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# Indicators of environmental sustainability in transport
An interdisciplinary approach to methods

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INDICATORS
OF ENVIRONMENTAL
SUSTAINABILITY
IN TRANSPORT

*An interdisciplinary
approach to methods*

Recherches

Robert Joumard
Henrik Gudmundsson
Editors

# Indicators of environmental sustainability in transport

## An interdisciplinary approach to methods

*Indicators of environmental sustainability in transport*

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# Contents

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The main characteristics of COST are a "bottom up approach" (the initiative of launching a COST Action comes from the European scientists themselves), "à la carte participation" (only countries interested in the Action participate), "equality of access" (participation is also open to the scientific communities of countries not belonging to the European Union) and flexible structure" (easy implementation and light management of the research initiatives). As precursor of advanced multidisciplinary research COST has a very important role for the realisation of the European Research Area (ERA) anticipating and complementing the activities of the Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of "Networks of Excellence" in many key scientific domains such as: Biomedicine and Molecular Biosciences; Food and Agriculture; Forests, their Products and Services; Materials, Physical and Nanosciences; Chemistry and Molecular Sciences and Technologies; Earth System Science and Environmental Management; Information and Communication Technologies; Transport and Urban Development; Individuals, Societies, Cultures and Health. It covers basic and more applied research and also addresses issues of pre-normative nature or of societal importance.

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# Executive summary

Environmental issues figure still more prominently in the decision-making processes concerning transport policies, plans, programmes, projects, or transport technologies. The environmental impacts to be considered increase in complexity and relevance, as do the decisions to be taken.

This report contributes to the development of methods to efficiently integrate complex environmental issues into the assessment and decision processes regarding transport. The main objective is to help to design harmonised methods for building better environmental impact indicators based on the existing knowledge, and to integrate these indicators into decision-making processes. Key elements to fulfill those objectives are criteria for indicator selection and methods for joint consideration of impacts through aggregation or multi-criteria analysis.

The authors of this report are thus concerned with how environmental impacts of transport can be measured, how measurements can be transformed into operational indicators, how several indicators can be jointly considered, and how indicators are used in planning and decision making.

We do not propose one new harmonised method. The work has included a wide state-of-the-art review, an assessment of existing methods and tools, and finally proposed improvements to the methodological elements mentioned above.

The research should be useful for persons involved in the selection and building of indicators, especially environmental impact indicators. It should also serve those using sets of such indicators, for problem identification, monitoring, planning, decision making, evaluation, or benchmarking of transport policies, plans, programmes, projects, or transport technologies.

This volume is the final report of the action COST 356 'EST - Towards the definition of a measurable environmentally sustainable transport' (http://cost356.inrets.fr). COST 356 was a collaboration among a network of scientists specialized in some environmental impacts ('natural' scientists), in decision making processes ('policy' scientists) or in transport and environment planning ('planning' scientists), each one involved in corresponding national or international research projects.

Chapter 1 'Indicators and their functions' aims at establishing and justifying how indicators are used in this report, addressing basic questions on the basis of a literature review: What are indicators, compared with other knowledge types and methodologies? When and why should indicators be used? What should an indicator measure? How should this measuring be performed? It introduces important distinctions between basic functions indicators can have, in particular between indicators as measurement tools, and indicators as policy

or decision making tools. Furthermore, this chapter discusses strengths and weaknesses of indicators with regard to such functions.

An indicator of environmental sustainability in transport is defined as 'a variable, based on measurements, representing potential or actual impacts on the environment, or factors that may cause such impacts, due to transport as accurately as possible and necessary'. Such indicators are often necessary, because full models to describe interactions between transport activity and environmental impacts are not available or not practical. There are many different types of indicators, each of which may be suitable to measure particular aspects or help decide on specific issues. There is hardly one indicator able to represent equally well all aspects of sustainable transport. In all cases, it is necessary to reflect why the indicator is needed, what is to be measured, and how it should be done. Indicators can be applied for symbolic or strategic purposes, as well as rational ones, and decision making contexts may differ in a way that suggests different representations of sustainable transport.

The aim of chapter 2 'Transport, environment and sustainability' is to describe what indicators are supposed to indicate, or in other terms to define what "environmental sustainability in transport" may mean and what the indicators should represent. We describe firstly the role of transport as a system, and then we present shortly key aspects of the concept of sustainable development. Finally different meanings of the concept of environment are presented, and we define it by considering the processes between the sources and the impacts.

Environmental impacts of transport include a wide variety of negative influences in connection with construction, use and disposal of transport system components. There is limited availability of frameworks to describe fully these impacts. For that purpose, we developed a new approach through the concept of 'chain of causality', defined as an homogeneous process between the transport system (or any other human activity) and a final target of the impacts on the environment, made by one or several stages or steps. 49 causal chains have been identified and these should form a core of a systematic framework of environmental description and assessment for transport. The clear definition and description of each chain is the necessary solid ground for the search for corresponding indicators: Each chain of causalities is here characterized in terms of transport source, final target, and process between both described through a wide variety of scientific knowledge. The consideration of a comprehensive list of independent causal chains allowed us to give a precise definition of the term 'environment'.

The dimensions and context of decision making appeared to be a suitable basis for choosing environmental indicators, because decision making context influences the perceived and actual needs for indicators and methods, but this is hard to systematize at a general level. Chapter 3 'The dimensions and context of transport decision making' describes the main differences in type of information that is needed in different transport decision making situations, such as strategic versus short-term ones, and in type of conditions for applying different types of indicators in such situations. Critical factors are likely to include especially the degree of consensus versus uncertainty about facts and

values respectively. Indeed, conflicts were said to be a 'normal feature' of transport decision making, which were, however, more or less strong, depending on the overall consensus on values and solutions. The application of structured processes for channelling and managing conflicts was suggested to be of great importance. Whereas in concrete project situations with little or no conflict they may serve as *quasi* decision makers, in situations of great conflict they are likely to only inform actors. Possible functional conditions for selecting suitable indicators include the decision making tier and related to this the stage in the policy cycle at which decision making occurs (strategic, tactic, operational), the transport modes covered, the administrative and functional boundaries, the spatial scale of the impacts, the type of formal requirements, the users and stakeholders involved as well as the timescale.

Indicator selection is rarely documented in practice, hence indicator lists are often applied with no or only not transparent justification. Chapter 4 'Criteria and methods for indicator assessment and selection' assumes that following certain procedures, methods and criteria, and making them explicit may contribute to enhance the quality as well as the legitimacy of proposed indicators, and may also help to identify areas with a need for new indicator building. Based on the description of the context made in chapter 3 and a literature review, criteria and methods for the assessment and selection of environmentally sustainable transport indicators were derived. These criteria were classified into three groups: measurement or representation, monitoring or operation, and management or application. Ten criteria were highlighted and equipped with interpretation and examples: validity, reliability, sensitivity, measurability, data availability, ethical concerns, transparency, interpretability, target relevance and actionability. A general and simplified approach for assessing indicators was proposed, along with a suggestion to undertake more specific indicator assessments where concrete planning situations or needs are taken into account.

The method and the criteria are exemplified in chapter 5 'Assessment of some indicators within an impact'. It looks in detail at indicators for seven chains of causality, chosen to be qualitatively different: direct toxicity of air pollutants, natural habitat fragmentation, non-renewable resource use, loss of cultural heritage due to land take, noise as annoyance to humans, greenhouse effect, and waste. Some chains are short and easily grasped whereas some are long, complicated and characterized by multiple interacting inter-relationships. There is also a large variability between chains in terms of available knowledge and indicator availability.

A review of potential indicators for each chain is undertaken using criteria and other elements provided in chapter 4 as a basic framework. The chain "greenhouse effect" is well described since substantial scientific effort has been put into clarifying its multiple and complicated chain steps, and broad consensus has been reached on the scientific underpinning of the widely used indicator Global Warming Potential as well as more recently proposed ones. In contrast, the chain "waste disposal" has only relatively recently become subject to deeper scientific study, and existing indicators appear to cover only some of the chain steps. Together with "noise" and "non-renewable resource use", this

chain is also an example where there is a wide range of indicators for different types of usage. This is in contrast to "loss of cultural heritage", where no indicator seems to have existed hitherto.

Typically, in decision making situations many indicators need to be handled together. Based on the outcomes of the previous chapters, on existing literature and on case studies, chapter 6 'Methods for joint consideration of indicators' deals with methods for a comprehensive joint consideration of environmentally sustainable transport indicators. After some introductory remarks on factors affecting joint consideration of indicators and related tasks, methods for building aggregated or composite indicators (such as life cycle assessment, ecological footprint, MIPS, and economic approaches), and common discrete and continuous multi-criteria methods are presented and evaluated from a general perspective, under abstraction of the specific application contexts.

The evaluation of indicators resulting from the application of typical joint consideration methods has shown that they differ in their performance with regard to criteria and categories defined in Chapter 4:
- Life cycle assessment methods such as the Ecological scarcity and the ReCiPe method appear to be medium to good performers regarding representation and operation issues and lower performers regarding application issues.
- The Material input per service-unit and the Ecological footprint are recommended for their operational character and the choice of a clear and well understandable assessment unit, however not for the non-additivity of their elements, at least according to what they are supposed to measure.
- Because of the variety of assumptions and methods, the economic indicators (external costs) do not appear to be very transparent, and the political process to build collective and official values is to be considered as being as important as the economic methods themselves.

General recommendations for the application of multi-criteria methods are difficult to establish under abstraction of the specific decision making context. In principle, every specific application case requires careful evaluation of existing methods and tools. Nevertheless, methods allowing to consider uncertainties and to set thresholds and constraints (such as ELECTRE III or TRI) seem to be particularly suitable in the context of (strong) sustainability.

The major challenge regarding multi-criteria decision analysis in the context of sustainability does not appear to be the development of more sophisticated methods, but rather to provide a consistent framework allowing to integrate the different stakeholders into the different types of (participatory) decision making processes, which guarantees mutual exchange of arguments and information, provides the participants with opportunities to add and challenge claims, and to create active understanding among them.

In addition to the above-mentioned general evaluation, chapter 6 describes five selected cases where methods to jointly consider indicators have been applied to transport policies, plans, projects or technologies, and identifies their strengths and weaknesses.

Chapter 7 identifies research needs, addressing topics for disciplinary as well as interdisciplinary research, in four fields: i) sustainability and environmental issues, ii) role of context for designing indicators, iii) design of indicators per impact on the environment, iv) joint consideration of environmental impact indicators.

In the conclusive chapter, we identify the major challenges in terms of paradigms, legitimacy of procedures, and role of context. We present the limits of the research and give some general recommendations in terms of research policy and methods to take into account environmental issue in the transport sector.

# Introduction

There is an increasing awareness of the need to promote more sustainable transport patterns in Europe and around the globe. It has therefore become still more important to be able to measure and assess the sustainability of present and future transport trends and policies within the global concept of sustainability. Environmental issues figure still more prominently in the decision-making processes concerning transport policies, plans, programmes, projects, or transport technologies. The environmental impacts to be considered increase in complexity and relevance, as do the decisions to be taken.

However in the transport field, critical observers have noted that environmental assessments often do not take into account properly the full variety of relevant environmental impacts, or are using markers, indices and more generally tools which do not adequately represent the impacts (e.g. Jeon and Amekudzi, 2005; May *et al*., 2007; Litman, 2008; Goger *et al*., 2009). Availability of good representations of the whole range of impacts on the environment is necessary to ensure environmental sustainability can be taken into account to a satisfactory degree. This is not least the case for the transport sector where there are many important concerns and impacts at stake. We give here two examples:

- The scientists gathered together to do this work are concerned that too often strategic environmental assessments consider only very few environmental impacts such as carbon dioxide emissions or noise, even a variety of possibly contradictory impacts may occur. Neglecting other environmental aspects jeopardizes the quality of the environmental assessment and thus not only the value of strategic environmental assessment as a basis for decision-making but also the credibility and sustainability of the decisions taken. When more than one or very few impacts are taken into account today, the way they are aggregated is often as simple as possible, independently of the real-world multi-criteria choice by the stakeholders. Clearly, there is a need for tools to make complex decision situations manageable without loosing too much of the information in the process of the necessary simplification.

