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SEVENTH FRAMEWORK PROGRAMME

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1 Summary

This document copes, from a methodological point of view, with one of the European Commission's ideas to improve air quality, implementing the most effective emission reduction measures at local, national and Community level, at the same time applying an overall integrated approach.

Starting from the background expertise of the partners and partly from the plans collected in the WP2 (through the database), this deliverable proposes an Integrated Assessment Modelling (IAM) framework based on EEA DPSIR (Drivers, Pressure, State, Impact, Responses) scheme and a systemic view. The proposed IAM framework is structured in modules interconnected through data flows, and considers as additional dimensions of the problem the "synergies among scales" (from regional, to national and European) and the "uncertainty analysis" (to evaluate and propagate uncertainty in the various modules composing the framework).

With the definition of different "levels of implementation complexity" for each of the DPSIR modules, the framework will be useful to suggest, to policy makers using IAMs, in which direction to develop and extend their IAM implementations, and how to better design Air Quality "Plans and Programmes".

1.1 Version History

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0.1	First Draft	20/11/2014	Claudio Carnevale, Giovanna Finzi, Marialuisa Volta (UNIBS), Giorgio Guariso (POLIMI).
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0.3	Third Draft	22/12/2014	John Duros (AUTH), Elsa Real (INERIS)
1.0	First version	27/12/2014	Claudio Carnevale, Giovanna Finzi, Marialuisa Volta (UNIBS)
1.1	Final Version	12/01/2015	Enrico Pisoni (JRC), Enrico Turrini (UNIBS), Catherine Bouland (ULB)

1.2 Summary of Changes

Version	Section(s)	Synopsis of Change
0.1	All	D3.1 review and introduction of uncertainty/sensitivity analysis methodology
0.2	7	Modification of section 7 structure and minor change in the text
0.3	7	Contribution to section 7 concerning uncertainty in IAM
1.0	All	Harmonization of contribution for uncertainty/sensitivity analysis and review of section 1-6.
1.1	All	Internal review of the document

2 Introduction

BACKGROUND AND MOTIVATION

As it is apparent from recitals 1 and especially 2 in the preamble to the Air Quality Directive 2008/50/EC (2008 AQD), European air quality legislation puts the main emphasis on protecting human health and the environment as a whole. Therefore it stresses that "it is particularly important to combat emissions of pollutants at source and to identify and implement the most effective emission reduction measures at local, national and Community level." The basic principles have already been formulated in the former so called air quality framework directive (96/62/EC) and its daughter directives (1999/30/EC, 2000/69/EC, 2002/3/EC, 2004/1007/EC). The concept of model based air quality management is now still more in the focus of air quality management with the 2008 AQD. Thus, "Air quality plans" according to AQD's Art. 23 (formerly "Plans and Programmes") are the strategic element, to be developed with the aim to reliably meet ambient air quality standards considering not only the effect of emission reduction measures on ambient air quality, but considering aspects of cost-effectiveness as well. The importance of model based approaches for air management becomes apparent again in connection with Art. 22 ("Postponement of attainment deadlines and exemption from the obligation to apply certain limit values") commonly called "notification for time extension". For both, "air quality plans" and "time extension", more elaborated requirements are formulated in Annex XV compared to former regulations. The implementing decision from 12 December 2011 (2011/850/EU) reflects this clearly, looking at the reporting obligations laid down there (Article 13, Annex II, Section H, I, J and especially K) and looking at the amount of information that has to be provided regularly. This important step forward has become real starting from 1 January 2014.

This document copes with one of the European Commission's ideas to implement the most effective emission reduction measures at local, national and Community level from a methodological point of view following an overall integrated approach at the same time.

In particular, this deliverable provides a methodological approach following a the DPSIR framework (see the detailed description of the DPSIR in the next sections) classifying (in broad terms) two possible decision pathways:

- **scenario analysis.** This is the approach mainly used at the moment to design "Plans and Programmes" at regional/local scale, selecting emission reduction measures based on expert judgment or Source Apportionment (see Deliverable D2.6), and testing the measures effect through scenario analysis (see Deliverable D2.3). It is clear that this approach does not guarantee that cost-effective measures are going to be selected, and only allows for "ex-post evaluation" of costs and other impacts. This approach goes in the directions of providing Air Quality improvements with "measures not entailing disproportionate costs" (as said in the 2008/50 Directive), since this is implicitly considered when selecting the set of measures to be tested.
- **optimization.** This approach allows for the selection of cost-effective measures for air quality improvement, through the solution of an optimization problem. In this

frame it is clear how (during optimization) a “feedback” is provided on the effectiveness/efficiency of the measures, in terms both of costs and effects, to select the set of measures that should be applied to improve air quality in an effective way. The concept of cost-effectiveness of measures is a key one, and was already addressed in Nagl et al., 2005, in which the authors proposed the “Establishment of a framework to identify (cost)-effective measures” as an option to improve the AQ planning process. Cost-effectiveness of measures is also cited e.g. in the Italian transposition (D.Lgs 155/2010) of 2008/50 Directive.

Before starting with the description of how these two alternative pathways can be implemented (with different levels of complexity for different parts of the plan), the DPSIR concept will be briefly summarized, explaining in broad terms how the Integrated Assessment Modelling (IAM) systems framework can be designed.

THE DPSIR FRAMEWORK CONCEPT

Starting from the need to provide a methodological support for the implementation of “air quality plans” at regional/local scale, and using both background knowledge and partly the data gathered in the WP2 (in which a Database of IAM approaches at regional and local scale has been compiled) the aim of this WP3 deliverable is to define the key elements of an Integrated Assessment Modelling framework. These elements will be created considering the EEA DPSIR concept (EEA, 2012) and a holistic approach, that should:

- Be modular, with data flows connecting each framework 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 experiences/approaches gathered in WP2 database and,
- Show, for each module of the framework, different “levels of implementation complexity”.

The last two points of the previous list 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 quality of his/her 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 their related effort. The final idea is to be able to classify each plan contained in the WP2 database, 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 for each plan.

In the next chapters, 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. Key areas to be addressed by research and innovation will be also pointed out, and finally two illustrative possible “decision pathways” (obtained applying the IAM framework) will be discussed.

3 A general overview of the Integrated Assessment system framework

The DPSIR analytical concept (Figure 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 the following:

- driving forces,
- pressures,
- state,
- impacts,
- responses,

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

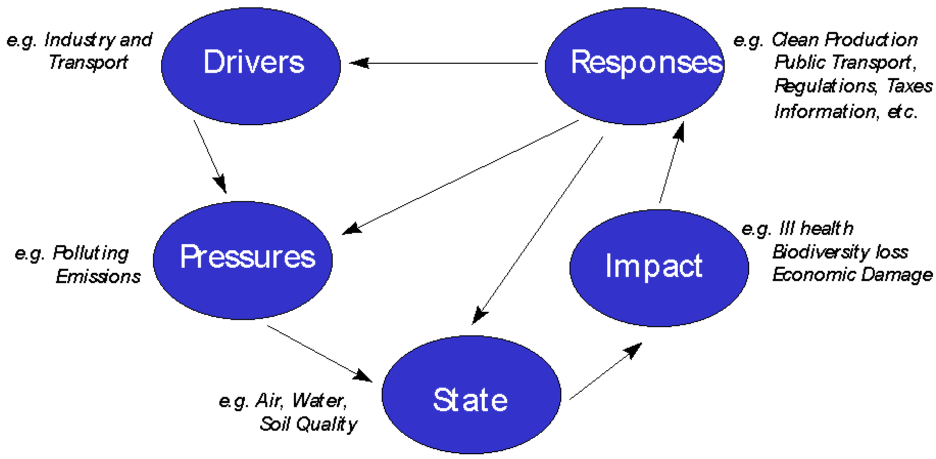

Figure 1: the general DPSIR EEA scheme (EEA, 2012).

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 [EEA, 2012].
Starting from these definitions and features, in the frame of the APPRAISAL project, it has been decided to adapt the DPSIR scheme to the Integrated Assessment Modelling (IAM) at regional (considering regional as a domain of few hundreds of kilometres) scale. So the DPSIR scheme shown in Figure 1 has been translated into the framework illustrated in Figure 2.

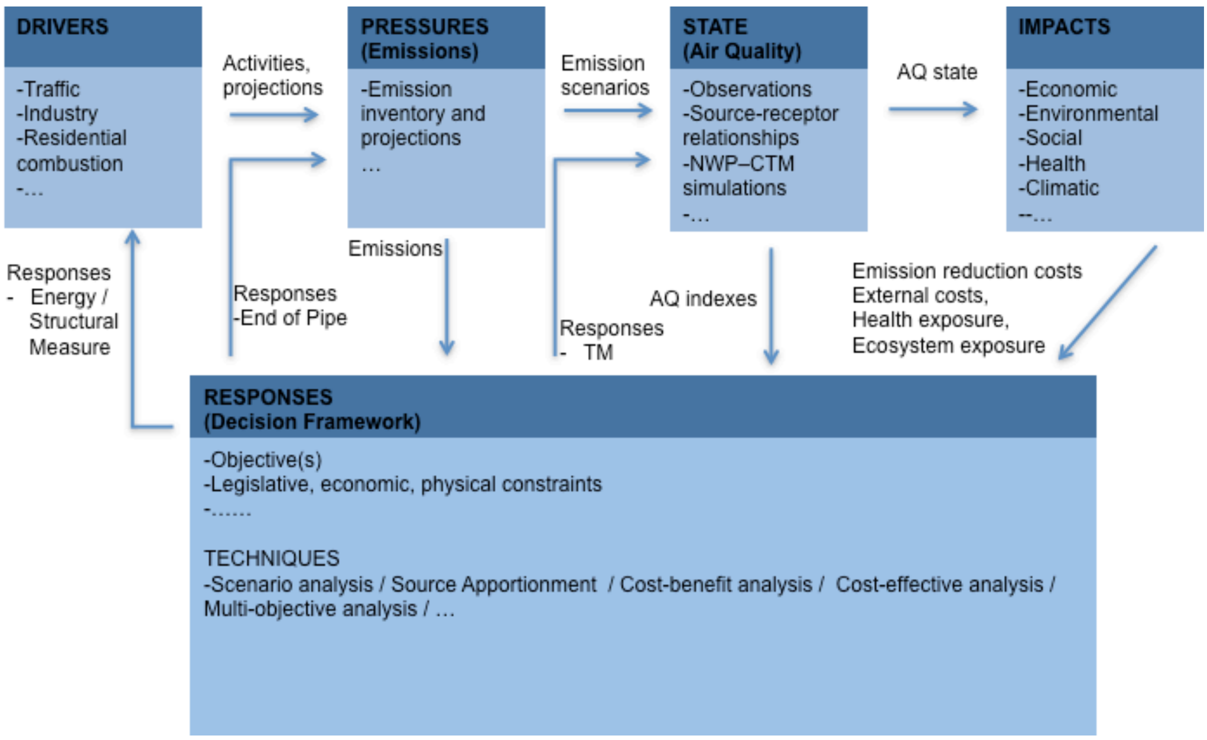

Figure 2: The DPSIR scheme adapted to IAM at regional/local scale. "Synergies among scales" and "uncertainties" are additional dimensions.

In particular, in the scheme in Figure 2, the meaning of each block is as follows (quoting from EEA glossary):

- DRIVERS: this block describes the "action 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.
- 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.
- IMPACTS: 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 monitored data, but most often 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 the IMPACTS. In particular, 3 diffent group of responses can be considered:

- Energy/Structural measures, impacting on the DRIVERS block and including both energy efficiency and population behaviour measures.
- End of Pipe measures, impacting on EMISSIONS and related to the introduction of new technologies affecting the level of emission for each activity.
- Technical measures, impacting directly on STATES and including technological improvements allowing to direct concentration reduction (e.g. ecological tarmac/concrete).

