efficiency measures” (often called “non-technical measures”, that reduce activity levels, e.g. acting on people behaviour, etc.).
- *Objectives*: these represent what a Decision Maker would like to improve/optimize. For instance, an objective could be to reach a given level of an AQI at minimum cost, or to use a predefined budget to minimize an AQI. More than one objective can be considered within the same problem (e.g. reducing two pollutants with a given budget).
- *Constraints*: these can be of different types, as legislative (i.e. new obligations on emission sources), economic (i.e. limited budget to be spent), physical (i.e. due to domain features), etc. Constraints can be mathematically formalized, if using a formal approach to take decisions; or they can be taken into account when making decisions, but without explicitly modelling them.
- *Implementation technique*: this represent, from an operational point of view, how all the ingredients already described (control variables, objectives, constraints) are put together and processed, to suggest one or more solution(s) to the problem. In some cases, the implementation would simply mean an expert advice, in other cases, the use of some piece of software running a suitable optimization procedure.

The RESPONSES block can again be described by three levels of complexity:

- **LEVEL 1**: Expert judgment and Scenario analysis. In this case the selection of measures to be adopted is based on expert opinion, with/without modelling support to test the consequences of a predefined emission reduction scenario. In this context, the costs of the emission reduction actions can be evaluated as an output of the procedure (even if in many cases they are not considered).
- **LEVEL 2**: Source Apportionment and Scenario analysis. In this case, the most significant sources of emissions are derived through a formal approach; this then allows to select the measures that should be applied. Again, emission reduction costs, if any, are usually evaluated as a model output.
- **LEVEL 3**: Optimization. In this case the whole decision framework is described through a mathematical approach (Carlson et al. 2004), and costs are usually taken into account. Different approaches (both in discrete and continuous setting) are available, as:

- *Cost-benefit analysis*: all costs (from emission reduction technologies to efficiency measures) and benefits (improvements of health or environmental quality conditions) associated to an emission scenario are evaluated in monetary terms and an algorithm searches for solutions that maximize the difference between benefits and costs among different scenarios.
- *Cost-effectiveness analysis*: due to the fact that quantifying benefits of non-material issues is strongly affected by subjective evaluations, the cost-effectiveness approach can be used instead. It searches for the best solutions considering non-monetizable issues (typically, health related matters) as constraints of a mathematical problem, the objective of which is simply the minimization of the sum of (relevant) costs (Amann et al. 2011).
- *Multi-objective analysis*: it selects the efficient solutions, considering all the objectives of the problem explicitly in a vector objective function (e.g., one AQI and costs), thus determining the trade-offs and the possible conflicts among them (Guariso et al. 2004; Pisoni et al. 2009).

## Output

The outputs of the decision framework are the measures to be implemented to change the connected blocks. There are different options to describe these responses, as:

- Macrosector level emission reductions: reductions are applied to all emissions (PRESSURES) belonging to a CORINAIR macrosector. This is a very aggregated approach, but can provide policy makers with some insight on how to prioritize the interventions and it is easy to implement (Carnevale et al. 2012a, b).
- “End-of-pipe technologies” also called “Technical measures”, (e.g. filters applied to power plant emissions, to cars, etc.). These measures are applied to reduce emissions (PRESSURES) before being released in the atmosphere. They neither modify the driving forces of emissions nor change the composition of energy systems or agricultural activities.
- “Efficiency measures” (or “Non-technical measures”) are those, that reduce anthropogenic DRIVERS. Such measures can be related to people behavioural changes (for instance, bicycle use instead of cars for personal mobility, temperature reduction in buildings) or to technologies that abate fuel consumption (use of high efficiency boilers, or of building thermal insulating coats, which reduce the overall energy demand). Localization decisions (e.g. building new industrial areas, or new highways) can also be considered as “efficiency measures”.
- Direct pollution reduction measures. These act directly on STATE to reduce the pollution already in the environment. Planting some species of PM absorbing trees in urban environments or using coatings photocatalytically decomposing nitrogen oxides belong to these types of measures.

### Synergies among scales

The main issue of this type is the fact that regional authorities have to decide actions constrained by “higher levels” decisions, i.e. coming from national or EU scale. In practical terms, this means that regional scale policies are constrained to consider the national/EU legislation as a starting point for their choices. In the effort to “go beyond CLE” within their regional domain, some “higher level” constraints cannot be disregarded or modified. This issue has to be considered for both Air Quality and Climate Change fields. In both cases, in fact, there are a lot of agreement/protocols that are already in force.

### Uncertainty

As stated in UNECE (2002), it is important that the decisions focus on robust strategies, that is to say on “policies that do not significantly change due to changes in the uncertain model elements”. This issue is linked to the need of defining a set of indexes and a methodology to measure the sensitivity of the decision problem solutions. It is in fact worth underlining that, while for air quality models the sensitivity can be measured by referring in one way or the other to field data (Thunis et al. 2012), for IAMs this is not possible, since an absolute “optimal” policy is not known and most of the times does not even exist. The traditional concept of model accuracy must thus be replaced by notions such as risk of a certain decision or regret of choosing one policy instead of another.

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