- A recent research study in which the environmental effects of different biofuels were compared (Williams *et al*., 2009) concluded that "additional research is needed [for] developing decision-support tools to identify and quantify environmental trade-offs and ensure sustainable biofuels production. [...] This research area should focus on the development of analytical tools that are capable of identifying, quantifying, and weighting uncertainties and potential trade-offs (e.g., minimizing greenhouse gas emissions vs. increasing aqueous effluent) associated with different biofuels production decisions".

The situation described above calls for the development of methods to efficiently integrate complex environmental issues into the assessment and decision processes. The main objective of the research presented in this report is thus to contribute to design harmonised methods to build better environmental impact indicators based on the existing knowledge, and to build methods to be applied to the decision making process of the transport sector in the different countries, in a systemic approach to environment and transport issues. We intend to identify harmonised and scientifically sound methods to build environmental indicators for the assessment of transport projects, plans, policies or technologies, and to integrate these indicators into decision-making processes by indicator selection or joint consideration through aggregation or multi-criteria analysis.

We are concerned with how environmental impacts of transport can be measured, how measurements can be transformed into operational indicators, how several indicators can be jointly considered, and how indicators are used in planning and decision making.

We do not propose a new harmonised method, but firstly made a wide state-of-the-art, then an assessment of existing methods and tools, and finally improved some methodological elements.

Scientists specialized in some environmental impacts ('natural' scientists), in decision making processes or in transport planning participated to this work along the period 2005 - 2010. The work was organised as a bottom-up approach trough a so-called COST action, i.e. a network of scientists and a coordination of national research projects (see a more detailed description of the COST framework in the acknowledgements). It was the action COST 356 'EST - Towards the definition of a measurable environmentally sustainable transport'.

The network was organised in three core scientific working groups. The first one basically adopted the environmental or natural science perspective and analysed which impacts are relevant, and how they could and should be described and measured: indicators are considered as measurement tools. The second one identified requirements for environmental sustainability indicators from the perspective of policy and planning processes, and identified methods to integrate them into decision making: indicators are considered as decision supporting tools. The third core scientific working group dealt with case studies of actual application of indicators and assessment methods.

An important and continuous part of the work consisted in discussing and integrating the results obtained from the application of each of these perspectives in-between the working groups.

More information on the networking, scientific activities and relevant literature can be found on the dedicated website http://cost356.inrets.fr.

The report is structured in six main chapters and in annexes. The chapter 1 'Indicators and their functions' aims at establishing and justifying how indicators

are used in this report, addressing basic questions: What are indicators, compared with other knowledge types and methodologies? When and why should indicators be used? What an indicator should measure? How should this measuring be performed? It introduces important distinctions between basic functions indicators can have, in particular between indicators as measurement tools, and indicators as policy or decision making tools. Furthermore, this chapter will discuss strengths and weaknesses of indicators with regard to such functions.

In this report, the indicators refer to interrelations between transport systems and the environmental issue. The aim of the chapter 2 'Transport, environment and sustainability' is to describe what indicators are supposed to indicate, or in other terms to define what "environmental sustainability in transport" may mean and what the indicators should represent. We describe the role of transport as a system; We present shortly some debates on the concept of sustainable development, and the concept of environment. We make a comprehensive description of the interrelations between transport system and environment.

While selecting indicators, which are expected to be used by decision makers, different decision making situations need to be considered. The chapter 3 'The dimensions and context of transport decision making' aims at describing different transport decision making situations, such as strategic versus short terms ones, and situations with more or less agreements over facts and values. It describes the main differences in type of information that is needed in different situations and of conditions for applying different types of indicators in such situations.

Indicator selection is rarely documented in practice, hence indicator lists are often applied with no or only not transparent justification. The chapter 4 'Criteria and methods for indicator assessment and selection' assumes that following certain procedures, methods and criteria, and making them explicit may contribute to enhance the quality as well as the legitimacy of proposed indicators, and may also help to identify areas with a need for new indicator building. It addresses ways to identify, assess and select specific indicators, using criteria of indicator quality and appropriateness and associated methodologies to apply and interpret the criteria.

The chapter 5 'Assessment of some indicators within an impact' looks in detail at indicators for seven impacts on the environment: direct toxicity of air pollutants, natural habitat fragmentation, non-renewable resource use, loss of cultural heritage due to land take, noise as annoyance to humans, greenhouse effect, and waste. A review of potential indicators for each impact is undertaken using criteria and other elements provided in chapter 4 as a basic framework.

Typically, in decision making situations many indicators need to be handled together. Based on the outcomes of the previous chapters, on existing literature and on case studies, chapter 6 'Methods for joint consideration of indicators' deals with methods for a comprehensive joint consideration of environmentally sustainable transport indicators, through aggregated and composite indicators as well as multi-criteria methods. It presents and assesses methods for building aggregated or composite indicators (life cycle assessment, ecological footprint,

MIPS, economic approaches), and then the main discrete and continuous multi-criteria methods. Finally it describes selected cases where methods to jointly consider indicators have been applied, and identifies their strengths and weaknesses.

The chapter 7 'Research needs' identifies research needs, addressing topics for disciplinary as well as interdisciplinary research.

In the conclusive chapter, we identify the major challenges, present the limits of the research and give some general recommendations in terms of research policy and methods to take into account environmental issue in the transport sector.

A glossary in Annex 1 presents the definition of the main terms and expressions specific to our field in order to clarify how the terms are used in this report.


This Report is the result of an effort of many researchers, all of who have generously devoted their knowledge and energy to its accomplishment. Over the course of preparing the report, differences in approaches, perceptions, and even definitions have emerged. Some of those differences are reflected in the text and it is important to stress that individual contributors may have different views on particular issues. As general editors we consider these differences as being productive rather than destructive, since they provide the basic ground for further research and the advancement of knowledge.

# 1. Indicators and their functions

**Authors: H. Gudmundsson, R. Joumard, R. Aschemann and A. Tennøy**

The term 'indicators' can be understood and used in a number of ways. The main purpose of this chapter is to establish and justify how indicators are used in this report. Another purpose is to introduce important distinctions between basic functions indicators can have, both generally speaking and in connection with the assessment of transport sustainability. In particular, a distinction is made between indicators as measurement tools, and indicators as policy or decision making tools. Furthermore, this chapter will discuss strengths and weaknesses of indicators with regard to such functions. This chapter thereby provides key conceptual foundations for the following chapters.

## 1.1. Concept and definition of indicators

Given the increasing interest in promoting sustainable transport in Europe and around the globe, the measurement and assessment of the sustainability of transport systems and policies is becoming more important. Indicators are increasingly being used to measure and assess the sustainability of transport. However, whilst indicators are useful tools, they also have their limitations. The purpose of this section is to provide a brief explanation of indicators, drawing from the literature on the subject, and to establish a definition to be used in the context of this report.

### 1.1.1. Defining indicators

An in-depth review of the literature was conducted to identify 'official' (and any other potentially relevant) definitions of the term 'indicator'. The purpose of the review was not to select a single definition, but to help identify the key functions that indicators can play, and to reveal the extent to which context-specific factors should be allowed to influence the definition of indicators. The review considered the following:
i)  General, generic or global definitions of indicators from dictionaries, encyclopaedia and academic contributions.
ii)  Definitions of 'environmental' indicators.
iii)  Definitions of indicators that take into account the context of sustainability.
iv)  Definitions of indicators that have been proposed within the specific field of sustainable transport.

A definition for use in this Report is proposed in the conclusions.

# 1.1.2. General definitions

The following definitions of the word 'indicator' were found in the literature:

A. A substance (as litmus) used to show visually (as by change of colour) the condition of a solution with respect to the presence of a particular material (such as a free acid or alkali) (Webster's dictionary).

B. An organism or ecological community so strictly associated with particular environmental conditions that its presence is indicative of the existence of these conditions (Webster's dictionary).

C. [Ecology]: Indicator species - a species whose presence is directly related to a particular quality in its environment at a given location (McGraw-Hill Encyclopaedia of Science and Technology).

D. [Economics]: Any of a group of statistical values (such as level of employment) that taken together give an indication of the health of the economy (Webster's dictionary).

E. [Biology]: An organism that can be used to determine the concentration of a chemical in the environment (McGraw-Hill Encyclopaedia of Science and Technology).

F. [Analytical chemistry]: A substance whose physical appearance is altered at or near the end point of a chemical titration (McGraw-Hill Encyclopaedia of Science and Technology).

G. A common term used to refer to the variables that we use to detect (…) concepts empirically (Bollen, 2001).

H. A variable that is directly associated with a latent variable, such that differences in the values of the latent variable mirror differences in the values of the indicator (Bollen, 2001).

I. At a more concrete level, indicators are variables (not 'values', as they are sometimes called). A variable is an operational representation of an attribute (quality, characteristic, property) of a system (Gallopin, 1996; 1997).

These general definitions of an indicator share many common elements. An indicator is generally understood to be a tool or a method which can be used to mirror or measure something in a way that adequately represents what is being measured. However, even these general definitions are often defined with respect to different measurement functions in different scientific domains (chemistry, biology, social science). In some (mostly natural science) definitions the indicator linkage can be strong (*e.g.* it is used to *determine* something). In other cases (social science, ecology) the linkage may be weaker, the indicator 'indicating' or *suggesting* something. An indicator is never assumed to provide a complete description of something.

## 1.1.3. Environmental indicators

The focus of this report is on indicators in the area of environmental assessment. It is therefore relevant to review definitions of environmental indicators in particular. The following ones are among those found in the literature:

J.  A parameter - or a value derived from parameters - which points to, provides information about, or describes the state of a phenomenon / environment / area, with a significance extending beyond that directly associated with a parameter value (OECD, 2003).

K.  A parameter - or a value derived from parameters - that describes the state of the environment and its impact on human beings, ecosystems and materials, the pressures on the environment, the driving forces, and the responses steering that system. An indicator is established through a selection and/or aggregation process to enable it to steer action (EEA, 2009d).

L.  A numerical value derived from actual measurements of a pressure, ambient condition, exposure, or human health or ecological condition in a specified geographic domain, whose trends over time represent or draw attention to underlying trends in the condition of the environment (USEPA, 2006).

These definitions of 'environmental indicators' are rather similar, and all concern measurement of aspects of the environment itself or interactions between humans and the environment. The definitions provide some guidance for what is required of environmental indicators. EEA mentions 'environmental impact' as one aspect. The basic notion of representation is clearly present here. According to an OECD definition, representation should go 'beyond' what is directly measured. This is identical to the general indicator function. However, the link between the subject and the indicator is often relatively weak for environmental indicators ('provides information about', 'describe', 'derived from', 'draw attention to'). Moreover, the measurement aspect is slightly downplayed, since environmental indicators may be *derived* from 'parameters' or *derived* from 'actual measurement'. EEA highlights the context of steering. USEPA highlights context as a physical time-space domain.

## 1.1.4. Sustainability indicators

Indicating sustainability is also a concern of the report. In this context, the large body of literature on sustainability indicators was reviewed. The following three definitions illustrate the wide range of interpretation of sustainability indicators:

M.  Sustainability indicators are quantitative measures of human wellbeing, economic activity, and natural processes and conditions; they are needed to sense the degree to which human activity may continue or expand in the future (Lee, 2001).

N. Sustainable development indicators: Statistical measures that give an indication of the sustainability of social, environmental and economic development (OECD, 2005).