Moreover, it as to be stressed also the fact that in some particular conditions, the pollution impact on human and ecosystem can lead to economical compensation.

It is worthwhile to note that Figure 2 scheme 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 Figure 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. All these "scale" issues are discussed within the next chapters, i.e. in the sections devoted to "synergies among scale".

4 A detailed analysis of the Integrated Assessment system framework modules

In this section, all the 5 building blocks (DPSIR) 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.

4.1 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. Since APPRAISAL mostly deals with city/local level assessments, special attention has been given to the sectors that are important for urban air quality (i.e. road traffic, off-road traffic and machinery, residential heating, energy production and industry). The next Table gives an overview of the most important activity parameters for each of these sectors. Sectors contributing mainly to regional level assessments (e.g. agriculture) have been discussed at a more general level.

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

4.1.1 Input

The core of the DRIVERS block is the input-functionality-output chain (or model), i.e. the output (i.e. activities) responds to the input (e.g. population, economical activities, transport needs etc.; legislative requirements, natural renewal rate of technology stocks) by practical definition of the functionality. The functioning DRIVERS block is especially important to attain reliable future projections.

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 goals (RESPONSES block) or "natural", non-forced development.

4.1.2 Functionality

The functionality defines the cause-effect relationship 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. Particularly for future projections it is essential that the output of the DRIVERS block realistically responds to the input. While for base year (often a specific past year for which a fairly complete set of data exists) inventory it is often adequate to attain directly the output of the DRIVERS block (e.g. transport kilometres driven or fuel use), whereas for projections the input-functionality-output chain needs to be functional (e.g. from transport need to kilometres driven or fuel use) in order to respond to the assumed future changes in economic activities, technology developments etc. This chain (or model) 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 as city or regional level models (bottom-up), allocated 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** is proposed:

- **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 more 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 at city (or regional) level 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 “city share” is defined using weighting surrogates (top-down approach). In general, a bottom-up approach can be considered to be more favourable as it uses, by definition, information from the respective city or region directly. However, in many cases it might be difficult to attain reliable, representative collected data from certain areas. Furthermore, technology stock inventory at sub-national level is often not practical, and national level data are used (top-down approach). In case of a top-down approach, the reliability of the activity estimate depends on the representativeness of the weighting surrogates used. In case representative weighting surrogates can be used for each sector, a top-down

approach can produce reliable activity estimates.
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.; legislative requirements, natural renewal rate of technology stocks) realistically translates into output (i.e. activities and technologies). Therefore the assessment of future developments of the DRIVERS block typically requires more sophisticated framework than what would be needed for the base year inventory.
In the following the main emission source sectors are introduced and some sector-specific features 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, e.g. traffic planning. 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 e.g. tire type, road surface type and climate conditions. Transport demand based modelling approaches enable also assessment of spatial changes.
Proposed three-level approach:

1. Allocation from national level traffic activity data (top-down). The allocation may be based on, e.g., population data (in relation to national total);
2. Activities based on city level traffic counts or other estimates (bottom-up). Allocation for vehicle categories and technologies might be, however, 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 locally distinguished data (e.g. city level traffic model).

Availability of activity data for **off-road traffic and machinery** is variable. E.g. for sea vessels, trains and airplanes activities often are relatively well known. On the other hand, activity data can be much more uncertain. E.g., top-down allocation of construction and maintenance machinery activities from national level might suffer from a lack of appropriate weighting surrogates. 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.
Proposed three-level approach:

1. Allocation from national level activity for each off-road and machinery sub-category, e.g. rail traffic, aviation, marine, harbours, military, agriculture machinery, industry, construction, maintenance etc. (top-down). The allocation may be based on respective sub-category surrogates (in relation to national total), e.g. harbour/military/agricultural/industrial activity or land use data, population etc.;
2. Based on city level estimates about respective activity (bottom-up), allocation for vehicle categories and technologies might be, based on national average (top-down);
3. Activities separated for each vehicle category and technology using city level survey data (bottom-up) or other locally specific data (e.g. city level model).

Residential combustion activities are often relatively uncertain. Especially for residential wood combustion, which is a major concern from the air quality perspective in many cities because of its high fine particle emissions, bottom-up approach 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 means, prospects of citizens' preferences (e.g. from questionnaires), 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 enable also assessment of spatial changes in the future.
In case there is no reliable local level activity estimate or top-down allocation procedure practicable, source apportionment techniques might be considered to detect an initial "order-of-magnitude" estimate of the residential combustion activities.
Proposed three-level approach:

1. Allocation from national level activity (top-down). The allocation may be based on a city level 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);
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 a large number of smaller plants (or if information is not available) it might be practical to use more general information (top-down approach). 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.
Proposed three-level approach:

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

Agriculture emissions are typically of minor concern in city level assessments. However, at national level, e.g. when compared against NEC requirements, agriculture is a major source of ammonia emissions and can be relatively important in PM emissions. Base year activity data includes 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 assess the impacts of urban air pollution and to provide information in an appropriate format 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 detail 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 emissions that may cause considerable impacts relatively near the source, e.g. impacts on human populations from sources with low emission altitude. The spatial allocation for point sources implies simply 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 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 as well as possible. 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 in a reasonable accuracy without specific road dust models.
Proposed three-level approach:

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 based on locally observed data.

Data availability for spatial allocation of **off-road traffic and machinery** is variable. In some cases 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.
Proposed three-level approach:

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 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 house-hold level heating systems do not need licenses. Therefore spatial allocation has to be based on some more general house-hold level data, e.g. building registers.
Proposed three-level approach:

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 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 be often 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.
Proposed three-level approach:

1. Coarse spatial allocation scheme for each fuel / industrial product based on the locations of the plants. Temporal variation based on general default variations.

2. Spatial allocation scheme for each fuel / industrial product and information about production and emission control technologies based on the locations of the plants and activity amounts for each energy production / industrial plants. Temporal variation based on general variation that takes into account local and/or plant-type based conditions (e.g. typical heating profiles, peak/base energy production features etc…).
3. Individual point source data used directly (bottom-up) in a detailed way, including data about production and emission control technologies. Temporal variation based on plant-based observed data.

For **agriculture**, the requirements for its spatial resolution are not as high as for urban emission sources. Horizontal resolution of approx. 10 x 10 km² 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 practical.

4.1.3 Output

The output of the DRIVERS block is used as an input to the PRESSURES block, i.e. emission calculation. 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 kilometers driven aggregated in such a way that it includes emission-wise relevant classification of sectors, sources and technologies. The level of detail of the activity needed is depending on the availability of specific emission factors. 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.

4.1.4 Synergies among scales

For the input-functionality-output chain, the consideration of different scales is an important one. In fact, activity 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.

4.2 Pressures

Air pollutant emissions act as pressures on the environment. Thus, the block PRESSURE 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/emitter (or atmospheric pollutant source) can be in general measured (as in large point sources) or estimated. These are generally calculated as the product of the activity of this emitter and 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 on urban structure (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 in a IAM scheme; so they will not be considered in the following descriptions.

The following sections aim at discussing the input data and the methodologies that are used to compute emissions and their uncertainties.

4.2.1 Input

Emissions depend on the DRIVERS (previously described) that need to be characterized in terms of activity types, activity trends, and associated emission factors (in some cases, DRIVERS could also already contain spatial/temporal details). Main features of the "Input" are described below.

EMISSION INVENTORY DATABASE
An emission is computed for a specific pollutant, emission source and spatial/temporal resolution. An emission inventory is a database combining emissions with a specific geographical area and time period (usually yearly-based). More specifically it contains:

- 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 have to be added (normally with the assumption that costs remain linear with respect to rates of application).

DATA COLLECTION

The methodology to be used to estimate emissions depends on the objective of the study, the availability of the data and their uncertainty. In all cases, it is always necessary to collect and use the best available data at the lowest possible scale, even if data homogeneity problems appear. In case of lack of detailed activity data or/and emission factors, it is necessary to collect such data at higher levels (national socio-economic statistics for example) to allow indirect estimations of the emission sources (Ponche, 2002).
Two main types of approaches are usually distinguished:

- The top-down approach: used when for a given area there is lack of detailed data and it is necessary to disaggregate emissions. 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 sales. In the bottom-up approach the emissions are directly computed from time and space activity values (described with their dependency on 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 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 (2013) 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 categories 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/diffuse over large area.

In order to categorize the anthropogenic sources, several classifications in terms of activity, sectors and fuel use are proposed. At European level, SNAP97 (Selected Nomenclature for Air Pollution) is a reference classification proposed by EEA, while in the present EMEP/EEA (2013) 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 kind 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 (2013) proposes a methodology to identify the major pollutants involved from all anthropogenic and natural emission processes. This handbook of emission factors by default is especially useful in case of lack of specific knowledge of the processes used in the investigation area. It gives only average values for Europe, trends and level of uncertainties which can be expected of these input data.

SPATIALIZED EMISSIONS INVENTORIES (SEIs), SCENARIOS AND PROJECTIONS
In the framework of AQ Integrated assessment, the emission inventory is often used as input to a model to simulate pollutant concentrations in the atmosphere. For this purpose, the emission inventory is 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 AQ “STATE”, and is generally used as basis to simulate emission scenarios and projections.

Emission scenarios could be produced in several ways depending of the objectives of the studies :

(1) by modifying the activity index or data. Some emissions sources can be added, removed or moved to other locations, the level of activity of that sources can also be changed (increased / decreased), etc… For traffic the number of mobile sources per unit time can be changed (including time distribution for defined periods as days, months, years).
(2) 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 for mobile source, 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 result of assumptions on the future projections of the activities and the emission factors. As detailed in EMEP/EEA (2013), future activity assumptions are based on a range of datasets including projections of industrial growth, population growth, changes in land use patterns, and transportation demand. Energy models are often based on general equilibrium theory and combine the above basic growth factors with energy price information to estimate energy demand by sector and fuel. These models can be used as a core dataset as long as the assumptions underpinning them are consistent with national economic strategies, policies and measures. Future emission factors should reflect technological advances, environmental regulations, deterioration in operating conditions and any expected changes in fuel formulations. Rates of penetration of new technologies and/or controls are important in developing the right sectorial emission factors for any particular projection year.

4.2.2 Functionality

The functionality of the PRESSURES block of an IAM aims at producing emission data or/and emission projections. From a general point of view, the PRESSURES can be estimated through 3 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 per default the top-down methodology. Uncertainties are not necessarily estimated. The level 1 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 at level 2 or 3. 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 the SNAP-NAPFUE classifications finest levels. Emission factors and activity data have to correspond to the specific activities of the studied area. The processes have to be detailed as well as possible to attribute the most representative emissions. In case of lack of data, the top-down can be used but with the help of complementary data to take into account the regional specificities. The uncertainties may be quantitatively calculated. The Monte Carlo method will be favoured whenever possible. The level is the best one to allow the generation of all kind of scenarios at the condition that the emission changes (between the SEI and the scenarios) are higher enough compared to the uncertainties of the SEI emission values.

From here onward these three levels of complexity will be detailed using the CORINAIR classification, and considering separately “methodologies to compute emissions”, and “to compute emission scenarios and projections”.