O. Sustainability indicators reflect the reproducibility of the way a given society utilises its environment (Opschoor and Reinders, 1991, p. 7).

In a similar way to the general definitions and their idea of representation, these definitions highlight the measurement aspect. However, here, the representation relates to complex notions - namely 'sustainability', 'reproducibility' or 'the degree to which human activity may be continued or expanded.' Hence, the link between the subject and the indicator can be very weak ('reflect', 'give an indication', 'sense').

Large parts of the literature deal with the role of sustainability indicators in decision making. In this context several additional elements are required for a sustainability indicator to be adequate, such as the need for it to be 'meaningful' and 'resonant' (motivating) for decision makers and stakeholders (Bossel, 1996; Meadows, 1996; Gray and Wiedemann, 1999; SCOPE *et al*., 2006).

# 1.1.5. Sustainable transport indicators

Definitions of indicators of in the literature on sustainability and transport include the following:

P. Selected, targeted, and compressed variables that reflect public concerns and are of use to decision-makers (Gilbert *et al*., 2002).

Q. Sustainable transport indicators (STIs) are regularly updated performance measures that help transport planners and managers to take into account the full range of economic, social and environmental impacts of their decisions (Lee *et al*., 2003).

R. A forecastable, quantifiable variable, usually with target value representing an objective, which symbolises environmental or other impacts of transport infrastructure plans (including ordinal scales: *e.g.* low, medium, high). The following types of indicator are also relevant (Fernandez, 2009).

S. An indicator is a way of quantifying objectives. For example, accident numbers would measure progress towards an overall safety objective. This type of indicator is often called an 'outcome' indicator, in that it measures part of the outcome of a strategy. It is also possible to define 'input' indicators, which measure what has been done (*e.g.* the length of bus lanes implemented) and 'process' indicators, which describe how the transport system is responding (*e.g.* the number of bus users) (KonSULT).

T. General principles regarding indicators in any urban mobility system: Indicators should support the decision-making capacity, in particular enabling proactive action to correct the performance path of a specific element or agent whenever signs of potential underperformance are identified… (Macario, 2005).

These definitions, even if rather varied, are again based on the idea of representation, similarly to the general definitions. However, they are much more focused on objectives, plans, policies, measures, *etc.* for *achieving* sustainable transport rather than on simple representation of items within a system. The definitions emphasise on the context of decision making. They draw on the general literature on sustainability indicators. An indicator applied in this area does not appear to be acceptable if it does not represent the information that is relevant to the performance of policies. The definition proposed by Fernandez (2009) is probably the most detailed, concise and elaborate to date, but it is also very restrictive in the sense that only 'quantifiable, forecastable' variables are acceptable. This does not appear to be fully justifiable in the context this report, where indicators may be equally relevant retrospectively, as in *ex-post* measurement. Also, it is restricted to transport infrastructure, which is too narrow for this report.

# 1.1.6. Summary and proposed definition

The indicators, which have been presented in the previous sections, may be categorised in the following manner:

− A marker or *sentinel*, indicating the presence or absence of something (see definitions A-C and F)
− A measurement tool, indicating variations along important dimensions of the indicated phenomenon (see definitions D, E, G-J, L-O and R.)
− A decision support tool allowing to take certain action (see definitions P, Q, partly S, and T)
− A combination of the above (see definition K and partly S)

The marker definition (absence or presence) is also a measurement tool, but a simplified one measuring only the presence or absence of something. Most of the definitions consider an indicator as a measurement tool, but some definitions include considerations about the use of such measurement tool: draw attention, quantify objectives, use by decision makers, help managers, measure progress.

The key notion is *representation*. An indicator has to represent something in an adequate and simplified manner, otherwise it serves little purpose. Representation assumes connections between three elements: the item being represented; the item representing it (the indicator), and the usage domain for which the representation has to be valid and acceptable, for example if the representation is simply to inform the public of the presence of a problem, or if it is to allow a consequential judgment, such as whether a legal act has been violated or not. The representation can emphasise mostly the link to the represented item, or to the domain for which the representation has to be valid.

In this report a clear distinction is therefore made between two aspects of indicators as representations:
− The characteristics of measurement.
− The characteristics of application for policy or decision making.

Both aspects have to be present before an indicator can be fully accepted in the context of environmental policy or sustainability assessment of transport. The measurement aspect seems fundamental to any indicator. The usage domain or application is essential for indicators to be applied correctly according to the purpose. This domain or context is a 'filter' for purely measurement-based indicators. In summary, the following simple definitions are adopted for this report:

- An **indicator** is a variable, based on measurements, representing as accurately as possible and necessary a phenomenon of interest.
- An **environmental impact indicator** is a variable, based on measurements, which represents an impact of human activity on the environment as accurately as possible and necessary.
- An **indicator of environmental sustainability in transport** is a variable, based on measurements, which represents potential or actual impacts on the environment - or factors that may cause such impacts - due to transport, as accurately as possible and necessary.

# 1.2. Indicator functions

Indicators can have a number of different functions with regard to different domains of use, such as scientific measurement, policy, plan, programme and project assessment, or public debates; an indicator can be good with regard to one function, such as to stimulate debate, but less so for another, such as to diagnose underlying causes of observed change. Moreover, some functions of indicators are intended, such as detecting whether an environmental condition is present or not, while others may not be so, such as accidentally suppressing knowledge about problems that are not easily quantifiable. In these respects, environmentally sustainable transport does not differ from other subjects in need of indicators. It is nevertheless important to be aware of such distinctions and take note of them in connection with the basic definitions provided here, particularly as these functions can suggest different methods to establish, assess or apply indicators, and may also underpin different types of recommendations.

We introduce two sets of distinctions that inform this report. The first distinction is for simplicity, labelled as one between generic 'measurement type' functions, versus 'policy or other decision making type' functions of indicators. The second distinction is between what we refer to as direct, instrumental or *intended* functions versus more non-instrumental or *unintended* ones. Both sets of distinctions are explained briefly here and more in depth in the following sections.

What we call 'measurement type' functions include ones such as 'description', 'distinction', 'simplification', 'aggregation', 'prediction', 'assessment', etc - all different attributes of a general indicator function of *representation of reality* (see the definition in section 1.1 above and further in Chapter 4 below). Indicators may be more or less well suited to serve such functions, depending on how strong,

well known, or agreed the causal links are between the phenomenon being represented and the chosen indicator of it. We expand on these functions in section 1.2.1.

What we call 'policy or decision making type' functions refer to tasks in, or aspects of policy and decision making (e.g. Policy, Plans, Programs or Projects) where indicators may serve some purpose, such as helping with problem identification, target setting, choice between alternative options, ex-ante evaluation, or general information. Here the general indicator function is *representation of the decision context*. We expand on those functions in section 1.2.2.

The 'decision type' functions obviously to some degree assume and build upon the 'measurement type' ones, as decision making of course depends on certain representations of reality (distinction, simplification, etc). However there are also other functions of indicators than those involved. This is where we introduce the second distinction between 'intended' or instrumental versus 'non-intended' or non-instrumental functions. By intended or instrumental functions of indicators, we refer to *specific informative services* an indicator can provide, such as, for example, to serve as an instrument to detect whether an environmental condition is present or not, or whether a target is met or not. However, as the literature on policy indicators suggests (see e.g. Innes, 1990; Hezri and Dovers, 2006; Boulanger, 2007), there are also other important, non-instrumental functions, such as the role of indicators in providing common reference frames, or the role of indicators in suppressing attention to certain aspects that are not measured. These functions may not be directly intended, but can nevertheless be important for an indicator being effective, appropriate or useful or not. We address such functions as part of section 1.2.2.

It seems that the notion of indicators is most often understood as a tool that must cater to both measurement and policy concerns (as emphasized by e.g. Turnhout *et al*., 2007). However, the indicator literature of course borders to more fundamental scientific literature, where notions of methodology and measurement are the prime concerns, not 'policy'.

## 1.2.1. Measurement functions of indicators

The main function of an indicator according to the definition given in section 1.1.6 ('a variable representing a phenomenon') is to be an instrument that measures a phenomenon. The measurement can be an element in subsequent assessment, decision making or communication.

It is important to differentiate clearly between the three interrelated aspects of measurement:

1) What should be measured? For instance which impact of which activity?
2) Why? What is the question, the purpose?
3) How should it be measured? The intrinsic qualities of any measurement tool have to be taken into account.

## 1.2.1.1.  What should be measured?

Before defining indicators for an assessment or an evaluation, the subject of the assessment or evaluation has to be clearly identified. The first step of any evaluation is therefore to describe in detail what has to be evaluated. This description has to be discussed and agreed at the end by its stakeholders. This discussion is a key point, because it show often that what should be evaluated is much more complex than foreseen, and multidimensional. Sometimes reference to different possible indicators is already part of this clarification process, but this has to be made explicit.

The in-depth analysis of what is to be evaluated forces firstly to define it and often to redefine it, secondly to understand its possible complexity. This description should be made via a text, without assuming any final indicator at this step. It is important that the description is to be agreed by the stakeholders of the evaluation, as further discussed in section 4.3 of this report.

In the field of the environmental impacts of a human activity, both the impact and the activity considered have to be defined. Concerning the definition of impacts, examples of distinctions include:

- Climate impacts: Greenhouse effect, climate change, global warming, global average temperature increase, and sea level rise are different concepts;
- Impacts on the biodiversity: loss of local species, loss of species, habitat change do not represent the same things;
- Noise impacts: noise level, disappearance of quiet areas, annoyance to people due to noise, effects on human health of noise, effects on animal health of noise, *etc.* are also different.

It is therefore essential to define what the 'environment' means: This is further discussed in sections 2.3 and 2.4.

At the same time the activity concerned has to be clearly defined. In the field of transport, transport, road transport, transport by trucks, mobility, person mobility or good mobility, etc. represent different realities, as are, for example, urban transport systems and public transport: It is the purpose of the section 2.1.

## 1.2.1.2.  Why: The purpose of the question

A further step is to establish whether the planned assessment allows one to answer certain predefined questions. Or in other words, why are we interested by a given assessment? The in-depth discussion of the reasons of the question to answer shows often that the question has to be redefined partially or totally.

For instance, in the case of an environmental impact of a human activity, are we mainly interested by the impact itself (its level or its targets), or by the reasons of the impact, or the reasons for its evolution over time? In this later case, one needs to ask: what are the parameters explaining the increase or decrease of the impact? Is for instance the transport sector a main or very marginal source of the impact?

What needs to be measured depends also upon who is interested in the answer; It is essential to understand the context of the problem (see section 1.2.1.4 and chapter 3).

A measurement tool (like an indicator) should be understood as a part of a reasoning puzzle. However, it cannot replace reasoning. As the perception of the problem, the question, or the solution are context dependent, reasoning itself is also context dependent. It does not mean that the tool used to measure has to depend on the context, but it means that input data of the tool can be context dependent, and the appropriateness of the tool to serve as representative indicator of a problem can be as well.

For instance, to assess if the decrease of the speed limit on motorways is efficient to improve the local air quality, a possible indicator is the emission of NOx. The function 'NOx emission' is not context-dependent, because it can be used in any situation (e.g. the European Artemis model: See Boulter and McCrae, 2007). The real question is if the evaluation of the NOx emissions allows to assess with regard to the purpose or reason, namely in this case the wish to know about impact on the local air quality. It questions the representativity of the indicator 'NOx emission" for the function "local air quality" assessment.

Annex 2 presents a typical environmental assessment on air pollution.

The question of why to measure can be discussed with reference to a set of measurement functions, such as, simple description of present a situation or trend, cross comparison over a range of entities, assessment with regard to a reference condition, forecast of a future condition, or identification of causal or determining factors behind observed conditions. Each kind of reason may suggest different types of indicators (as discussed in section 1.3), or lead to a rejection of indicators.