METHODOLOGIES TO COMPUTE EMISSIONS
EMEP/EEA (2009) classified the methodologies to compute the emissions following three levels of increasing complexity. The ‘LEVEL 1’ method is a simple method using default emission factors only. To upgrade a LEVEL 1 to a LEVEL 2 method, the default emission factors should be replaced by country-specific or technology-specific emission factors. This might also require a further split of the activity data over a range of different technologies, implicitly aggregated in the LEVEL 1 method. A LEVEL 3 method could be regarded as a method that uses the latest scientific knowledge in more sophisticated approaches and models.
More in detail:

- LEVEL 1: A method using readily available statistical data on the intensity of processes (activity rates) and default emission factors. These emission factors assume a linear relation between the intensity of the process and the resulting emissions. The LEVEL 1 default emission factors also assume an average or typical process description. This is the simplest method, has the highest level of uncertainty and should not be used to estimate emissions from key categories.

- LEVEL 2: similar to LEVEL 1 but uses more specific emission factors developed on the basis of knowledge of the types of processes and specific process conditions that apply in the area for which the inventory is being developed. LEVEL 2 methods are more complex, will reduce the level of uncertainty, and are considered adequate for estimating emissions for key categories.
- LEVEL 3: defined as any methodology more detailed than LEVEL 2; hence there is a wide range of LEVEL 3 methodologies. At the one end of the range there are methodologies similar to LEVEL 2 (i.e. activity data x emission factor) but with a greater disaggregation of activity data and emission factors. At the other end of the range there are complex, dynamic models in which the processes leading to emissions are described in great detail.

METHODOLOGIES TO COMPUTE EMISSION SCENARIOS AND PROJECTIONS

Emission scenarios may be built directly from the SEIs by reducing the total emissions per grid boxes. These scenarios (and the correspondent CTM simulations) are then used for instance to (1) give general indications of the possible evolution of the air quality, (2) identify simplified equations that represent the links between emissions and concentrations in a complex IAM.

EMEP/EEA (2013) also 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 basic 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 of future changes to 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, taking account 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.

4.2.3 Output

A first output is an emission inventory that gives the amount of different pollutants released in the atmosphere by all the different sources. These sources are classified using the processes producing the pollution (biogenic, industrial, transport-related, agricultural, etc.). These are also classified using 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 Spatialized Emission Inventory (SEI), that represents the amount of different pollutants released in each cell of the mesh used by an Air Quality Model (AQM). To get this SEI the spatial information about the distribution of the sources (point, line and area) have to be projected on the AQM mesh (normally a matrix of square cells over which the model equations are discretized). 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 AQM. But, on the other hand, the information concerning the distribution of source categories as well as the accuracy of the source locations are lost.

4.2.4 Synergies among scales

The synergy among scale is a challenge that needs a continuous attention since many efforts are needed to build emission inventories from the collection of data (issued from a very important number of institutions) to the management of the database, and it involves consequently many European, national and local institutes and experts. EMEP participated significantly in the harmonization of the methodologies to collect data, build emission inventory and projections, assess uncertainties. European reporting and research projects (as GAINS model) also helped to build a consistent European database to start European IAM (Amann et al., 2011).

In theory, it is possible to use the spatial characteristics and locations of the emission sources (emission inventories, including emission of all types of sources i.e. point, line and area) 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). So, the first output of the large scale SEIs are based more on area than point and line sources in comparison with 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 SEI 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 like cities), 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.

A key and challenging issue is related to emission projections, since these depend on political, socio-economic and technical issues. Regional emission projections have to take into account European and national legislation/trends and national and European projections need regular feedbacks on the expected local emission trends.

4.3 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. Also, in addition to the spatial dimension, the AQ state 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 can be calculated, such as aggregation of the initial AQ data e.g. to provide the number of PM10 daily exceedances on a cell, the annual mean of NO_2 aggregated over a domain, etc. In this document we will focus on concentrations as a state indicator, even if the content would be basically the same for deposition.

The STATE can be in some way modified/nudged to a preferred reference state, through RESPONSES (decisions) that are going to affect DRIVERS, PRESSURE and then consequently the STATE itself. In general these responses act on both activity level and emissions (pressures). It can also be noticed that the PRESSURES block can act directly on the IMPACT block, if simplifying the scheme and assuming a direct relationship between emissions and concentrations, but STATE would represent a more realistic expression of exposure to air quality knowing the behaviour of pollutants in the air after being emitted.

4.3.1 Input

In IAM, the AQ state is often described as a response to different pressures, including emissions inventories and projections, constituting driving forces on which society can act at the spatial scale of the study. Other forcings are meteorological conditions and pollution coming from the larger scale. Depending on the method chosen to perform an IAM, these forcings can be treated explicitly (this is the case when using a numerical model, through 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.

4.3.2 Functionality

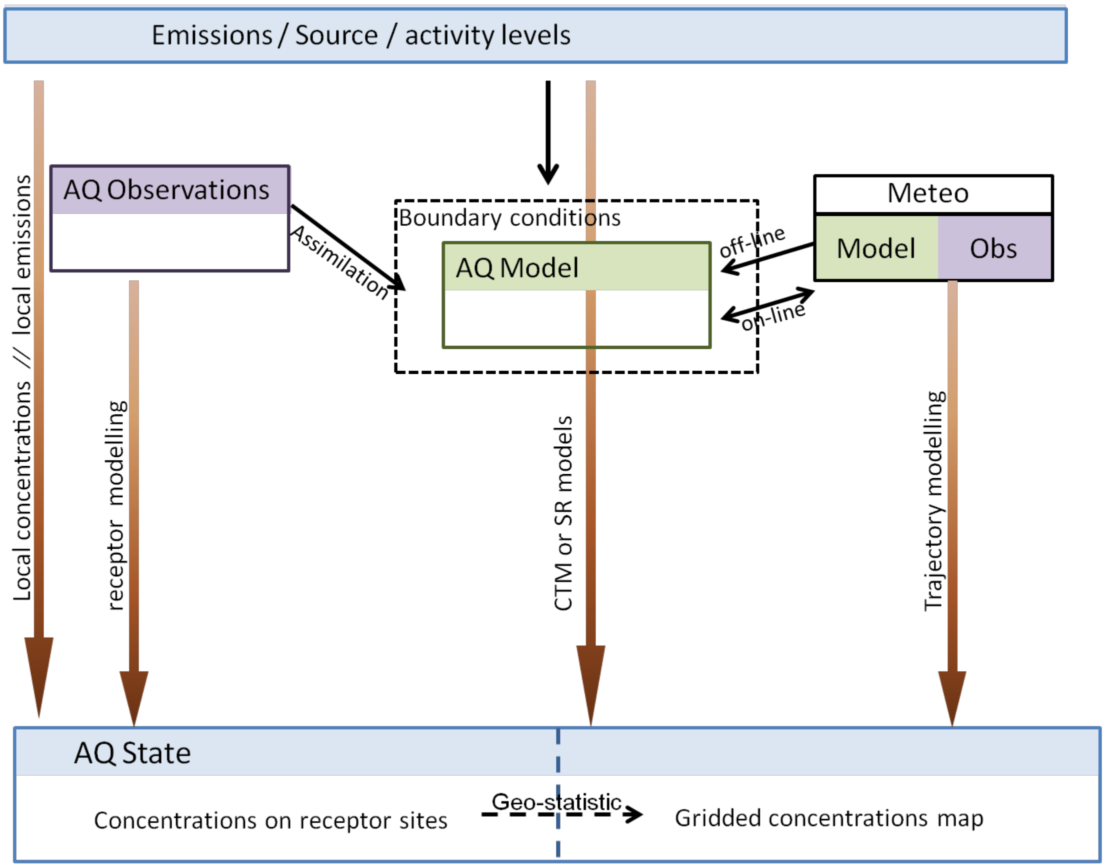

Figure 3: Schematic of the different methodologies to estimate AQ state and to relate it to source contribution

There are several methods to perform an IAM, depending on its objective and on the available tools. Some of them involve representation of the AQ state through numerical models, but other are only based on AQ observations and emission sources. The different methods that can be used to evaluate the AQ state, i.e. pollutant concentrations, are summarized in Figure 3 and will be described in the following paragraphs. In parallel to the approaches used to define pollutant concentrations, methods are also often defined to estimate the contribution of the sources (emissions) to the concentration (i.e. source apportionment).

In terms of complexity classification, the level 1 method does not involve any AQ models and is based on measurements. The level 2 method is based on AQ modelling tools: the AQ state is mainly described using a model, adapted to the studied scale. It can be local scale model (street canyon model, obstacle resolving fluid dynamic model, Gaussian model etc...) or larger scale model (Eulerian model, lagrangian model etc...). The level 3 method is also based on AQ modelling tools but consists in developing a full chain of AQ downscaling models, from the large scale to the smaller one, by one-way or two-way nesting. These 3 levels describing the AQ state are defined according to their level of complexity and not their accuracy, that also depend on the pollutant under consideration.

I.e. if the IAM is focused on a local pollutant that has a short lifetime and depends mainly on local emission, as e.g. NO_2, a full chain of downscaling models from the European to the local scale may not be necessary. The limitations and main applications of the different approaches are described in the following paragraphs.

More in detail, the STATE proposed **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 geo-statistic 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**: 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 data 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.
- **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 feedbacks 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. For each part of the downscaling chain, emissions should be adapted to the model in term of spatial and temporal resolution.

If the IAM is a prospective study, aiming to evaluate future policy scenario, 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 also 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 resolution of the meteorological model should be adapted to the one of AQ model. For prospective IAM, using meteorological data from a specific year rises the problem of its 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 interannual variability in meteorology.
In this context of modelling concentrations via an AQ model, links between sources and concentrations can be estimated through the calculation of **surrogate models**. 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. This method is time-consuming as one full model run has to be done for each source contribution estimation. Therefore, such calculations are generally limited to estimate large emission sector

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 is substituted by a more computational efficient *surrogate model* based on simplifications of the AQ model. This *surrogate model* directly links the available decision variables (activity level changes/emission control measures) 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 (nonlinearities, chemical reactivities etc...), Also, a key issue i*n this context* is related to the "Design of Experiment", t*h*at is to say the number of CTM simulations required to provide data for surrogate models identification (Carnevale et al., 2012b).

4.3.3 Output

The output of the STATE block is 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, depending on the IAM objectives. From these concentrations, AQ indexes may be calculated through spatial/temporal aggregations, such as number of PM_{10} daily exceedances, or annual mean of NO_2. Other variable describing the STATE could be related to pollution depositions and climate change indicators (CO2 emissions, global warming potential, etc…)

4.3.4 Synergies among scales

Using a downscaling models 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_3 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., 5 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_3 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 metrics, such as global warming potential or radiative forcing.

4.4 Impacts

The block on IMPACTS describes the consequences of any alterations or modifications of environmental conditions related to the STATE of air quality, 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 valuation of human health or of ecosystems.

In IAM the choice of IMPACT would primarily allow to support decisions (RESPONSES) that would eventually influence the complete chain starting from the DRIVERS, and going to AQ exposure (STATE) and its related sources (PRESSURE).

APPRAISAL deals with local to regional scales, and special attention has been paid on health issues, that are important for local and regional decision making. At this stage only health issues will be discussed in the next sections.

4.4.1 Input

In IAM, the assessment of human health is understood as the health response related to the exposure to air quality (STATE), and can be calculated using data that describe the air quality (AQ), data describing the concerned population 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 (PRESSURE).

In support to decisions (RESPONSES), health impacts assessments (HIA) are made for a single pollutant – effects relationship. The choice of the pollutant to perform HIA on is influenced by its correlation to the set of actions (RESPONSE), the knowledge of its contribution to the AQ (PRESSURE and STATE) and the availability of a dose-response function. Actually, available dose-response functions are limited to single pollutants even if knowledge shows that several pollutants can interact towards a single health effect or a single pollutant could be involved in several different health outcome. So the choice of a pollutant to perform HIA (Health Impact Assessment) in IAM is more restricted by the available knowledge on health effects and on the way to measure those effects than by the data set provided by the STATE block. Moreover, the selection of input data depends on the availability of a causal function to derive health output and the needed data to use for the calculation.
The level of needed details on the exposure data (STATE & population) 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

DATA COLLECTION

Air Quality data: The data from the STATE block are concentrations of pollutants and can be expressed as different levels of complexity (such as level of concentration measured at a monitoring site, levels of concentration averaged for several monitoring stations or determined using an AQ model), they represent the exposure of the concerned population. The data from the PRESSURE block are concentration of released pollutants contributing to the exposure of the population. The contribution is represented by the intake fraction of the concerned population.

Population data: Depending on the level of complexity there would be two approaches to address population data. Data could come from a larger set for instance a national set, this would be considered as a top-down approach. Or data are locally collected form registries or hospital admissions in the concerned city and would qualify for bottom-up approach. The data to collect depend on the reason to perform health impact assessment and towards a specific set of actions (RESPONSE).

Dose-response functions: Dose-response functions are regularly up-dated with the most recent health information based on epidemiological studies to integrate local, cultural and demographic specificities. Recent cohort studies have up-dated dose-response functions of the major air pollutants and their best known health effects for European populations (i.e., ESCAPE

Cohort studies allow to understand better the mechanisms related to the onset or exacerbation of health outcomes related to pollutants exposure and define the shape of the mathematical function that describe better those relationship. Dose-response function are pollutant and effects specific. The availability of a dose-response function does not impair the level of complexity decided to perform HIA it represents the causal relationship between exposure and effect and uncertainties related to causality.

For instance:

- If the RESPONSE is focusing on residential wood burning, the pollutant – health effect relationship chosen could focus on polycyclic aromatic hydrocarbons (PAH) or PM10 and respiratory health. The correlated population data comes from medical registries for health outcomes and, mortality.
- If the RESPONSE is related to traffic management (decrease of speed, change of fuel, technological solutions,…) another pollutant-health effect relationship would be preferred such as PM2,5 or better the Black Carbon/NO and the health indicators could be mortality from registries, cardio-vascular health outcomes from hospital data or exacerbation of respiratory health from hospital emergency visits.
- If the RESPONSE to optimize needs a global assessment of the health related to air quality of the population to be compared with several interventions, prospective or counterfactual approaches will be chosen. General population data are to be computed in regard with exposure data being concentration of pollutants considered as indicators of major exposures, PM2,5, O3 and NO2 would be preferred choice as dose-response functions have recently been up-dated, data related to population exposure come from STATE block and PRESSURE block

provides the sources contribution (source apportionment).

4.4.2 Functionality

The methodology to be used to estimate health impacts depends on the objectives of the use of the IMPACT block in IAM, the availability of the data and their uncertainty.

The functionality describes the cause-effect relationship of the input and the output. This input-functionality-output chain can be implemented at different levels of complexity. The functionality of the IMPACT block is expressed in the dose-response function. Regularly up-dated, dose-response functions are developed to mathematically characterize the causal relationship between exposure to a single pollutant and health outcomes (recent review come from cohort meta-analysis such as: Pascal et al, 2013; Adam et al, 2014; Beelen et al, 2014; Newby et al, 2014; Wang et al, 2014)

This implementation depends on the strength and the robustness of the causal relationship between the exposure indicator (STATE or PRESSURE) and the health indicator chosen to support the decisions to be taken. The chosen approach (retrospective, prospective, counterfactual (see D2.4)) to compute health impact does not restrict the level of complexity to be applied; it only demands more or less detailed data on the input-output chain. Uncertainties in the results are linked to the strength of the causal relationship described by the dose-response function

The way to built the IMPACT block depends on the level of complexity reached for input (STATE and PRESSURE) but also the level of details gathered on the population:

- **LEVEL 1**: A simple complexity is represented by the use of a coarse description of the 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. The population description would mainly come from a top-down approach For example: the number of hospital emergency visits related to increased ozone levels for a city or region as a ratio to the national number of hospital emergency visits. The results would be expressed as number of health outcome related to the exposure and can be monetarized with the appropriate mathematical function. The uncertainty is related to the description of both the exposure and the population.
- **LEVEL 2**: More detailed description of exposure and of population allows to a more complex description of the computed IMPACT. The dose-response function is similar to that used in level 1, but the exposure is described with spatial and temporal details from the STATE block and a bottom-up approach is used to describe the population. For instance a locally collected register for health outcomes, number of hospital visits is used. Here as well results can be used for further economic valuation. The uncertainty is related to the description of both the exposure and the population
- **LEVEL 3**: A detailed temporal and spatial resolution for exposure from STATE block and a temporal and spatial description of the concerned population using collected data with a bottom-up approach, will allow a rather detailed computed health

information. The dose-function response is still the same as for the other 2 levels of complexity. The use of parameters such as distance to road, spatial distribution of inhabitants and presence of vulnerable groups, for instance, will allow the results to be more representative to the local situation.. For examples: The number of hospital emergency visits of those who live in greener or more traffic areas of a city related to local changes in ozone.

The functionality in the IMPACT chain remains as robust as the dose-response function is. Comparison of health impact of policies or interventions (RESPONSES), setting of health objectives for long term action plan are some of the uses that are provided by the IMPACT block. The further computation of health impact into health benefits of reduction of exposure, monetarization or economic valuation or willingness to pay are examples of subsequent indicators used to support decisions whether at urban scale or international scale (Le Tertre et al, 2013, Chanel et al, 2014, Istamto et al, 2014).

4.4.3 Output

The output of the IMPACT block is used as an input to the RESPONSES block, Therefore it needs to contain all relevant information for the calculation of the chosen health indicator.

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 e.g. expressed as such (i.e., number of attributable deaths) or translated into YOLL, DALY, life expectancy related to changes in exposure when computed in scenarios assessment. Attributable health outcomes (death or any other effect) are estimated assessing the outcome observed comparing 2 situations or scenarios, the first is a baseline using the current distribution of the health outcome and the second is the rate of outcome reflecting the exposure (Brunekreef 2007). These health outcomes are than classified as avoidable, or premature if their exposure is reduced for instance. 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. Health gains from the reduction of the risk factor (here air pollution) reflects better the multiple parameters to health being the increase of life expectancy, the difficult notion of prematurity in death, inequalities l-related to other factors than air quality.

The output representativeness depends on the level of detail of population data.

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

The valuation of human health into economic or work related indicators such as sick-leave from work has to be computed using human health assessment and translating it into other indicators, the result’s representativeness depending on a detailed description of the STATE, health data and an available function for valuation.

4.4.4 Synergies among scales

The consideration of different scales is important to describe the blocks “STATE”, “PRESSURE”, “RESPONSE”. 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 PRESSURE 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 multi-local scale IAM with re-distribution to each local city of their own data.

4.5 Responses

The RESPONSES block represent the Decision Framework, that is to say the set of techniques/approaches that can be used to take decisions on emission reduction measures to be applied or on changes in activities (driving forces)..

4.5.1 Input

Input required for this block is:

- *Emissions.* Emission detail is "driven" by the control variables (emission reduction measures) detail. It means that, if control variables act at a macrosector level, emissions should be described with the same level of detail (i.e. a sector detail would not be necessary in this case). The same is true for the spatial domain and the spatial discretization;
- *Air Quality Indexes* (AQI). When taking decisions on a spatial domain and a time varying process, some form of compact representation of the situation is essential. Evolving pollutant concentration at different sites (measured or produced by some model) must thus be summarized into one or more AQI(s). In most cases, these AQI(s) are directly computed following EU legislation, but other definitions are possible, that may better represent the local conditions. How they can be compared and/or combined is a specific task of the RESPONSE block.
- *Impacts.* These are directly derived by emissions (as in the case of the emission reduction costs) or by AQIs, through suitable relations (as in the case of external costs, health exposure, ecosystem exposure, …). While AQI(s) 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 RESPONSE 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.

4.5.2 Functionality

As it has been said, this block is devoted to suggest responses to the decision maker, to reduce precursor emissions and subsequently to improve the selected AQIs (Vlachokostas et al., 2009) and their sub-sequent IMPACTS.
The main components of a Decision framework are:

- *Control variables*: these represent the emission reduction 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). In case of single technologies, a further classification distinguishes between "end-of-pipe measures" (applied to reduce emissions at the "pipe" of an emitting activity) and "efficiency measures" (that reduce activity levels, e.g. acting on the people behaviour, etc…). Also localization decisions (e.g. moving activities to different areas) can be considered part of these efficiency measures.

- *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 pollutant 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.

The RESPONSES block can be described considering three levels of complexity:

- **LEVEL 1**: Expert judgment and Scenario analysis. In this case the selection of emission abatement measures is based on expert opinion, with/without modelling support to test the consequences of a predefined emission reduction scenario on AQIs. 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 sources of emissions that are mainly influencing AQI are derived through a formal approach; this then allows to select the measures that should be applied to improve the AQI(s). 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 world) 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 has been introduced. 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 sum of (possibly, some) 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).

4.5.3 Output

The output of the decision framework are the responses (emission reduction measures) to be implemented to improve air quality. There are different options to describe these responses:

- Macrosector level emission reductions. Precursor emissions (to improve air quality) are provided at a CORINAIR macrosector-pollutant level. This is a very aggregated approach, but can provide policy makers with some insight on how to prioritize the interventions (Carnevale et al., 2012).
- “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 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”, also called "Non technical measures". These measures reduce anthropogenic driving forces that generate pollution. 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”.

4.5.4 Synergies among scales

The main issue in relation to “synergies among scales” is the fact that regional authorities have to take decisions 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 Current Legislation (CLE) 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 in force, and that represent the starting point for the regional actions.

5 Key areas to be addressed by research and innovation

5.1 Drivers

There were considerable uncertainties identified for the DRIVERS block assessment framework for all the main emission source sectors contributing to local level, especially for road traffic, non-road traffic and machinery and residential combustion.

Of these, most severe uncertainties were estimated for residential combustion sector (as for residential wood combustion). Furthermore, residential wood combustion has been recently found as one of the major contributors to fine particle and other organic air pollution in many urban areas in Europe. Future research needs for residential wood combustion DRIVERS block assessment concern mainly:

- Activity amount assessment
- Combustion appliance and user's practice information
- Spatial assessment (i.e. gridding)

Residential wood combustion activity information can rarely be based on sale statistics because a lot of the wood fuel is from private stock and is used privately. Furthermore, house-hold level wood heating system stock is often poorly known because such information is rarely gathered into registers. Therefore activity and combustion technology estimates have to be often based on questionnaire information about wood use amounts, frequencies and used combustion appliances. Additionally, the questionnaire could include information about wood combustion user's practices (the ways of batching, ignition, combustion air supply, fuel quality etc.) because these parameters may have essential impact on emission factors and would be therefore needed in the PRESSURES block assessment.

Spatial assessment (i.e. gridding) of residential wood combustion activities is important in order to assess the impacts of possible emission reduction measures and other interventions on local air quality inside the city area. Gridding might be challenging because of the lack of building registers with house-hold level information about residential wood heating appliances. Spatial distribution of residential wood combustion activities typically differ considerably from that of many other urban emission sources (e.g. traffic) or most of the simple gridding surrogates (e.g. population density), and therefore the direct use of these surrogates results in severely incorrect spatial distribution.