## 1.2.1.3.  How to measure?

The third important question is how the measurement has to be conducted, and then how the measurement tool should be designed and built.

The fundamental requirement of any measurement tool, including indicators, is representativity of what it is supposed to measure: at the best, proportionality, and accuracy. From a measurement point of view, a good indicator, for example, would give the exact and precise level of what it is supposed to measure. To be accurate, an indicator should take into account all the relevant aspects of the process (sometime called contextual aspects), with the same accuracy, and be proportional to the final impacts. But as the same time, it has to be simple, using for example averages with different levels of aggregation like say, urban / rural, day / night etc. This can be contradictory.

When what is to be represented is not directly measurable (for instance for an *ex-ante* evaluation) and is the output of a complex process, the most accurate way may be to use a full modelling taking into account as far as possible all the influencing parameters of the process (in the case of an environmental impact, the full process of its chain of causalities - presented in

section 2.4.1 - has to be modelled). We are then far from what we have defined as an indicator, namely as a variable, representing as accurately as possible and necessary a phenomenon of interest.

However, models, as well as indicators entail uncertainties as measurement tools. There are four main types of errors that occur in any modelling (and then in environmental modelling), as pointed among others by De Jongh (1988):

– Process errors – the model is unable to describe the actual processes of cause and effect, omitting important parts of the process or the influence of some important parameters. The errors in baseline data or in data internal to the model are a part of the process errors. The unknown cumulative effects, the discussion about whether and how to include long-term effects (see section 6.2.5.3) and all the unpredictable events that can impact a project participate to process errors.

– Simplification errors – the model simplifies the reality by assuming that only certain processes are important, and by including only those. It is the known and conscious part of the process errors;

– Boundary errors - the model is used outside its range of validity. It is used in circumstance where it should not be used, it is not valid for the problem at hand, or some input parameters are outside their admitted boundaries.

– Error in input data – such error can be transmitted to the output data when it concerns important parameters of the model. Such error is especially important when the model is in fact a series of models, the outputs of the preceding being used as input data of the next; Here the models are usually developed and used by different and independent teams.

Complex predictions, involving links of assumptions that rest on each other, can build up to substantial uncertainties.

Practical guidance / recommendations suggest that uncertainties and data limitations should be well documented and all assumptions made should be clearly stated. Qualitative predictions should not be "guessed": they should be supported by evidence, such as references to research, discussions or consultation. This is crucial to transparency and acceptability of the results.

## 1.2.1.4. Summing up

As argued the most important aspect of choosing an approach to measurement, using tools such as indicators, or models, is the building of the whole methodology to answer the questions posed, what has here been called the reasoning. Reasoning comes with asking a range of questions, such as:
–   What is to be measured, ideally before specific indicators are introduced
–   What is the purpose of or reasons for the measurement
–   What are the main explaining parameters of the situation
–   Whether it is it possible to transform a correspondence into a causality
–   If the tool really measures what is required
–   If there is any potential bias in the data or predefined indicators
–   If the tool is applicable to the conditions studied.

## 1.2.2. Policy-type functions

Functions, which aid decision-making or the development of policy, can be characterised in different ways. For example, Briguglio (2003) proposes the following functions of indicators in the area of sustainability:

- To support decision-making
- To set targets and establish standards
- To disseminate information
- To focus the discussion
- To promote the idea of integrated action
- To monitor and evaluate developments.

**Figure 1. General indicator policy functions**
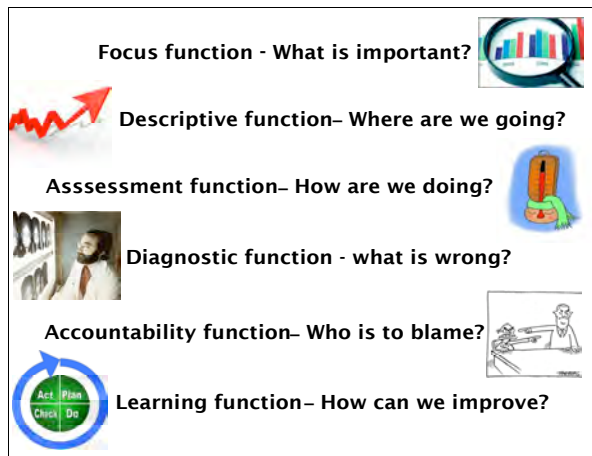


A more general list of what we can call instrumental or intended indicator functions has been generated from reviewing the literature as illustrated in Figure 1. Of course there are other possible ways to depict policy functions.

The policy type functions are more or less policy specific manifestations of one or more of underlying measurement functions discussed in section 1.2.1. The proposed policy functions as defined here refer primarily to different stages in an idealised policy development process, where each step may apply indicators in a new role. For example, indicators would be required to *ex-post* diagnose the results of a programme for completing the road network in a region. The specific information required might include descriptions of the transport situation with and without the programme, and progress relative to the programme objectives. If the evaluation is required quickly (*e.g.* for a management meeting to determine whether the programme should continue or end), then simple indicators may be sufficient. On the other hand, if the evaluation needs to be detailed and in-depth, then simple indicators will probably be inappropriate. The policy functions of indicators for sustainable transport are discussed further in Chapter 3 of the Report.

Apart from the intended informative functions of an indicator (or set of indicators) in a decision-making or policy situation, it has been observed in policy and indicator research that indicators are not always used according to the instrumental function for which they were designed (e.g. Innes, 1998; 1990; Nicolas *et al*., 2003; Sager and Ravlum, 2005; Hezri, 2005).

Firstly, actual indicator use may be more or less badly designed to perform some informative services for which it is intended (Mayer, 2008). This can be due to problems such as poor representativeness, a mismatch between the indicator and the policy function, incomplete data, inappropriate aggregation methodology, incompatibility with the overall analytic scheme, or unskilled handling. In such cases the effect of using the indicator might be to disinform, distort, disrupt, bias or confuse the decision-making process, rather than supporting it. The problem may not necessarily lie with the measurement capacity of the indicator, but can also be due to vaguely specified or 'impossible' policy objectives. The criteria which are used to define the quality of indicators are discussed in Chapter 4.

Secondly, indicators may also have entirely different roles that are not related to what is being measured. Several other types of information role have been studied (in addition to the instrumental functions) (Weiss, 1979; Beyer and Trice, 1982; de Bruijn, 2002; Amara *et al*., 2004; Hezri, 2005; Boulanger, 2007). These include the following:

- A '*symbolic*' role, where information is used to justify decisions already taken, or courses of action already chosen. A symbolic role can be when the graph of an indicator is used in a policy report to justify a new measure, even if the indicator was actually not considered when designing the policy. The indicator symbolises the will to act rationally based on timely information, even if this may not have taken place (see e.g. Dahler-Larsen 1998).

- A '*tactical*' role, where policy makers refer to the mere existence of an indicator system to postpone, avoid or justify a decision. An example could be the reference made to using the TERM indicator system for the coming mid-term review in a footnote of the European Commissions 2001 Transport policy white paper (CEC, 2001), as discussed by Gudmundsson (2003).

- A '*process role*', where the information provision process (rather than its results) is used to develop a planning approach. For example, according to Rydin (2002, p. 10 ff), it is sometimes the process to identify and select sustainability indicators that sets an authority on track towards considering more sustainable policies, rather then the indicator 'tools' themselves,

- An '*enlightenment role*', where indicators are influential in shaping general perceptions (or defining problems) among policy actors, even if the indicator is not used in any measurement or decision function. An example of the latter is the indicator 'ice-breaking date of the River Tornio', which some policy makers in Finland's parliament have accepted as an appropriate conceptualisation of climate change, even if they do not use it for any particular policy decision (Rosenström, 2002).

In this report the primary emphasis is on the *intended* functions (measurement and decision making) of indicators. The unintended functions are considered secondary, but it is important to include awareness of possible misuses, and other unintended functions, when particular cases of indicator use are studied, and recommendations concerning indicator use are given. Highly complex, ill-defined or contested phenomena (like 'sustainable transport') are particularly at risk of generating indicators that misguide or legitimize rather than inform actions. In short, awareness of non-instrumental indicator roles is crucial to understanding the significant *limitations* of indicators as either measurement or decision-making tools.

# 1.3. Types of indicators and their strengths, weaknesses and limits

A wide range of indicator types exist, meaning indicators that are different in the way they measure the phenomena they are supposed to represent and the purpose of the representation. Not any type of indicator can measure any dimension or manifestation of a phenomenon; moreover, not any type of indicator can serve any type of generic or decision related function. This is why it matters to give some consideration to indicator types.

Different typologies of indicators exist. Some typologies organize indicators with regard to generic measurement functions; others to decision making or policy functions; others again to both, or to other aspects.

Fernandez (2009) introduces the following distinctions:

− *Output indicator*: An indicator that measures the direct output of the plan or programme. These indicators measure progress in achieving plan or programme objectives, targets and policies.
− *Significant effect indicator*: An indicator that measures the significant effects of the plan or programme.
− *Contextual indicator*: An indicator that measures changes in the context within which a plan or programme is being prepared or implemented.

The more basic measurement distinction is between quantitative and qualitative indicators (see discussion about indicator definitions in section 1.1.6). Often quantitative indicators are preferred, because of the potential precision and reproducibility provided by standard numerical metrics. For some items however, qualitative indicators are the only possibility, or the best option, even from a measurment point of view (e.g. measuring attitudes; or the presence or absence of a particular transport planning strategy). A bit more developed is the following typology of measurement approaches (adapted from Spangenberg *et al.*, 2002),

− Nominal scale indicators; consisting of only two values: a certain characteristic is either existing or not.

- − Ordinal scale indicators; based on a hierarchy of qualitative states, e.g. in degrees of satisfaction ('very'; 'somewhat'; 'neutral'; 'etc); the rank but not the distance needs to be known.
- − Cardinal scale indicators; giving full quantitative information; allowing a range of simple or sophisticated mathematcal transformations.

Next, indicators can be typologised with regard to the 'range' of the representative space they aim to cover; a point in time; a time series (diachronic); across entities (synchronic), or a combination. The cross section (synchronic) can refer to multiple types of entities, individuals, groups, sectors, spatial levels, countries etc.

With regard to monitoring and policy related functions of indicators the European Environment Agency (EEA, 1999) has defined a simple typology used for environmental reporting:

- − Type A: Descriptive indicators, helping to identify what is happening to the environment
- − Type B: Normative indicators, helping to assess a problem, using a standard, criterion or target
- − Type C: Ratio or efficiency indicators, helping to assess relative improvement
- − Type D: 'Total Welfare indicators', helping to aggregate information about impacts in one number

Combining typologies allows the construction of a two-dimensional matrix typology as shown in Table 1.