To consider gridding methodologies for residential wood combustion, the key question is availability of spatial (GIS) data. An optimal situation would be to have a building register with house coordinates and information about wood heating devices and their use. However, such data is rarely available. If there is a building register with information about main building types that are relevant for the wood use in the country (e.g. residential/other, apartment/detached/semi-detached), and an estimation about urban/rural differences in wood use, a relatively good approximation for large area average can be achieved. In case of absence of building register, population data could be used.

A more general new future research line related to DRIVERS should be devoted to the integration of bottom-up and top-down inventories. In fact at the moment there are inconsistencies between bottom-up (local/regional) and top-down (EU level) approaches and tool, and this can prevent the implementation of a fully integrated approach connecting various governance scales. Also, while activity levels (DRIVERS) are usually available at international/national level, this is not the case at regional/local scales, where only emission inventories (PRESSURES) are compiled; this aspect can also cause inconsistencies among data provided at different levels of governance.

A further key issue for future research is related to the estimation of how the economic sectors will develop and adapt in the future, also taking into account the current downturn.

5.2 Pressures

About emissions, key areas to be investigated by research and innovation concern various topics.

Concerning the general methodology to build emission inventories there is the need for

- harmonization of bottom-up and top-down approaches, used at different scales, to create emission inventories;
- approaches to improve the quality of the emission inventories (inverse modelling for emissions improvement, new model chains to describe projections, …) ;
- disaggregation coefficients (spatial and time ones) to be adapted to regional and local scales, especially for CO, PM and NH_3 emissions.

Input data related to the calculation of emission projections, with the need for

- Bottom-up and top-down emission inventories integration and consistency, to allow “seamless” integration of measures from local to EU level, and vice versa;
- consistency of all data has to be improved; transport sector has still some missing data concerning the composition of the real vehicle fleet, especially concerning the split between the different categories of age of vehicles and the type of engines (gasoline/ diesel);
- for biogenic emissions, the landuse, the meteorological data and the topography (slopes and orientation) need finer description according to the species which can effectively be taken into account mostly in mountainous and coastal areas.
- distributions of the different species of forest trees and plants adapted to the areas of study;

Emissions factors, that need to be more specific to the effective sources, as for

- PM components (e.g. BC, metal, UFP, wildfires)
- Other gaseous pollutants (VOC, SLCP, reactive nitrogen)
- HFC emissions from refrigeration and air conditioning equipment and the NO2 emissions from cars equipped with catalytic converters;

- NO2 from agricultural soils due to the use of fertilizers;
- totally unknown sources, as peatlands CH_4, and very little known as swamps and wet zones;
- aggregated emission factors used for road traffic: it has to be constantly improved because of the constant changes and evolutions of the real vehicle fleets at local, regional and higher levels. Measurements have to be performed in situ to fit real traffic situations;

5.3 State

Key areas to be addressed by research and innovation in the STATE module are:

- Refinements of air quality assessment and exposure. Research directions could be devoted to better represents local scale in AQ modelling for IAM. This could be done through the use of Computational Fluid Dynamics models for local and street level modeling, or using sub-grid scale model and sub-grid parameterization in CTM. One of the challenging issue in local scale modelling is related to emissions. Concerning meteorological models, a better use of urban module in meso-scale model would benefit to regional and more local studies, and help to link model at different scales;
- Monitoring based on the joint use of ground-based and remote-sensing methods, to assess the “current” AQ situation;
- Better understanding of sources of various fraction of PM;
- Climate change considerations. Long-term study integrated assessment should take into account both air quality and climate change issues. In this framework, it is important to develop the use of future meteorological simulation for running AQ models. More extensively, a challenge is the development in IAM of online chemical transport model, which allow the study of feedback interactions between meteorological/chemical processes within the atmosphere, and to take into account AQ/climate change interactions;
- Validation of AQ simulation for future policy scenarios. It is important to work to develop a common methodology to combine measurement data in a reference year with modelling results for future policy scenarios;
- Surrogate modelling. Issues are related to extend surrogate model approaches, to properly describe nonlinearities in secondary pollution concentrations and improve the “Design of Experiments” (that is to say, the phase that allows for the choice of set of Chemical Transport Models simulations required to train surrogate models).

5.4 Impacts

Key areas to be addressed by research and innovation, in the IMPACTS module, are related to:

- Refinements of air pollution impact on health and exposure;
- The detailed reconstruction of the population patterns in the domains under study; in particular it is important to study how to correctly reconstruct spatial and temporal patterns of the population, to compute the real exposure of the population (i.e., reconstructing how population is moving during the day to go to work, school, etc..

and not using "average" population patterns). At the moment, "static" population maps are often used to perform HIA studies;
- Detailed and localized dose-response functions, at the moment often related to average values at EU level, and not properly describing local features;
- Dose-functions for exposure to multiple pollutants;
- Description and computation of health effects of low dose exposure of the major air pollutants;
- Mortality and morbidity factors of long term exposure, in particular to NO_2 and O_3;
- Effects of NO_2 exposure in particularly polluted environments (i.e. busy roads) and short-term exposure to extreme levels;
- Environmental impacts of reactive nitrogen and interlinks with climate/global change.
- How to integrate health in decision related to air quality action plans

5.5 Responses

Key areas to be addressed by research and innovation, in the RESPONSES module, are:

- Refinements of mitigation and adaptation options and measures;
- Inclusion of socio-economic aspects;
- Integration of AQ aspects into other policy areas;
- "Efficiency measure". The use of these measures is now limited to scenario analysis, because it is very difficult to estimate the costs of such measures, particularly, because they impact many other sectors beside air quality. For instance, car sharing has the potential to reduce not only exhaust emissions, but also accidents and noise. How can the overall cost be associated to the benefits in such diverse sectors? It will be necessary to further investigate such actions. Also, an additional complexity is related to the use of these measures in an optimization frameworks; from this point of view, new formal approaches should be devised;
- IAM nesting. As it is already done with CTMs, a research direction could be devoted to developing IAMs nesting capabilities (both one-way and two-way nesting) to easily manage EU/national constraints at regional level, and at the same time to provide feedbacks from the regional to the EU/national scale;
- IAM approaches harmonization and guidelines. It is important to work to develop guidelines and harmonize approaches to implement IAMs. This work will partly be done in the frame of APPRAISAL, but it is necessary to continue these activities in order to guarantee that local/regional plans can be compared and integrated, when necessary.
- Air Quality and Climate Change issues. At the moment, national climate change policies simply dictate some constraint to local air quality plans, but it is well known that also local air quality policies (e.g. the reduction of aerosols) can have consequences in terms of climate change. In a "resource limited" world, the aspect of maximizing the efficiency of the actions (to get win-win solutions for AQ and CC) will become of extreme importance and this requires a guideline to integrate climate change policies (normally established at national or even international levels) with air quality plans developed at regional/local level;
- Dynamics. All current approaches are static, in the sense that they devise a solution to be reached at a given time horizon (say, for instance, in 2020). However, the

system we would like to control is non-stationary (see the effect of the current economic crisis) and thus it may be more supportive for decision maker to know where to currently invest with the highest priority in order to follow a certain path to the target condition (Shih et al., 1998), but with the ability of modifying the decisions in case of system evolution differing from the projected one. This involves the necessity of flexibly adding into the plans the advent of new technologies and the ability to determine the cost of scrapping old plants to substitute them with newer ones. This essentially means designing a new generation of Decision Support Systems to be intended more as control dashboards, than planning tools;

- Benefit evaluation. Related to the dynamic problem is the issue of how to evaluate future benefits of air quality investments. If economy has defined since long how to account for investment costs lasting for a period in the future, this is more difficult for benefits that are not monetizable or last in the future for an unknown period. How can we account for a 20% improvement of an AQI ten years from now? What is the benefit from a reduction of PM_{10} today that will decrease cardiovascular problems in a population sometime in the future? What are the other parameters that could interfere and how would they evolve in a time frame of 10 years?

6 Examples of the IAM framework application

In this section two possible implementations of the IAM framework are presented. The two examples represent extreme cases ("open-loop" and "closed-loop", as described in the introduction of this Deliverable), that combine the use of different DPSIR blocks, and different levels of complexity for decision framework and modelling approach.

6.1 Scenario analysis from University of Aveiro

In this example the DPSIR scheme is applied in the scenario mode, considering the PRESSURE and STATE blocks in a very detailed way, and the RESPONSES block in a scenario analysis mode. To study the effects of selected PM_{10} reduction measures, the air quality modelling system TAPM has been applied over the Northern region of Portugal, for one year (Borrego et al, 2012). The Air Pollution Model (TAPM) is a 3-D Eulerian model with nesting capabilities, which predicts meteorology and air pollution concentrations in a Graphical User Interface. The model has two components: the meteorological prognostic, and the air pollution concentrations component. The meteorological module of TAPM is an incompressible, optionally non-hydrostatic, primitive equation model with terrain-following coordinates for 3D simulations. The results from the meteorological module are one of the inputs to the air pollution component.

PRESSURES

For the base scenario, annual emissions data (PRESSURES) are obtained from the Portuguese national inventory and spatially downscaled to the sub-municipality level for each pollutant and each activity sector. The national emissions inventory takes into account annual emissions from line sources (streets and highways), area sources (industrial and residential combustion, solvents and others) and large point sources. These annual emission data for each pollutant and activity sector are then spatially and temporally disaggregated in order to obtain the resolution required for the study domain simulation. For the reduction scenarios, the emission values of PM_{10} are estimated based on the implementation of selected reduction measures.

STATE

The state in this case is described by PM_{10} concentrations, simulated for each hour. In order to investigate the impact of the designed PM_{10} reduction measures on the air quality of Northern Portugal, TAPM is applied over the study region, which includes the agglomerations of Porto Litoral, Vale do Ave and Vale do Sousa, where the PM_{10} concentrations exceeded the legislated limit values. The application considered three domains through the nesting approach: the outer domain covers an area of 1080 × 1080 km^2, with a spatial resolution of 43.2 × 43.2 km^2, and the inner domain had an area of 120 × 120 km^2, with a resolution of 4.8 × 4.8 km^2.

RESPONSES

In terms of responses, the TAPM model has been applied in a scenario analysis mode, describing at first the base case situation, and then the concentration results if applying together the following measures:

- Traffic
    - Introduction of low emission fleet in public transportation and improvement of public transport network
    - Renewal of taxis and solid waste collection vehicles
    - Decrease of heavy vehicles circulation in the urban areas
    - Low Emission Zones
    - Banning traffic from selected streets
- Industry
    - Improvement of industrial PM retention systems
    - Reinforcement of the inspection of industry sources
    - Establishment of emissions standards for industrial clusters and business activities in urban areas
- Residential combustion
    - Use of certified combustion appliances with PM emissions reduction

From this brief description, it is clear that in this case the DPSIR IAM implementation is mainly focused on the description of the effects (on the pollution concentrations) of a predefined list of emission reduction measures (so applying a “scenario analysis”).

6.2 Environmental Costs Model from VITO

In this “closed-loop” implementation, DRIVERS, PRESSURES and RESPONSES block are applied, with the RESPONSES block modelled through an optimization approach.

In particular, the MKM (Environmental Cost Model) model is applied. MKM is a techno-economic, bottom-up optimization model that can be used to contribute to a more efficient environmental policy. When optimizing, cost efficiency is generally the central objective, but the model can also be used to assess different variants of the optimal solution, or to estimate future emissions The MKM consists of a comprehensive and detailed database with information on emission sources and possible reduction measures, and an algorithm in MARKAL (MARKet ALlocation model) to perform the calculations.

The building blocks of a MARKAL model are demand for energy (heat, electricity) and products (e.g. steel), emissions, energy (e.g. coal, oil, gas), materials (e.g. ores) and technologies (e.g. power plants, boilers, end-of pipe or process integrated reduction techniques). Each of the blocks is quantitatively described by a set of technical and / or economic parameters. As MARKAL makes projections over a time horizon of 50 years (5-year intervals), both current as well as future technologies are included in the model. Both the supply and the demand side are modelled. The model selects an activity level of technologies that minimizes overall system costs and that balances demand and supply. Key model assumptions include a free market with full market transparency. Model calculations are based on linear programming in GAMS with the solver CPLEX to allow solve ‘mixed integer’ problems (i.e. involving discrete variables like ‘investment decision’ adopting the value 0 or 1).
The MKM is currently operational for Flanders for:

- the sectors energy, industry, residential, tertiary, horticulture,
- the greenhouse gases CO_2, N_2O, CH_4, (F-gas industry),
- the air pollutants NOx, SO_2, PM, NMVOC (combustion).

DRIVERS

The drivers include the different levels of demand for an energy service (e.g. heating, lighting) or production output that should be met. They thus constitute key determinants for the various environmental pressures considered (see below).

Drivers influence the response through the optimisation constraints. In each period, demand for useful energy and production volumes must (at least) be met using existing or new capacity. In each period, the amount of imported and produced products must be the same as the amount consumed and exported.

There is also a feedback from responses to drivers as demands are partially determined endogenously. In other words, adopted technologies can change energy demand. In case of price elasticity, demand may also change due to an increase or decrease of price.

PRESSURES

Pressures include the various pollutants, such as NOx, SO_2, and CO_2. For the different (sub) sectors, various sector specific pollutants are defined. Also the pressures influence the response through the optimization constraints. Emission constraints for one or more pollutants can be set at the level of sectors (e.g. chemistry) or regions (e.g. Flanders).

RESPONSES

The responses include the various technologies that can be used to meet demand, including different types of energy production plants, process integrated measures (more energy efficiency or different production process), and end-of pipe air pollution reduction techniques. A distinction is made between maintaining a certain capacity, and effectively using that capacity.

This example is based on a complex (optimization based) implementation of the RESPONSES block, even if used without the STATE module implementation (in fact all the computations are based on DRIVERS and PRESSURE modules). This application is not a scenario analysis; in fact the decision maker does not want to test the effect on concentrations of a predefined list of measures; on the contrary he wants to derive, from the model application, a suggested list of optimal measures to be applied (even if this choice is performed considering a very simple STATE module, that equal emissions to concentrations).

7 UNCERTAINTY and SENSITIVITY ANALYSIS

Uncertainty and Sensitivity analyses are key issues in the definition and evaluation of emission control strategies. The main goal of uncertainty analysis is to assess the effects of the input parameter uncertainties on the computed results. Instead, sensitivity analysis is defined as the study of how model output variation and/or uncertainty (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources. The two analyses have to be used together, usually starting by the uncertainty analysis.

One of the most important issue to be addressed at the beginning of both the analyses is the definition of what can be considered as input for them. Since considering input as the only source of uncertainty can limit the study, in these analyses each factor that can lead to a variation in the output of the model is usually considered an input (so, not only the traditional “model input”, like initial and boundary conditions, but also parameterizations, and numerical algorithms used by the models). Starting from this definition, it is clear that the difference between the theoretical definition of uncertainty used in this frame and the the one used in AQ directives mainly related to model evaluation (see DEL2.5).

Before starting the discussion on the wide range of techniques applied in last decade to perform both these kind of analyses, a few word about the traditional expert judgement approach have to be highlighted. In fact, expert judgement is the easiest way for obtaining information on uncertainty levels of a certain decision (uncertainty analysis) and/or about the most relevant uncertainty sources related to it (sensitivity analysis). Obviously, this approach can be widely criticized as subjective, but in situation characterized by lack of data it is still the only way to produce a qualitative ranking among different options using uncertainty as a measure (O’Hagan et al. 2006).

In the next sections a review of the main techniques that can be used to perform uncertainty and sensitivity analysis will be briefly presented and the application impact of these analysis will be investigated in the IAM framework introduced in chapter 2.

7.1 Uncertainty Analysis

As already stated, the main goal of uncertainty analysis is to assess the effects of input/parameter uncertainties on the computed results.
This analysis can be performed in an analytical way or (most widely) using a Monte-Carlo approach.

ANALYTICAL METHODS FOR UNCERTAINTY ANALYSIS
For relatively simple relationships, statistical error propagation analytical methods can be used for uncertainty analysis. Variance propagation is the analytical approach most frequently used for uncertainty analysis of simple equations (Martz and Waller, 1982; Morgan and Henrion, 1990).

NUMERICAL METHODS FOR UNCERTAINTY ANALYSIS
To overcome problems related to analytical methods, a series of numerical methods to perform uncertainty analysis has been presented in literature. The most commonly used

are:

1. Monte Carlo simulation (Rubinstein, 1981), where a relatively large set of sampling values of the input hypercube are used to drive the model (or a statistically simplified version of the model) and the variance of the results is estimated (Downing et al., 1985). The sampling is usually performed using either the Simple Random Sampling or the Latin Hypercube Sampling (Morgan and Henrion, 1990).
2. Differential uncertainty analysis (Cacuci, 1981; Worley, 1987), in which the partial derivatives of the model response with respect to the input are used to estimate uncertainty.
3. First-order analysis employing Taylor expansions (Scavia et al., 1981), where a numerical approximation of the analytical variance propagation equations is computed.

7.2 Sensitivity Analysis

Sensitivity analysis can address a high number of useful issues for each block of the IAM. It can help in uncovering technical errors in the model, identifying critical regions in the space of the inputs, establishing research priorities and simplifying models.
There is a large number of approaches available to perform a sensitivity analysis, mainly belonging to the following families:

- Partial derivatives methods.
- Regression analysis.
- Variance decomposition methods.
- Elementary effects.

In general all the procedures perform the following steps:

1. Definition of the bound/probability distribution of each considered source uncertainty;
2. Definition of the output variable to be analysed;
3. Design of Experiments (closely related to the selected method) used to propagate the source uncertainty through the model;
4. Computation of the model output for the scenarios defined in (3) through the Design of Experiment;
5. Computation of the sensitivity measures of interest.

Sometimes, the procedure will follow a two-stage approach: the first iteration defines the most important sources to be better investigated in the second (usually more detailed) one, that can apply a different method with respect to the first phase.

DERIVATIVE METHODS
In literature most of the sensitivity studies are based on partial derivative computation. Indeed, the derivative $\partial Y/\partial X_i$ of an output Y versus an input X_i can be thought as a mathematical definition of the sensitivity of Y versus X_i. Moreover, a number of software implementation of models includes routines for the efficient computation of system derivatives (Rabitz, 1989; Turanyi, 1990; Varma et al., 1999; Saltelli et al., 2000). The

derivative-based approach is usually very efficient in terms of computational time. Moreover, derivatives are meaningful at the base point where they are computed and do not provide information about the remaining part of the space of the input factors.

REGRESSION ANALYSIS
Regression analysis, in the context of sensitivity analysis, implies fitting a linear regression to the model response and using standardized regression coefficients as direct measures of sensitivity. This method is therefore most suitable when the model response may be assumed as linear; the linearity hypothesis can be confirmed by an high value of the determination coefficient. Regression analysis is simple and has low computational costs. The main drawback is that if the relationship is highly non linear, the fitting regression could be far from the initial model (Saltelli et al., 2000).

VARIANCE-BASED METHODS
A set of methods based on the investigation of the contribution of single (or group of) input variance to the output variance are presented in literature. Usually, these methods are computational very expensive due to the variance estimation process. That is why recent research aims to find efficient numerical algorithms for the Design of Experiments. The most detailed methods are based on the work of the Russian mathematician I. M. Sobol, and are based on the computation/estimation of the following sensitivity indexes (Sobol, 1993, Homma and Saltelli, 1996):

- First order sensitivity index: $S_i = \frac{V[E(Y/X_i]}{V(Y)}$. It represents the pure effect of each input factor on the variance of the output.
- Second order sensitivity index: $S_{ij} = \frac{V[E(Y/X_i,X_j]-V[E(Y/X_i]-V[E(Y/X_j]}{V(Y)}$. It represents the effect of the interaction between two factor on the variance of the output.
- Total effect: $S_{Ti} = \frac{V[E(Y/X_{\sim i}]}{V(Y)}$. It represents the overall effect of the input (considering also all the interaction between the other terms) on the variance of the output.

The most important feature and relationship between the terms are:

- $\sum_i S_i + \sum_i \sum_{j>i} S_{ij} + \cdots + S_{123\ldots k} = 1$
- $S_{Ti} = S_1 + S_{12} + S_{13} + \cdots + S_{123\ldots k}$
- $\sum_i S_{Ti} > 1$

The computation of the indexes is usually performed evaluating the output of the model in a subset of points of the input hypercube, selected by mean of a Monte-Carlo/Quasi Monte-Carlo method (Morokoff and Caflish, 1995). In the application, first order effect and total effect are computed. In this way, information about the “pure” and the total impact (including, as stated before, all the interaction terms) of each factor can be estimated. In particular cases (ozone/PM10 formation) also some high order effect can be computed. This is the case, for example, of the combined effect of NOx-VOC in the formation/accumulation of ozone, or of the link between inorganic gas precursors for PM10.

ELEMENTARY EFFECT
The elementary effect method is a screening method allowing to highlight a limited number of important input factors among the many contributing to the output of the system (Morris, 1991, Campolongo et al., 2007) .
The idea is to define two sensitivity indexes with the aim of determining which input can have negligible, linear and additive or nonlinear (or involved in interaction) effect on the output through the computation of the so-called elementary effects defined as:

$$EE(X)_i = \frac{[Y(X_1, X_2, \dots X_i + \Delta, \dots X_k) - Y(X_1, X_2, \dots, X_k]}{\Delta}$$

The idea is to compute the elementary effect for a subset of input values obtained by randomly sampling the input hypercube, in order to obtain a distribution function F_i for each of the input factors. The two sensitivity indexes used in this context are respectively the estimation the mean and the standard deviation for each distribution. The mean assesses the overall influence of the factor on the output, while the standard deviation provides an evaluation of nonlinearities and interactions with the other input. Sometimes also the distribution of the absolute value of the elementary effect is considered, in order to avoid compensation in the mean value.
In order to estimate the sensitivity, the design of experiments has to be focused on the problem of sampling a number of elementary effects to be used for the definition of each distribution function. A full method will require for r samples and for each one of the k input a number of 2rk model evaluation. A more efficient sampling method is based on the computation of r different intersecting trajectory including (k+1) points in the input space, for a total of r(k+1) sample points (Morris, 1991).

7.3 Uncertainty/Sensitivity analysis in IAM

In order to be most useful, the IAM should also include information about the source of uncertainty related to each of the integrated block. In addition, the information related to the uncertainty of the considered decision and on the impacts of the decisions could ensure the users to better evaluate the trade-offs among different policies.
In this frame, the methodologies presented before can be used to assess the uncertainty in the results of the IAM (uncertainty analysis) and to identify the uncertainty sources with higher impacts (sensitivity analysis) in order to define if, how and where addressing the research.
The analysis is a very complex task due to the fact that IAM is implemented, by definition, by a set of integrated models, whose input are usually uncertain and whose output can become the input of the next stages. This fact makes the analytical and partial derivative related methods for both uncertainty and sensitivity analysis quite impossible to be used on the overall system, and sometimes also for a portion of it. For instance, even if the computation of the uncertainty propagated from an emission factor to an emission value is quite simple to be computed analytically, how to compute later the uncertainty on the output of a CTM model (STATE block) due to uncertainty on its emissions? Moreover, more complex is the model, more uncertainty should be introduced in its formulation (chemical kinetics rate, chemical mechanism, numerical solver) and for this reason, the

use of numerical methods is necessary.