### Table 1. Two dimensional indicator typology (16 types)

| Range / *Type* | Point | Time series | Cross section | Time + cross section |
|---|---|---|---|---|
| *Descriptive* | $x$ | $x_{t1}\ldots x_{tn}$ | $x^{A1}$ ... $x^{An}$ | $x_{t1}^{A1} \ldots x_{tn}^{A1}$ ... $x_{t1}^{An} \ldots x_{tn}^{An}$ |
| *Normative* | $x/x_T$ | $x_{t1}\ldots x_{tn}/x_T$ | $x^{A1}/x_T$ ... $x^{An}/x_T$ | $x_{t1}^{A1}/x_T \ldots x_{tn}^{A1}/x_T$ ... $x_{t1}^{An}/x_T \ldots x_{tn}^{An}/x_T$ |
| *Efficiency* | $x/y$ | $x_{t1}/y_{t1}\ldots x_{tn}/y_{tn}$ | $x^{A1}/y^{A1}$ ... $x^{An}/y^{An}$ | $x_{t1}^{A1}/y_{t1}^{A1} \ldots x_{tn}^{A1}/y_{tn}^{A1}$ ... $x_{t1}^{An}/y_{t1}^{An} \ldots x_{tn}^{An}/y_{tn}^{An}$ |
| *Aggregate* | $[x+y+z]$ | $[x+y+z]_{t1}\ldots[x+y+z]_{tn}$ | $[x+y+z]^{A1}$ ... $[x+y+z]^{An}$ | $[x+y+z]_{t1}^{A1} \ldots [x+y+z]_{tn}^{A1}$ ... $[x+y+z]_{t1}^{An} \ldots [x+y+z]_{tn}^{An}$ |

Notation: x, y, z  = indicators of phenomena X, Y, Z
$t_1$.. $t_n$,  = units in time (e.g. years)
$A_1$.. $A_n$  = units in space (e.g. countries)
T  = Target (e.g. 100 tons of $SO_2$)

**Table 2. Indicative overview of potential strengths and weaknesses of indicator types from policy and decision making point of view**

|  | Strengths | Weaknesses |
|---|---|---|
| Descriptive | Clear, simple<br>Limited intrinsic bias | Selective, narrow, dull<br>Limited actionability |
| Normative | Supports assessment<br>Accountability | Sensitive to target level<br>Manipulative |
| Ratio | Support comparisons<br>Diagnose critical trends or mechanisms | Disregards absolute values, limits |
| Total | Rich content<br>Allows 'high level' judgment | Opaque; Misleading<br>Limited actionability |

'Type D' indicators in EEA terminology, or aggregates, need of course not to be confined to measures of 'total welfare'; more local aggregations are used, and also biophysical aggregates like 'acidification potential' or 'Ozone Depletion Factor' (Fusco and Salby 1999) exist . Aggregates in terms of e.g. 'ecosystem health' have also been proposed, although more controversial (Jørgensen *et al*., 2005). Thermodynamic concepts such as entropy, exergy etc have been applied, and sustainability has been measured using 'capital' approaches, either 'disaggregate for natural, social, and economic capital, or as 'full' (or 'weak') aggregation, like in the concept of 'Genuine Savings'. Sustainability indices remain controversial (Hueting and Reijnders, 2004; Böhringer and Jochem, 2007; Mayer, 2008).

A special kind of aggregate indicators are composite. They link as aggregates to the 'type D' in EEA's terminology above, but miss any intrinsic parameter in which to perform the aggregation. The OECD defines composites as follows,

"A composite indicator is formed when individual indicators are compiled into a single index, on the basis of an underlying model of the multi-dimensional concept that is being measured. A composite indicator measures multi-dimensional concepts (e.g. competitiveness, e-trade or environmental quality) which cannot be captured by a single indicator" (OECD, 2005).

***Strengths and weaknesses with regard to indicator types***

Table 2 provides a rough assessment of some potential strengths and weaknesses of different types of indicators to inspire hypothesis formulation. It is based on discussions in Mayer (2008) and Hardi and DeSouza-Huletey (2000), but does not pretend to summarize consensus in previous research.

With regard to policy, decision making and management situations, another typology is often used, namely the 'production system', or input-output-outcome approach. This typology distinguishes between indicators describing different stages of a project or the performance of an organisation (Carter *et al*., 1993):

| Input indicator: | Resources required to provide a service or product (e.g. manpower, planning costs) |
|---|---|
| Process indicator: | The way the service is produced (e.g. public or private) |
| Output indicator: | The services, products or results (e.g. number of cycle lane kilometres built) |
| Outcome indicator: | The impact or final results (e.g. clean air) |
| Efficiency indicator: | Ratio input / output |
| Effectiveness indicator | Ratio input / goals |

In the case of sustainable transport, indicators of performance management could be relevant to assess the efficiency of sustainable transport plans and their effectiveness with regard to fulfilment of sustainable transport objectives.

The next section on indicator frameworks will address indicator types for different hierarchical stages of environmental planning problem, which is another way to conceive indicator typologies.

# 1.4. Indicator frameworks

Often, indicator frameworks are used in order to systematically classify indicators according to their attributes and character. Moreover, such a framework represents a more or less simplified version of the underlying concept of reality and it makes this world's view explicit to a specific audience, e.g. decision-makers. Indicator frameworks can also focus on particular intended applications of the indicators and thereby help to compose a set of indicators that is relevant for the particular usage domain.

According to Lyytimäki and Roenström (2008, p. 303) conceptual frameworks should help connect indicator systems to theory, provide an organizing structure, help identify useful indicators and data gaps, ensure indicator comparability, and facilitate communication with the public and decision makers.

In the context of this report, an indicator framework may also be seen as a helping tools to perform 'joint consideration' of several impacts together, as discussed in Chapter 6.

One of the most common indicator framework is based on the DPSIR-approach, which is "the causal framework for describing the interactions between society and the environment adopted by the European Environment Agency: driving forces, pressures, states, impacts, responses" (EEA, 2009a). As a causal framework, the DPSIR-approach is based on the assumption of 'chains of causalities': A causal chain can be defined as an ordered sequence of events or issues, in which any one event or issue in the chain causes the next one: For instance, land take needed for a road construction leads to habitat fragmentation. In section 2.4.2, we list 49 chains of causalities for the

environmental consequences of transport systems. Please see section 2.4 of this report for a deepened consideration of causal chains.

The Table 3 illustrates the DPSIR approach, using selected (out of a total of 40) TERM ("indicators of the transport and environment report mechanism") indicators developed by the EEA (2009b) for the transport sector.

**Table 3. DPSIR classification of selected TERM indicators of EEA (2009b)**

| Number | Indicator | Category (within DPSIR) |
|--------|-----------|-------------------------|
| TERM 01 | Transport final energy consumption by mode | D |
| TERM 02 | Transport emissions of greenhouse gases | P |
| TERM 06 | Fragmentation of ecosystems and habits by transport infrastructure | S |
| TERM 09 | Transport accident fatalities | I |
| TERM 37 | National monitoring systems | R |

An unequivocal allocation of the indicators to only one of the five groups is not always possible, but the DPSIR-approach can be seen as a useful model, see the following example for illustration:

The construction of roads (measured by the indicator 'length of road') is a driving force of environmental change, as it causes many effects, not only environmental ones. One of those effects is fragmentation, measured e.g. by the additional amount of fragmentation, caused by the new road. Such a pressure on the environment leads to a change of the state of environment through the fragmentation of habitats, measurable through the decrease of the habitats concerned. In the next stage of the chain of causalities, the fragmentation causes impacts on population, eco-systems, economy etc.: For instance the impact causes an increased number of dead animals, which failed in crossing the road. A response in order to ease that impact would be to forbid the traffic during the night hours.

Figure 2 offers another example of the DPSIR approach and underlines, that its first four elements establish a chain (driving forces leads to pressure, that pressure leads to a change of the state of the environment, that changed state causes an impact), whereas its fifth element, the response, has effects on all other four elements mentioned.

An extension of the DPSIR-approach has been recommended by Niemeijer and de Groot (2008): They pledge to use an enhanced DPSIR framework, a so called 'eDPSIR', that does not to consider individual causal chains, but looks '…at causal networks in which multiple causal chains interact and inter-connect'.

**Figure 2. DPSIR approach and the interactions of its elements
(EEA, 2009c)**
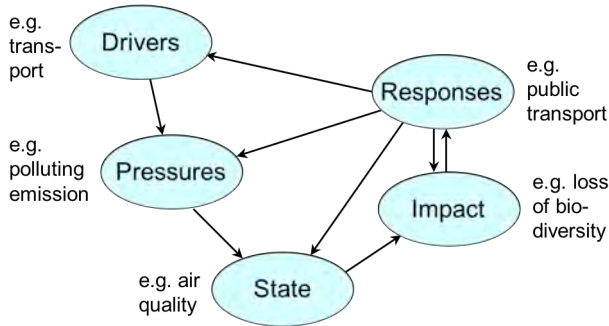


The DPSIR indicator framework is an extension of the PSR model developed by the Organisation for Economic Co-operation and Development (EEA, 2009a). An important variant to the DPSIR approach is the DPSEEA model, shown in Figure 3: Its first "E" stands for "exposure", the second "E" for "effect" and the "A" for "actions(s)"; it was developed by the World Health Organization (WHO). Thus, the DPSEEA model is mainly applied for environmental health indicators, as it "reflects the link between exposures and health effects as determined by many different factors operating through a chain of events, and clearly shows the many entry points for interventions" (EEHIS, 2009).

The DPSEEA model is "useful in designing a system of environmental health indicators within the decision-making context" (WHO, 2009). Similar to the DPSIR approach, it is a causal chain (driving forces lead to pressures, those pressures affect the state of environment / health, that causes an exposure and consequently an effect), whereas the actions taken influence all five elements mentioned.

**Figure 3. DPSEEA model (WHO, 2009b)**
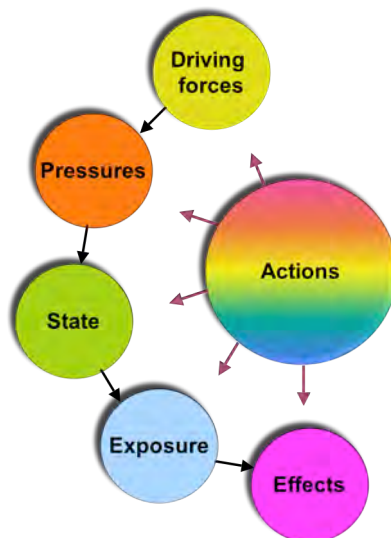
Another very popular framework is the allocation of indicators to the three pillars of sustainable development, i.e. to its economic, social or environmental dimension. Of course, this distinction cannot be made clearly in many cases, as several indicators represent more than one dimension or it is not easy to unequivocally assign them.

The causal chain of "input-output-outcome" can also be used as a framework for indicators. In general, "input" means resources putting into a system, "output" stands for products and "outcome" for results, effects or impacts. The surveillance of traffic through the police could serve as an example: Its input is e.g. the cost per inspection of one vehicle, the output is the proportion of inspected vehicles related to the traffic quantity, and the outcome is the decrease of accidents or fatalities in relation to the mileage performance.

Of course, there are more indicator frameworks to mention, all of which are organising systems of indicators in a special way and are applicable to the transport context: The widely used life-cycle-analysis (LCA) approach allocates the indicators to certain life stages of a product, a system, a service, a technology or a process by considering all its procedural stages "from cradle to grave". In the transport sector, one could list "building of the transport infrastructure", "production of the vehicles", "environmental effects of transport", "maintenance and servicing" and finally "recycling and disposal" as an example for those LCA stages.

### Strengths and weaknesses with regard to frameworks

Generally, indicator frameworks - like the described ones - consist of a selection of single indicators. This set of indicators is ideally chosen regarding the framework's character, direction and purpose. With such a framework it is possible to measure progress against certain objectives, outcomes, thresholds etc. of transport strategies (e.g. policies, plans and programmes) and projects. Moreover, such a framework is a tool to inform, monitor and evaluate transport-related projects and strategies in order to support e.g. decision-makers and planners.

To evaluate the strengths, weaknesses and limits of indicator frameworks, one can examine its single elements, thus go a step backwards.

Frameworks may however also be considered from the point of view of overall weaknesses. Essentially frameworks will always highlight some features and suppress others; hence it seems often difficult to agree broadly on uniting frameworks for subjects such as sustainable development, even among experts (see e.g. discussion in Meadows, 1996, p. 40 ff).