7.3.1 Uncertainty sources for IAM systems

Table 7-1 resumes the most important uncertainty sources for each block of DPSIR scheme. In the table, referred to Figure 2, the effect of each source is considered as direct if the connection between input and output is related to the same block, and indirect if the uncertainty in the source has effect on the block through the output of a connected block. For instance, the uncertainty on emission factors directly affects the output of the Pressures block, that is connected to the state one. For this reason, the impact of this uncertainty source on the state block is indirect.

Uncertainty Sources	Drivers	Pressure	States	Impact	Response
Road Traffic – Non exhaust emission parameters	direct	indirect	Indirect	indirect	indirect
Residential Combustion – wood	direct	indirect	indirect	indirect	indirect
Gridding procedure	direct	direct	direct	direct	direct
Emission factors	-	direct	indirect	indirect	indirect
Scale adaptation	-	direct	direct	direct	direct
Temporal adaptation	-	-	direct	direct	direct
Chemical Mechanism	-	direct	direct	indirect	indirect
Modelling Formalization	-	direct	direct	direct	direct
Meteorology selection (one meteo scenario/more meteo scenario)	-	direct	direct	indirect	indirect
Meteorology modelling	-	direct	direct	indirect	indirect
Source-Receptor modelling	-	-	direct	indirect	indirect
Dose-response formalization	-	-	-	direct	indirect
Concentration-response formalization	-	-	-	direct	indirect

Table 1: Different uncertainty sources with their impact (direct/indirect) for each block of the DPSIR scheme.

According to Table 7-1, the uncertainty sources can be split in general uncertainty sources (directly affecting more than one DPSIR block) or uncertainty directly affecting only one DPSIR block. The first category includes methodological issues as the temporal/spatial scale, the chemical details used in the context and the formalization/parameterization selection virtually performed in each block.

In the next subsections, a brief discussion about the specific uncertainty sources for each DPSIR block is presented.

DRIVERS

Uncertainties of DRIVERS block components have been partly discussed in previous chapters. A short summary of the main challenges for the main 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 house-hold 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.

PRESSURES

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. The structural accuracy estimates the inventory structure ability to calculate as precisely as possible the real emissions. This uncertainty can be split into 3 contributions
    - inaccuracy due to aggregations: the emissions are calculated on defined spatial and time scales and for some of them these scales are different from the real emissions ones. This can be due to lack of information on the emission processes or on the variability of the real emissions;
    - incompleteness, which means that an emission inventory may be inaccurate due to the absence of emission sources because of a limited understanding of the emission processes;
    - inaccurate mathematical formulation and calculation errors: the mathematical formulation used is generally inaccurate (simplified), for example by considering that the relation between emission and activity is supposed linear, which is generally not true.
- **inaccuracy on the input data** (i.e. activity data, emission factors).

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.

STATES

When the AQ state is evaluated through measurements only, uncertainties are related to the measurements themselves, to the geo-statistical 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 Deliverable 2.5. 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 (see Deliverable 2.5 for a definition of this concept) 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 IAM, estimating the AQ state over a relatively short temporal period (up to one year) introduces uncertainties on the representativeness of the AQ state itself.

IMPACTS

Health impact analysis relies on two main processes, namely exposure assessment and epidemiological analysis relating exposure to the health outcome. These two processes include a number of basic steps, finally leading to the quantification of the expected atmospheric pollution induced health burden in the target population, most commonly expressed in terms of years of life lost attributable to the exposure to the atmospheric pollutant (s) under study (Krzyzanowski et al., 2002). Assumptions and uncertainties related to each process may significantly influence the result of the analysis. The main sources of uncertainty in HIA studies can be summarised as follows:

1. Uncertainties in estimating the impact for each health outcome. This uncertainty is mainly related to the health-outcome frequencies data. Mortality may be considered generally accurate, but frequency measures of morbidity and data on health-care systems contain uncertainties (Künzli et al., 2000). Furthermore, in contrast to directly countable events listed in national health statistics (eg, deaths or injuries due to traffic accidents), it is not possible to directly identify the victims of mixtures with cumulative toxicity, such as smoking or air pollutants. Also, the health outcomes may not be specifically linked to air pollution due to synergistic effects with other factors.
2. Uncertainties in exposure assessment. Poor exposure assessment is an important source of uncertainty in HIA (Martuzzi et al., 2003) and can result from errors and biases in either air quality models or in exposure models (Fuentes, 2009). The different sources of error and uncertainties in the exposure models result from variability not modelled or incorrectly modelled, inaccurate inputs, errors in coding, simplifications of physical, chemical and biological processes to form the conceptual models, and flaws in the conceptual model. Emission and meteorological input data accuracy and physical/chemistry assumptions and parameterisations in the air quality model largely affect the reliability of its results on the spatial distribution of ambient pollutant concentrations. Furthermore, statistical methods (e.g. kriging) used to produce higher resolved air pollution fields starting from air quality model results and other inputs (local observations, emissions etc) may also introduce uncertainties at specific locations far away from the observations.
3. Uncertainties related to the concentration-response functions, estimated by epidemiological models: Some of the formal approaches for uncertainty analysis in epidemiological concentration-response models include Bayesian analysis, Monte Carlo analysis and model intercomparison (Fuentes, 2009).
4. Uncertainties concerning the temporal scale of effects, i.e. the latency times from exposure to adverse event. This is an uncertainty mainly associated with long-term exposure studies, as acute effects follow exposure by a few days (Martuzzi et al., 2003).

RESPONSES

Uncertainty and sensitivity analysis problems have been extensively discussed in Deliverable 2.5. Also, as stated in UNECE (2002), it is important that RESPONSE decision approach focuses 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.

7.3.2 Uncertainty/Sensitivity analysis state-of-the-art for IAM systems

In literature, there are very few works concerning the application of uncertainty/sensitivity analysis in the IAM considered as a whole system. The most complete works in this frame are due by Uusitalo et al (2015), presenting a quite complete methodological review concerning possible application of uncertainty and sensitivity analysis in IAM, and by Oxley and ApSimon (2007), presenting a review of the issues related to uncertainty in IAM, particularly focusing on space and time resolution and on the problem of uncertainty propagation in integrated system.
Tables 7-2 and 7-3 show how, for the single DPSIR blocks, literature is more complete in particular for the States block, where a lot of work on uncertainty/sensitivity of air quality modelling has been performed in last decades. Moreover, literature produced for this block include some works related to a simplified version of the Montecarlo approach based on ensemble techniques (Boynard, 2011, Zabkar, 2013) in particular focusing on uncertainty evaluation.

More in general, with the exception of (Freeman, 1986) all the works use a numerical approach based on different level of complexity of Montecarlo simulation. This is probably due to the increasing computational capacity and to the relatively newness of the problem treatment in the context, causing scientist to directly start the study from the numerical approaches both for uncertainty and sensitivity analysis.

Uncertainty Methodology	Drivers	Pressures	States	Impacts	Responses
Analytical Methods	-	-	Freeman et al., 1986.	-	-
Numerical Methods	Kouridis et al., 2010	Kouridis et al., 2010	Zabkar et al., 2013	Fuentes, 2009	Baroni et al., 2013
	Kioutsioukis et al., 2004	IPCC, 2000	Boynard et al., 2011	Chart-asa and Mac Donald Gibson, 2015	Pisoni et al., 2010
	Crosetto and Tarantola, 2001		Cheng and Sandu, 2009		
			Hanna et al., 2001		
			Isukapall et al., 1998		
			Tatang et al., 1997		
			Uliasz, 1988		
			Gao et al., 1996		
			Irwin et al., 1987		

Table 2: In literature methodology applied for uncertainty analysis in each DPSIR block

Sensitivity Methodology	Drivers	Pressures	States	Impacts	Responses
Analytical Methods	-	-	-	-	-
Numerical Methods	Kouridis et al., 2010	Kouridis et al., 2010	Martien et al, 2006	Chart-asa and Gibson, 2015	Butler et al., 2014
	Kioutsioukis et al., 2004		Hakami 2004		Baroni et al. 2013
	Crosetto and Tarantola, 2001		Hakami 2003		Pisoni et al., 2010.
			Menut et al., 2000		Ravalico et al., 2009
			Yang et al., 1997		Rios Insua, 1991
			Carmichaelet al., 1997		
			Seigneur et al., 1981		
			Cukier et al., 1973		

Table 3: In literature methodology applied for sensitivity analysis in each DPSIR block

8 References

- Adam M. et al (2014). Adult lung function and long-term air pollution exposure. ESCAPE: a multicentre cohort study and meta-analysis. ERJ Express 16 September 2014 doi:10.1183/09031936.00130014.
- Amann M. et al. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications, Environmental Modelling & Software, 26, 1489-150.
- Baroni G., Carnevale C., Finzi G., Pisoni E., Turrini E. Volta M. (2013). Uncertainty analysis in air quality control systems. Proceeding of the Conference in Decision and Control 2013, 6792-6797.
- Beelen R. et al (2014). Long-term exposure to air pollution and cardio-vascular mortality: An analysis of 22 European cohorts. Epidemiology 25(3):368-378
- Borrego et al. (2012). Plans and Programmes to improve air quality over Portugal: a numerical modelling approach. Internation Journal of Environment and Pollution, 48, 60-68.
- Boynard, A., Beekman, M., Foret, G., Ung, A., Szopa, S., Schmechtig, C., Coman, A. (2011). An ensemble assessment of regional ozone model uncertainty with an explicit error representation. Atmospheric Environment, 45:784-793.
- Brunekreef B. (2007). The brave new world of lives sacrificed and saved, death attributed and avoided. Epidemiology, 18(6):785-788.
- Butler, M.P., Reed P.M., Fisher-Vanden, K., Keller, K., Wagener, T. (2014). Identifying parametric controls and dependencies in integrated assessment model using global sensitivity analysis. Environmental Modelling and Software, 59:10-29.
- Cacuci, D. G. (1981). Sensitivity Theory for Nonlinear Systems. Part I and II. J. Math. Physics 22:2794.
- Campolongo, F., J. Cariboni, A. Saltelli (2007). An effective screening design for sensitivity analysis of large models. Environmental Modelling and Software 22:1509-1518.
- Carmichael G.R., Sandu A., Potra F. (1997). Sensitivity analysis for atmospheric chemistry models via automatic differentiation. Atmospheric Environment, 31, 475-489.
- Carnevale C. et al., (2012). Defining a nonlinear control problem to reduce particulate matter population exposure, Atmospheric Environment, 55, 410-416.
- Carnevale C., Finzi G., Guariso G., Pisoni E., Volta M. (2012b). Surrogate models to compute optimal air quality planning policies at a regional scale, Environmental Modelling and Software, 34, 44-50.
- Carslon D. et al. (2004). Large-scale convex optimization methods for air quality policy assessment. Automatica, 40, 385–395.
- Chanel O. et al, (2014) Economic valuation of the mortality benefits of a regulation on SO2 in 20 European cities. The European Journal Of Public Health Advance Access, 24 February 2014: 1-6.
- Chart-asa C., MacDonald Gibson J. (2015). Health impact assessment of traffic related air pollution at the urban project scale: influence of variability and uncertainty. Science of the Total Environment, 506, 409-421.
- Cheng H., Sandu A. (2009) Uncertainty quantification and apportionment in air quality models using the polynomial chaos methods. Environmental Modelling and Software, 24, 917-925.
- Crosetto M., Tarantola S. (2001) Uncertainty and sensitivity analysis: tools for GIS-based