Conceptual elements of a framework may for example not fit the particular needs of a particular usage domain. For this reason the environmental P-S-R framework had to be adjusted to D-S-R for the UN Commission on Sustainable Development (Mortensen, 1997). Similarly, the rejection of the European TERM indicator framework as the main basis to inform the mid-term assessment of the European transport policy White paper, could be argued (see e.g. Borken, 2006). It may also be the other way around, a framework applied in practical policy assessment may ignore dimensions that are important for successful

policy making. For example, according to Dale and Beyeler (2001), ecological monitoring programs often use only a small number of indicators and therefore fail to take into account the full complexity of the ecological system being monitored. This may lead further to poorly informed management decisions. According to Lyytimäki and Rosenström (2008), frameworks are even sometimes pieced together after the indicators are already selected, simply in order to justify the selection of certain indicators.

However, as also argued by Lyytimäki and Rosenström (2008), even if the key requirement of a conceptual framework may be its ability to help reflect complex reality as objectively as possible, the usability of a conceptual framework is also essential. It is therefore necessary to use specific frameworks for specific purposes. The so-called 'Fitness-for-purpose' test applied in the European Transforum project may be one way to assess this (Tuominen *et al*., 2008). A problem with indicator sets tightly fitted to context could however be limited ability to compare with indicators over time or space.

All in all it seems that the identification of suitable indicator sets should consider the appropriateness of existing frameworks as well as of the individual indicators.

Methodologies for the assessment of indicators is further discussed in Chapter 4.

# 1.5. Conclusions

Indicators are variables that can be used to measure different aspects of the environmental sustainability of transport, and to aid in a variety of decision making situations. More specifically we have defined an indicator of environmentally sustainable transport as a variable, based on measurements, representing potential or actual impacts on the environment, or factors that may cause such impacts, due to transport systems, policies, as accurately as possible and necessary.

Indicators are often necessary, because full models to describe interactions between transport activity and environmental impacts are not available or not practical. Also decision making contexts may differ in a way that suggests different representations of sustainable transport; for example, if only one particular impact such a noise is on the agenda, indicators of other impact may be considered irrelevant (although in fact they are not), or if a decision on a new technology is needed at an early stage before the full environmental impacts are known, indicators for pressures and state of environment may have to be used. Each type of indicator may have specific strengths and weaknesses in various situations and contexts. This is explored further in the following chapters of the report.

There are many different types of indicators, each of which may be suitable to measure particular aspects or help decide on specific issues. There is hardly one indicator able to represent equally well all aspects of sustainable transport. In general indicators can not replace reasoning and interpretation; it is

necessary to reflect why the indicator is needed, what is to be measured, and how it should be done. Often a set of indicators will be necessary and here frameworks can be helpful to organize indicators in a way so all relevant dimensions are covered. There is not a generally agreed framework for organising sustainable transport indicators today; some of the key elements of frameworks refer to which stages or links in a chain of causality of a problem an indicator represents, and which functions the indicators have.

Indicators are technical tools for measurement, and many have intended functions in policy making, but it is not always their measurement capacity that determines how they are used in practice. Indicators can be applied for symbolic or strategic purposes, as well. Considering the potential wider indicator functions – with positive and negative aspects – of the indicators should be part of the reasoning.

# 2. Transport, environment and sustainability

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**With the contribution of other authors for the descriptions of the chains of causalities in Annex 6.**

The aim of this chapter is to describe what indicators are supposed to indicate, or in other terms to define what "environmental sustainability in transport" may mean and what the context of indicators is.

In section 2.1, we present the role of transport as a system and its interrelations with other systems.

In section 2.2, in order the term of 'sustainable' not to be a simple flag, we present the understanding of sustainable development that informs this report and discuss some important implications of the concept, including: time appraisal, governance, weak versus strong sustainability, substitutability of components, and critical natural capital.

In section 2.3, we analyze the ways environment is taken into consideration, firstly within the concept of sustainable development, then in the general literature. The different impacts on the environment are listed, together with the ways they are classified through an analytic or global perspective.

In section 2.4, we introduce the concept of chain of causalities to present the different processes between a source (i.e. transport) and final environmental targets. The consideration of the impacts from the literature and the chain concept allow us to propose a typology of 49 chains of causalities covering most transport impacts.

## 2.1. Transport systems

The transport system is firstly described not as a system but as a field of activity, with emphasis on its role in the society and the growing questioning of its consequences on the environment. We then give definitions of a 'transport system', and finally we explore its link with other systems and the need to define precisely or not a transport system to assess the environmental impact of a change of the transport system.

## 2.1.1. Role and consequences of transport

Transport is a key factor in modern economies. An efficient transport system is a fundamental prerequisite for the function and development of modern society. The transport system provides industry and people with facilities for the exchange of people, goods and ideas. It has become an essential part of human life since people need to move on an everyday basis in order to have access to work or education. The ability to travel and to ship goods at low cost over long distances, as provided through a complex of transport systems and networks, has enhanced humankind's economic, social and personal well-being. It has been a major factor in increasing access to health care, education, employment and recreation and improved access to a wider range of consumer goods has dramatically improved standards of living all over the globe.

Two aspects, which obtain particular attention in the transport literature, are *mobility* and *accessibility*. These two aspects are the main outputs of a transport system. They are related, but often confused concepts that can have distinct meanings in policy terms. Mobility is a measure of the agency with which people choose to move themselves or their goods around. Mobility for people and goods depends on the availability, affordability and efficiency of transport systems. Accessibility or the perceived proximity of desired destinations are heavily influenced by the transport mode being used. Accessibility is concerned not with behaviour, but with the opportunity, or potential, provided by the transport and land-use system for different types of people to engage in activities.

Transport policy decisions affect the mobility of populations and businesses and hereby influence prosperity, growth in GDP and employment across the economy. The effects are twofold:

- Increasing economic development causes more traffic. Increasing amounts of goods, greater transport distances, enhanced division of labour (globalisation), new production technologies (e.g. just-in-time production), higher levels of commuter traffic and an increase in business travel are producing a growth in goods transport and production-related passenger transport. The increase in the prosperity of private households, together with the reduction in the working week and the working life, are producing an increase in holiday and leisure transport.

- The mobility of people and goods is a precondition for greater productivity and economic growth. The latter result from enhanced division of labour, faster structural change, the exploitation of new raw and other materials and greater competitiveness in international trade. Mobility is therefore an important factor in the dynamics of economic growth.

Road transport clearly plays a predominant role in EU-27 transport, be it that of passengers or of goods. In the EU-27, about 6.2 trillion passenger-kilometres (pkm) were performed by four main modes in 2006 (see Table 4). Over the period 1995 to 2006, air passenger transport displayed by far the largest average annual growth rate (4.6 %). Moreover, road goods transport

performance grew by 3.5 % yearly on average from 1995-2006. Except the four modes shown, a share of performance was accounted for by Oil pipeline (135 billion tonne-km, namely 3 %).

**Table 4. Transport volumes by transport mode in the European Union (EU-27) in 2006. Billion person-kilometres and billion tonne-kilometres, respectively (Eurostat, 2009)**

| | | Road | Rail | Maritime / water-ways | Air | Total |
|---|---|---|---|---|---|---|
| **Personal transport** | (billion person-km) | 5124.3 | 467.9 | 39.9 | 547 | 6179.1 |
| | (per cent) | 83 | 7 | 1 | 9 | 100 |
| | Increase (%/year) 1995-2006 | 3.6 | 1 | 0 | 4.6 | |
| **Freight** | (billion tonne-km) | 1888 | 435 | 1683 | 3 | 4009 |
| | (per cent) | 46 | 10 | 41 | 0 | 97 |
| | Increase (%/year) 1995-2006 | 3.5 | 1.1 | 2.7 | 3.8 | |

One of the objectives of the 2001 White Paper is the decoupling transport growth from GDP growth. Decoupling has taken place on the passenger side, where gross domestic product (GDP, measured at constant 1995 prices) grew at an average yearly rate of 2.4 % from 1995 to 2006, while goods transport performance, measured in tonne-kilometres, grew at 2.8 % yearly. Over the period, passenger transport performance, measured in passenger-kilometres, grew at an average yearly rate of 1.7 % (Eurostat, 2009).

Transport at the turn of the century displays several unsustainable trends and the environmental aspects of transport have been subject to increasing concern. Continued growth in the number of motorised vehicles and their dependence on fossil fuels was given growing awareness. Emissions from the burning of motor vehicle fuel contribute to global and local damage to ecosystems and human health. The entrance of the catalytic converter in the early 90-ies greatly reduced the emission of a range of pollutants from road traffic but the $CO_2$ emission remained a problem. Concurrent with the development of equipment reducing the exhaust emissions, there was a shift from viewing the environmental effects merely as an end-of-the pipe issue to taking a more holistic view of the environmental burden from transport. The unsustainable dependence of the transport system on fossil fuels was given growing awareness. Also, the energy issue became a question of rapidly growing concern worldwide, intimately coupled with the climate-change issue, which is currently the main focus. The climate-change issue has greatly contributed to the overarching question of sustainability having become a major question of worldwide concern today. Other issues currently receiving growing attention are the consumption of other natural resources than fossil fuels, i.e. minerals used for the transport sector, the land-take by transport infrastructure, the fragmentation of landscapes and habitats, as well as disturbance (noise, air and water pollution) to people and animals caused by traffic.

For politicians, engineers, designers, policy makers, and the general public, the balance between mobility and sustainability is an enormous challenge. Environmental issues are an increasingly important part of the design and planning stage of any means of transport with a focus on minimising or mitigating ensuing impacts. The emerging discipline of sustainable development is a response to the growing aware that current levels and forms of economic activity threaten the planet's life-support systems. The implementation of sustainable development demands the design of systems consistent with ecological principles, namely, economic development subject to constraints imposed by the natural systems. The basic criteria to design and construct an environmentally sustainable transport system are: environmental stewardship by co-ordinated multidisciplinary teamwork, the implementation of best practices and policies and the development of environmental performance indicators (Kehagia, 2009). The combination of meeting accessible and effective mobility while improving the natural, built and social environment is the essence of sustainable transport. For these reasons, engineers are increasingly undertaking design problems in which a holistic understanding of natural systems in needed. Transport projects can be planned, designed, built, operated and maintained in such a way that when assessed, on an overall basis, they represent a net positive to the environment.

## 2.1.2. Defining a transport system

As transport interacts with other parts of the society and economy, the identification of what is included in 'transport' and what is not requires a more specific delimitation.

Transport itself involves the movement of people or objects in space, measured, for example, in person kilometres or ton kilometres. Vehicles of different kinds (cars, carriages, ships, airplanes etc) are essential for most types of transport. The movement of vehicles (without considering what is moved) can be characterized as traffic, measured in for example vehicle kilometres.

The notion of transport systems suggests the idea that different elements are linked and interdependent, forming a system, "a combination of interacting elements organized to achieve one or more stated purposes" (ISO/IEC 15288: 2008, p. 4). In the case of transport, this idea expresses the interaction of traffic, infrastructures, mobility, and other components, to produce transport (and traffic).

The question 'what is a transport system' can be answered quite differently. Two different ways to define a transport system are generally found in transport studies literature (see e.g. Van Acker and Witlox, 2005): one that refers to the physical and organisational elements that produce transport, or the 'supply' of transport, and a broader one that incorporates the interaction between demand and supply of transport.

The first type of transport system definition considers what is moving and what is directly needed for movement: vehicles, network facilities, information and control system. It includes the operators (drivers, pilots, captains, system

supervisors and controllers, etc), and the communication and facilitation devices (lights, signals, radio, software for flight control etc).

The second type of transport system definition, including both supply and demand, enlarges the first definition with the elements and their relationships producing the transport demand. Such elements can be, for example, the housing structures, the industrial and agricultural production system, tourism, labour market etc.

Here we choose to delimit a transport system according to the first, most classical sense, with transport systems confined to the 'supply' side of components. However, missing from most transport system definitions is mentioning of the energy carriers used to drive the systems. The energy (fuel, propulsion) is not only important from the environmental point of view, but also a logically essential element for a transport system to produce movement.

Taking into account this we can use the following definition, which is modified from Papacostas and Prevedouros (1992):

"A transport system may be defined as consisting of the fixed facilities, the flow entities, the energy carriers, and the control units that permit people, goods and other objects to overcome the friction of geographical space".

Transport systems may be further distinguished in various ways, such as:

- the different functions they have (movement of people, goods, waste or all of these)

- the different infrastructure types they use (road, rail, seaports, airports, etc)

- the different energy carriers the use (fossil, electrical, human-powered etc)

- their different location contexts (e.g. urban versus intercity)

Each typology may have different implications for how to identify and delimitate the environmental effects of the transport system. In the present analysis the method as such is not dependent on such distinctions.

## 2.1.3. Transport interacting with other systems

The transport system is also often considered as a sub-system of wider systems, for example as a subsystem of communication systems, of transport-land-use system, of logistics or supply chain system, of production systems, or economic or social systems generally. It means that no system is completely independent and that the concept of system is partly an intellectual and artificial attempt to simplify a complex reality.

Assumptions concerning system delimitations and the interactions between transport and other systems are clearly not inconsequential for describing the environmental impacts of transport system, since the wider systems they are part of may generate different or additional sets of interrelations to the environment than those stemming from the transport system itself.

The present study tries to adopt a life cycle perspective on transport systems, which for each transport system component or product (vehicles, infrastructure etc) considers the consequences on the environment of production, existence, use and disposal, in addition to the consequences of the traffic service itself.

A number of wider system interrelations may also be envisaged, for example:

– A transport investment may influence land-use decisions, and thus cause additional environmental impacts associated with urban development (e.g. shifting location choices from one type of landscape to another with different ecological sensitivity).

– Suppressed transport demand may lead to shift consumer demand to higher domestic energy consumption instead, with additional effects not directly related to the transport system as such.

– In developing countries, forests are sometimes cut down to provide firewood or agricultural land for inhabitants in new settlement established randomly as a result of a new road opening (Cropper *et al*., 1999). This could be seen as an indirect effect of the road building.

Arguably, especially in a sustainability context (see section 2.2), environmental assessment due to transport systems changes should include all possible system interactions. A full comprehensive description of the effects of changes to economy, society, or environment from changes in transport activities or system does however not exist today. Assessments will always be somehow partial, but it is important to be clear about any such delimitations.

In this report, we apply a system delimitation, where only changes in transport itself and in the transport system components (as defined above) are considered as 'transport changes', while changes induced in other systems or sectors as a result of changes in transport provision or service (e.g. more consumption of pristine land due to cheaper transport becoming available, or additional energy use in households due to suppression of transport) are not considered.

The concept of 'chains of causalities' presented in section 2.4 seems in principle able to extend to any such additional indirect consequences, even if these causalities would be for example economic or behavioural.

## 2.2. Sustainable Development

The World Commission on Environment and Development, called Brundtland Commission, is usually credited with one of the first definitions of what is understood today by sustainable development. In *Our Common Future* (WCED, 1987), the Commission defined the sustainable development as the "development that meets the needs of the present without compromising the

ability of future generations to meet their own needs". The report continues: "It contains within it two key concepts:

- The concept of "needs" in particular the essential needs of the world's poor and future generations, to which overriding priority should be given, and

- The idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs".

**Table 5. Some definitions and interpretations of sustainable development and sustainability**

| Study | Definition |
|-------|------------|
| Pearce *et al.* (1989) | Sustainable development involves devising a social and economic system which ensures that real incomes rise, that educational standards increase, that health improves, that the general quality of life is advanced. |
| IUCN, UNEP, WWF (1991) | Sustainable development involves improving the quality of human life whilst living within the carrying capacity of the ecosystems. |
| Holdgate (1993) | Development is about realising resource potential, sustainable development of renewable natural resources implies respecting limits to the development process, even though these limits are adjustable by technology. |
| Pearce (1993) | Sustainable development is concerned with the development of a society where the costs of development are not transferred to future generations, or at least an attempt is made to compensate for such costs. |
| HMSO (1994) | Most societies want to achieve economic development to secure higher standards of living, now and for future generations. They also seek to protect and enhance their environment, now and for their children. Sustainable development tries to reconcile these two objectives. |
| Spedding (1996) | In an attempt to explain sustainability, Spedding gives two propositions that fit the concept. Sustainability must be based on resources that will not be exhausted, and it must not create unacceptable pollution. |
| Esty *et al.* (2005) | Sustainability is a characteristic of dynamic systems that maintain themselves over time. |

As noted by Gudmundsson (2007), this does not mean that essential needs of environmental limits were not addressed before. However, the term 'sustainability' implies a more comprehensive, long-term and integrated approach than had previously been the case.

In the years since then, countless alternative, enhanced or modified definitions have been proposed, and some of these are summarised in Table 5. The current variety of interpretations placed on sustainability - and the numerous attempts on the part of governments and other organisations to address sustainability issues - renders it difficult to define the term more

precisely for general application. Daly (1991) argued that the lack of a precise definition of the term 'sustainable development' is not all bad. It has allowed a considerable consensus to evolve in support of the idea that it is both morally and economically wrong to treat the world as 'a business in liquidation'. Spedding (1996) indicates that the word falls into the category commonly known as 'umbrella words' (other such words include 'freedom' and 'truth' – words which are in common use but are hard to define precisely). However, others have also argued that the lack of a clear definition has been detrimental, in that it has allowed 'business as usual' to continue, without achieving the behavioural and other changes needed in order to reach an environmentally sustainable development (see e.g. O'Riordan, 1988).

There has also been a proliferation of sustainability-related terminology and usage. This has coincided with the explosion in information relating to the threats posed to the environment by human activity. It seems that virtually any activity can be represented as potentially being sustainable, and as a consequence of this (false) assumption, many are wondering whether there is any need at all to worry about the environment. In the next first section, we describe the main components of the concept of sustainable development, its dimensions or main elements. After that, we define 'environmental sustainability' as well as 'environmentally sustainable transport'. We then focus on the various contemporary debates on sustainable development, which have consequences on the methods for measuring environmental sustainability. These include e.g. weak vs. strong sustainability, critical natural capital, and internal environment substitutability.

# 2.2.1. The main dimensions of sustainability

Sustainable development is often defined through various dimensions. A first set of dimensions include the three substantive aspects or pillars: economic, social, environmental. A second set of dimensions includes transversal issues including e.g. long term effects, needs, and governance. Both sets of dimensions are clearly not comparable, not on the same level: If the long term and the needs could be used to specify the first set of dimensions, the institutional dimension (governance) is rather a framework for managing the other dimensions.

## 2.2.1.1.  The three constituent elements

It is generally recognised that the field of sustainable development can be conceptually broken down into three constituent elements: economic, social and environmental. These elements are often termed the three 'pillars' of sustainability, and any form of sustainable development must balance economic, social and environmental objectives. The interactions between the three pillars are somewhat open to interpretation, a shown in section 2.2.3. The graphical presentations of the pillars differ a lot on their relationships, as shown Figure 4, where the 5th version represents the hierarchy of economic, social and environmental spheres according to Passet (1979).

**Figure 4. Five different versions of the three constituent element model,
and their meaning in terms of relationships,
adapted from Gudmundsson (2007)**



1: trade-offs

2: solidarity or dependence

3: independence

4: limited dependence

5: hierarchy
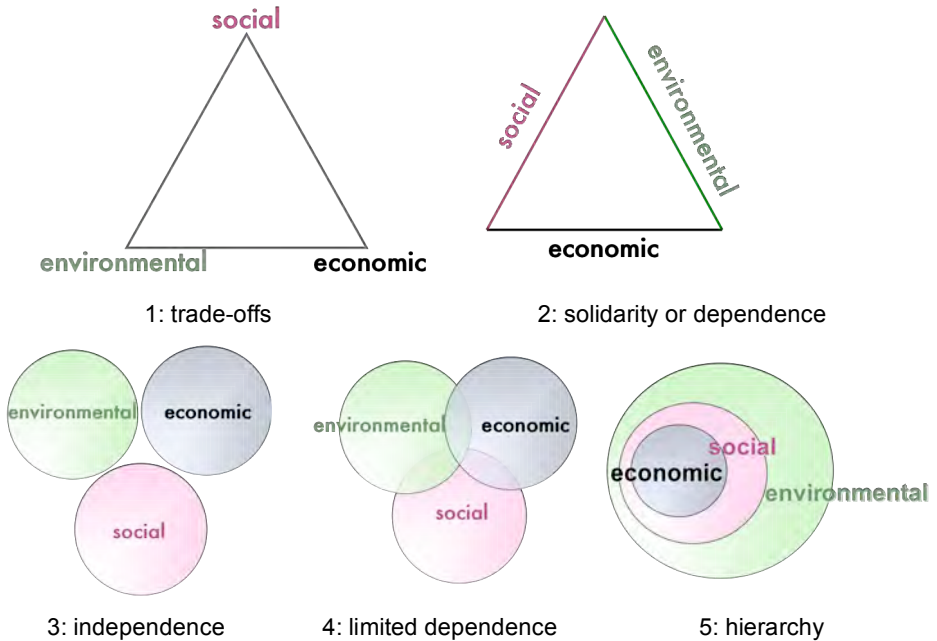
Definitions of sustainability increasingly include a broader range of issues, and these often relate to sub-divisions of the three pillars. Some examples of sustainability issues are provided in Table 6 (more are listed in Table 49 and Table 50 in Annex 3 on page 295). The economic element is often quite well defined (added value, income) as the taking into account of the long term. The social aspect is rarely stated explicitly and can be a source of confusion: It sometimes includes all societal aspects, including quality of life or health impacts, but does not include always equity between humans. Sometimes it concerns only governance. The environmental pillar is not always well defined as noted in section 2.3.1.

**Table 6. Sustainability issues (Victoria Transport Policy Institute, 2007)**

| Economic | Social | Environmental |
|---|---|---|
| Affordability | Equity | Pollution prevention |
| Resource efficiency | Human health | Climate protection |
| Cost internalisation | Education | Biodiversity |
| Trade and business activity | Community | Precautionary action |
| Employment | Quality of life | Avoidance of irreversibility |
| Productivity | Public participation | Habitat preservation |
| Tax burden | | Aesthetics |

Mauerhofer (2008) and Lélé (1991) reported that despite the wide consensus of the three main ingredients of sustainability, different opinions are expressed about their interrelationship and lack of consistency in its interpretation. Occurring insufficiencies are mainly misinterpretation of embeddings, misjudgement of equity between the three sustainabilities, a lack of expression of limitations, and a lack of adequate decision support. Ahlheim (2009) noticed that during the process of development, economic aspects typically dominate the thinking of politicians and of citizens in the first phase while social and environmental aspects follow with a certain time lag.

## 2.2.1.2. The three additional issues

The concept of sustainable development is often presented with three other issues, which are transversal compared to the three pillars: the needs, in particular the essential needs, the taking into account of the long term (future generations), and the institutional aspects (governance).

No definition of the concept of needs is well established. Nobody can tell us the limits of the needs even among the most essential, except maybe food, although defining the needs by the solvable demand, i.e. the income determining the amount of the needs (Rist, 2002). It is for instance impossible to define transport or mobility needs that are valid for everyone. Max-Neef *et al.* (1991) and then Rauschmayer *et al.* (2008) define fundamental human needs as the most fundamental dimensions of human flourishing, i.e. the reasons for action that need no further justification: Subsistence, protection, affection, understanding, participation etc. Beside these individual needs, one could also consider that some collective needs should be added as equity and solidarity, which often lead the debates on sustainable development.