model implementation. International Geographic Information, 15, 415-437.
- Cukier R.I., Fortuin C.M. Shler K.E., Petschek A.G., Schibly J.H. (1973). Study of the sensitivity of coupled reaction systems to uncertainties in rate coefficients. Journal of Chemistry Physics, 59, 3873-3878.
- Downing, D. J., Gardner R.H., Hoffman F.O. (1985). An Examination of Response-Surface Methodologies for Uncertainty Analysis in Assessment Models. Technometrics 27, 151-163.
- EMEP/EEA air pollutant emission inventory guidebook (2013), EMEP/EEA.
- EEA (2012). Europe's environment: An Assessment of Assessments (2012).
- Freeman, D.L., Egami, R.T., Robinson, N.F., Watson, J.G. (1986), A Method for Propagating Measurement Uncertainties through Dispersion Models, J. Air Poll. Cont. Assoc. 36, 246–253.
- Fuentes M. (2009). Statistical issues in health impact assessment at the state and local levels, Air Qual Atmos Health, 2(1): 47–55.
- Gao D., Stockwell W.R., Milford J.B. (1996). Global uncertainty analysis of a regional-scale gas-phase chemistry mechanism. Journal of Geophysical Research, 101, 9107-9119.
- Hakami A., Odman M.T., Russel A.G. (2003). High-order, direct sensitivity analysis of multidimensional air quality models. Environ Sci Technol, 37, 2442–2452.
- Hakami A., Odman M.T., Russell A.G. (2004). Nonlinearity in atmospheric response: a direct sensitivity analysis approach. J Geophys Res, 109.
- Hanna S.R., Lu Z., Frey H.C., Vukovich N.W.J., Arunachalam S., Fernau M., et al. (2001). Uncertainties in predicted ozone concentrations due to input uncertainties for the UAM-V photochemical grid model applied to the July 1995 OTAG domain, Atmos Environ, 35, 891–903
- Homma, T., Saltelli A. (1996). Importance measures in global sensitivity analysis of nonlinear models. Reliability Engineering and System Safety 52, 1–17.
- IPCC (2000). Good practice guidance and uncertainty management in National Greenhouse Gas Inventories, http://www.ipcc-nggip.iges.or.jp/public/gp/gpgaum.htm
- Irwin J.S., Rao S.T., Petersen W.B., Turner D.B. (1987). Relating Error Bounds for Maximum Concentration Estimates to Diffusion Meteorology Uncertainty, Atmos. Environ., 21, 1927–1937.
- Istamto T., Houthuijs D., Lebret E. (2014). Willingness to pay to avoid health risks from road-traffic-related air pollution and noise across five countries. Science of the Total Environment, 497-498:420-429.
- Isukapalli S.S., Roy A., Georgeopoulos, P.G. (1998). Stochastic Response Surface Methods (SRSMs) for Uncertainty Characterization and Propagation: Application to Environmental and Biological Systems, Risk Analysis, 18, 351–363.
- Kioutsioukis, I. Tarantola, S:, Saltelli, A. (2004) Uncertainty and global sensitivity analysis of road transport emission estimates. Atmospheric Environment 38:6609-6620.
- Kouridis, C., Gkatzoflias D., Kioutsioukis I., Ntziachristos L., Pastorello C., Dilara P. (2010). Uncertainty Estimates and Guidance for Road Transport Emission Calculations, JRC Scientific and Technical Reports, EUR 24296 EN.
- Krzyzanowski M., Cohen A., Anderson R. and the WHO Working Group (2002). Quantification of health effects of exposure to air pollution, Occupational & Environmental Medicine, 59:791-793.
- Künzli N., Kaiser R., Medina S., Studnicka M., Chanel O., Filliger P., Herry M., Horak Jr

F., Puybonnieux-Texier V., Quénel P., Schneider J., Seethaler R., Vergnaud J.-C., Sommer H. (2000). Public-health impact of outdoor and traffic-related air pollution: a European assessment, THE LANCET, 356:795-801.
- Le Tertre A., Henschel S., Atkinson R., Analitis A., Zeka A., Katsouyanni K., Goodman P., Medina S. (2014). Impact of legislative changes to reduce the sulphur content in fuels in Europe on daily mortality in 20 European cities: an analysis of data from the APHEKOM project. Air Quality Atmospheric Health, doi:10.1007/s11869-013-0215-x
- Martien P., Harley R., Cacuci D. (2006). Adjoint sensitivity analysis for a threedimensional photochemical model: implementation and method comparison. Environ Sci Technol, 40:2663–70.
- Martuzzi M., Krzyzanowski M. and Bertollini R. (2003). Health impact assessment of air pollution: providing further evidence for public health action, European Respiratory Journal, 21: 86–91.
- Menut L., Vautard R., Beekmann M., Honoré C. (2000). Sensitivity of photochemical pollution using the adjoint of a simpli_ed chemistry-transport model. Journal of Geophysical Research, 105,15379-15402.
- Martz, H. F., Waller R.A. (1982). Bayesian Reliability Analysis. John Wiley & Sons, New York.
- Morgan, M. G., Henrion M. (1990). Uncertainty, A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press, New York.
- Morokoff W.J., Caflisch R.E. (1996). Quasi-Monte Carlo integration, J. Comput. Phys. 122, 218--230.
- Morris, M. D. (1991). Factorial sampling plans for preliminary computational experiments. Technometrics, 33, 161–174.
- Nagl C. et al. (2005). ASSESSMENT OF PLANS AND PROGRAMMES REPORTED UNDER 1996/62/EC – FINAL REPORT, Service contract to the European Commission - DG Environment, Contract No. 070402/2005/421167/MAR/C1".
- Newby D. et al (2014). Expert position paper on air pollution and cardiovascular disease. European Heart Journal Advance Access 9 December 2014, doi:10.1093/eurheart/Ehu458.
- O'Hagan A., Buck C.E., Daneshkhah A., Eiser J.R., Garthwaite P.H., Jenkinson D.J., Oakley J.E., Rakow T. (2006). Uncertain Judgements e Eliciting Experts' Probabilities. Wiley.
- Oxley, T., ApSimon, H.M. (2007). Space, time and nesting Integrated Assessment Models. Environmental Modelling and Software, 22:1732-1749.
- Pascal M., et al (2013). Assessing the public health impacts of urban air pollution in 25 European cities: Results of the Aphekom project. Science of the Total Environment 449:390-400.
- Pisoni E., Carnevale C., Volta M. (2009). Multi-criteria analysis for PM10 planning, Atmospheric Environment, 43, 4833-4842.
- Pisoni, E., Carnevale, C., Volta, M. (2010) Sensitivity to spatial resolution of modelling systems designing air quality control policies. Environmental Modelling and Software, 25:66-73.
- Ponche J.-L. (2002). The spatialized emission inventories : a tool for the Air Quality Management French IGPB-WCRP News Letters (in french).
- Rabitz, H. (1989). System analysis at molecular scale. Science, 246, 221–226.
- Ravalico, J.K., Maier, H.R., Dandy, G.C. (2009) Sensitivity analysis for decision-making

using the MORE method – A Pareto approach. Reliability Engineering and System Safety, 94:1229-1237.
- Rios-Insua D., French S. (1991). A framework for sensitivity analysis in discrete multi-objective decision-making. European Journal of Operational Research, 54,176-190.
- Rubinstein, R. Y. (1981). Simulation and the Monte Carlo Method. Wiley, New York.
- Saltelli, A., Chan K. and M. Scott M. (2000). Sensitivity Analysis. Wiley Series in Probability and Statistics. New York: John Wiley & Sons, Ltd.
- Scavia, D., Powers W.F., Canale R.P., Moody J.L. (1981). Comparison of First-Order Error Analysis and Monte Carlo Simulation in Time-Dependent Lake Eutrophication Models. Water Resources Research 17, 1051-1059.
- Seigneur C., Tesche T.W., Roth P.M., Reid L.E. (1981). Sensitivity of a complex urban air quality model to input data. Journal of Applied Meteorology, 20, 1020-1040.
- Singh V., Carnevale C., Finzi G., Pisoni E., Volta M. (2011). A cokriging based approach to reconstruct air pollution maps, processing measurement station concentrations and deterministic model simulations, Environmental Modelling & Software, 26, 778-786.
- Sobol I. M. (1993). Sensitivity analysis for non-linear mathematical models. Mathematical Modelling and Computational Experiment 1, 407–414. English translation of Russian original paper Sobol' (1990).
- Tatang M.A., Pan W., Prinn R.G., McRae G.J., 1997. An efficient method for parametric uncertainty analysis of numerical geophysical models. Journal of Geophysical Research, 102, 21925-21932.
- Thunis P. et al., (2012). A tool to evaluate air quality model performances in regulatory applications, Environmental Modelling & Software, 38, 220–230.
- Turanyi, T. (1990). Sensitivity analysis of complex kinetic systems. Tools and applications. Journal of Mathematical Chemistry, 5, 203–248.
- Uliasz M. (1988). Application of the FAST Method to Analyze the Sensitivity–Uncertainty of a Lagrangian Model of Sulphur Transport in Europe, Water, Air and Soil Pollution, 40, 33–49.
- UNECE (2002). Progress Report Prepared by the Chairman of the Task Force on Integrated Assessment Modelling, United Nations Economic Commission for Europe, Geneva, Switzerland.
- Uusitalo L., Lehikoinen A., Helle I., Myrberg K. (2015). An overview of methods to evaluate uncertainty of deterministic model in decision support, Environmental Modelling and Software, 63, 24-31.
- Vlachokostas C. et al. (2009). Decision support system for the evaluation of urban air pollution control options: Application for particulate pollution in Thessaloniki, Greece, Science of the Total Environment, 407, 5937–5948.
- Varma, A., M. Morbidelli M., and H. Wu H. (1999). Parametric Sensitivity in Chemical Systems. Cambridge University Press.
- Wang M. et al (2014). Long-term exposure to elemental constituents of particulate matter and cardiovascular mortality in 19 European cohorts: Results from the ESCAPE and TRANSPHORM projects. Environmental International 66:97-106.
- Werner S. (2009). Optimization of the spatialized emission inventories : estimation of uncertainties, determination of the emission factors of black carbon from the road traffic. Application to the ESCOMPTE and Nord Pas-de-Calais Region emission inventories). PhD Thesis, University of Strasbourg, Department of Chemistry (in french).
- Wilson N, Blakely T., Foster R.H., Hadorn D., Vos T. (2012). Prioritizing risk factors to

identify preventive interventions for economic assessment. Bulletin of the World Health Organization 90, 88-96.
- Worley, B. A. (1987). Deterministic Uncertainty Analysis. ORNL-6428. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Yang Y-J., Wilkinson J.G., Russell A.G. (1997). Fast, direct analysis of multidimensional photochemical models. Environmental Science and Technology, 31, 2859-2868.
- Zabkar R., Koracin D., Rakovec J. (2013). A WRF/Chem sensitivity study using ensemble modelling for a high ozone episode in Slovenia and the Northern Adriatic area. Atmospheric Environment 77:990-1004.