The second additional dimension, the long term, corresponds to the future generations, in contrast with the present ones. It means often some decades, but could also mean some centuries or some millennia. It raises the issue of the time perspective of the decision making, which is first important from an ethical point of view, with that necessity to take into account the forthcoming generations (Bruntland, 1987). But it is also very accurate for the scientific and technical approach, with the problem of taking time into consideration in an indicator: this is for example the question of the global warming power of different gases to measure the greenhouse effect (see section 5.6), or the problem of the discount rate for the economists (see section 6.2.5.3).

Concerning the third additional dimension, the meaning of the term governance is and stays very variable, not well clarified, insubstantial in many cases, but also sometimes very well designed (Hermet *et al.*, 2005; Joumard, 2009). A first meaning, basic, is the way of governing, the tools for governing, and the government: It adds nothing to these expressions.

Robinson and Tinker (1997) raised the need for social imperative to provide systems of governance that propagate the values that people want to live by. Haque (1999) stated that the cooperative global environmental governance regime envisioned at the 1992 Earth Summit in Rio is still in an institutional incubator while neoliberal economic globalization has become fully operational.

**Table 7. Major elements of three approaches to sustainable development (Sneddon, 2006)**

| Ecological economics | Political ecology | Development as freedom |
|---|---|---|
| Critique of neoclassical economic arguments (e.g., "development as growth" model) | Radical critique of global political economy and its ecological effects | "Internal" critique of development theory |
| Incorporation of ecological concerns into economic methodologies and theory | Sensitivity to structural forces impeding sustainability transformations; attention to discourse and power | Prioritization of political rights, basic human needs, economic opportunities and equity over aggregate economic output in development thinking |
| Concern with intergenerational equity, 'degrees' of sustainability, valuation | Incorporation of ecological concerns into critical social theory | Normative: human well-being; expansion of individual rights; maintain focus on development but with radical reorientation |
| Normative: ecological and social sustainability; environmental and social ethics; reform of existing institutions | Normative: social justice, equity and ecological integrity; radical changes necessary in existing institutions | |

Meadowcroft (2005) considers sustainable development to be a major governance challenge of the 21st century. If societal development trajectories are to be realigned on to more sustainable pathways major changes will be required to existing processes and practices of governance. Sneddon *et al*. (2006) summarized Table 7 the contributions of the three approaches to a pluralistic, transdisciplinary strategy for confronting sustainability. Among all cited elements, governance seems to be of importance to be considered for the achievement of any objective under sustainable development.

But the term has an already long history, which gives him a more precise meaning, and which is always more or less present behind its use. The 'governance' or 'involvement' principle is a term that frequently appears in the declaration and the texts of the 1992 Rio Summit. The final declaration claims for instance that "*Environmental issues are best handled with participation of all concerned citizens, at the relevant level. [...] States shall facilitate and encourage public awareness and participation by making information widely available*" (UNCED, 1992, 10th principle). The participation of the women, the youth, and indigenous or local communities is claimed to be essential to achieve sustainable development (principles 20, 21 and 22).

Another aspect of the governance often discussed in the sustainable development debates is the involvement of the society in the decision making, through its multiple stakeholders, by participating to working groups, consultation groups etc. It is supposed to answer an increased complexity of the

society running (Innes, 1995), but such complexity is few demonstrated or illustrated. Warren (2008, p. 5) for instance lists issues where the political choice can be only thematic and made by those who are directly interested and impacted by the subject: "Protests over airport expansion, medical coverage, poverty issues, changes in GMO regulations, forest management, struggles over neighbourhood development, energy pricing". These issues seem rather to raise society issues than local ones. The focus on the complexity of the contemporary societies could justify the role of the experts, as the citizens and the political organisations seem no more competent enough to analyze and, at the end, to decide (Crozier *et al*., 1975). On the other hand, Guibert and Harribey (2005) or Fourniau and Tafere (2007) take the example of the consensus conferences and citizen seminars to lead some technical choices. To go further, some models of decision making are presented in chapter 3, and especially the communicative planning model built on similar principles than governance (see section 3.2.5).

## 2.2.2. Environmental sustainability, environmentally sustainable transport

The environmental pillar of the sustainability, as defined in section 2.2.1.1, can be called "environmental sustainability".

Environmentally sustainable transport (EST) can be defined in two ways:
− as the application of environmental sustainability to the transport sector or to elements of this sector
− as the environmental pillar of sustainable transport, which make necessary the definition of the concept of sustainable transport.

There is no generally accepted definition of the term 'sustainable transport' (like its synonyms 'sustainable transportation', 'sustainable travel' and sustainable mobility'). The expression is often used in order to describe all forms of transport which minimise environmental impacts, such as public transport, car sharing, walking and cycling, as well as technologies such as electric and hybrid vehicles and biofuels. More details on this are given in Annex 3.

While conceptualising sustainable transport using the 'three E's' of environment, equity, and economy is widely accepted according to Hall (2002, 2006), the problem with this approach is that it has the potential to perpetuate the status quo by only focusing on change *within* the transport sector to the exclusion of change *across* sectors. Transport is only one sector and it must work in conjunction with other sectors or areas - such as energy, manufacturing, and housing / land use - if system transformations are to be made towards sustainable development (Hall, 2006). In other words, a sector such as transport or agriculture cannot be characterised as sustainable or unsustainable, because it is not independent from the other sectors. However, transport can be characterised either to contribute or not to contribute to the sustainability of society, all other things being equal. A good illustration of this here is biofuels: From a transport point of view, biofuels are or could be sustainable (considering only transport energy), because it could be a

renewable source of energy. But if the production of biofuels is made to the detriment of the diet of a large part of the world population, biofuels cannot be characterized as sustainable.

Taking into account the difficulty to define the concept of sustainable transport, we use in this report the first definition of Environmentally sustainable transport above, based on the environmental pillar of sustainability.

## 2.2.3. Weak and strong approaches of sustainable development

The literature identifies two main meanings or variants of the sustainability concept: The first one, so-called "weak", by some authors wrongly assumed as implicit in the Brundtland's report, is often applied by experts in economics and decision makers. The second, so-called "strong" has a more frequent usage in environmental analysis.

According to the **weak approach** of sustainable development, the natural capital is a component of the total capital. This one is therefore composed by all the productive goods, so-called productive capital, the human capital and the stock of knowledge and know-how of the people, so-called social capital, and the resources and natural goods, renewable or not, so-called natural capital. These different types of capital are supposed measurable and equivalent. The annuities due to the use of the natural capital by the present generation can be reinvested in the form of a reproducible economic capital, to be transmitted to the future generations. Then oil consumption, i.e. a decrease of the natural capital, can be compensated by the creation of industrial goods it allows, i.e. by an increase of the productive capital for instance. The scarcity of the natural capital can therefore be neutralized and changed into a simple question of economic efficiency, as this approach is based on the assumption of a high substitutability in the time and space between the natural, social and economic capitals, and inside the natural capital, between the components air, water, earth, biomass... In these conditions, the sustainable development of an economic sector is not limited by an ecological constraint.

The environmental issues are systematically monetarized (see section 6.2.5) in order to make them comparable to economic values and therefore to integer them in balance sheets (green accounting, analysis as cost-benefit etc), used to take decisions aiming at getting an economic optimum. The research of the highest economic development is here the main objective, with the hypothesis that the environment answers, as the economy, to a market, to be thought to be able to take into account the long term.

This approach, often qualified as neoliberal, considers an economic optimum based on the "free" choice of the stakeholders, what are the consumers and the other economic stakeholders (Froger, 1993). It does not refer to the citizenship and to the democracy, but replaces these concepts by the notion of good governance (see section 2.2.1.2), using technocratic processes to express the social demand.

The second variant of sustainable development is the **strong approach**, which claims the irreducible character of the natural capital. It means that the sustainable development should comply with the ecological constraints due to the preservation of the quantity and the quality of the natural capital, i.e. the nature.

If the economic activity represents a determining component of the human activities, it expresses only partially the relationships between humans. The symbolic burden of the goods and services we consume, the values of solidarity and justice, the religious or artistic feelings, among other examples, do impact obviously the economic world, its rules, the products and trade off it generates. However, they transcend it and widely exceed it. In a parallel step, from the biological rhythms each individual has to respect until the big bio-physico-chemical balances of the planet, any human society is a part of a natural world, from which it cannot escape – it is consubstantial with it. Therefore, if a hierarchical relationship should be made between the three pillars, the economic one has to respect the social and economic constraints because it is included in both. René Passet (1979) represented this inclusion through the shape of three circles fitted together (5th version in Figure 4).

The sustainable development of an economic sector is therefore always defined as the permanent economic activity preserving the levels of each kind of natural capital of the area where it is over the biosphere reproducibility thresholds. The exploitation of natural resources must allow the ecosystems to regenerate and survive. This rule implies according to some economists (Georgescu-Roegen, 1979; Daly, 1994; Rist, 2002; Rahnema, 2003; Maréchal, 2005) nil, indeed negative, growth rates in the developed countries. But the economic growth can also be based on something else than the exploitation of non-renewable resources, and the share of immaterial or renewable goods could increase.

The specificity of the strong approach of sustainability is then to look for a equilibrium between its three pillars and not for a global, one-dimensional, almost mathematical optimum. The logic or rationality is now a logic similar to the logic of an ecosystem. The collective (political) decision cannot be organised according to a principle of economic optimisation (Froger, 1993). This conception opens the debate, recognises its complexity, and therefore does not pretend to offer simple solutions to a complex issue, as a unique evaluation tool. It invites also to wonder about the importance of each natural element, and asks to evaluate, to measure independently the economic wealth, the social wealth and the environmental wealth (Gadrey and Jany-Catrice, 2005). The strong approach of sustainability emphasizes after all on the citizenship, on the real participation of all to the decision making, in the dynamics of the democratic idea. The institutions, which implement the constitutional state and the democracy, play here the main role.

While accepting the argument that the "total capital" is one and that the "natural" capital is but a part of it, accepting an unrestricted trade-off between the environmental and others parts – economic and social – of the "total" capital may clash against the prevailing regulations, both national and at EU level: The severity of certain impacts, if beyond a certain threshold of legally binding

benchmark values, cannot be accepted and would barely go through a statutory process of public participation. Hence, the dilemma weak vs. strong sustainability should be considered somehow fallacious in its formulation; the trade-off between environmental, social and economic capital does exist, but notice should be taken that the severity of certain impacts may not overpass statutorily approved values, as elements of natural capital and, likewise economic and social ones, cannot be replaced presently (ozone layer, for example).

If the non-replaceability of the economic, social and environmental pillars is accepted under certain conditions, it should surely be extended to a number of irreversible or almost irreversible impacts (see section 2.2.5).

As the Swiss Federal Council Strategy for Sustainable Development highlights (SFC, 2008), the sustainable development introduces in human decisions the concept of limitations, in other words, the idea that the environment does not have an unlimited ability to provide resources and to assimilate wastes and emissions.

To move towards sustainable development, economic efficiency, social solidarity and environmental responsibility are interconnected goals and must not be considered in isolation. Therefore, economic development can only be sustainable if it is accompanied by healthy ecosystems and the wellbeing of people. At the same time, these three goals can conflict with one another in certain areas. The idea behind sustainable development is to make improvements, render the decision-making process transparent and find long-term solutions (SFC, 2008).

Decisions have to be taken based on to balance out the three pillars of sustainability. This is not convenient for decision makers, because each dimension has to yield in favour of others. Only in very specific cases, one of the pillars can be totally replaced, and this is hardly ever the environment. This does not impede democratically elected politicians acting within a statutorily approved planning process to impose their criteria, related to their goals, as long as the development alternative to be implemented can be labelled sustainable.

## 2.2.4. The critical natural capital

Weak and strong sustainability are 'archetype' positions about substitutability. Now economists agree that some part of environment would not be replaceable, and should be managed with critical limits in mind, as it is not possible to value as an income or capital value. Most environmentalists agree in parallel that not every unit in nature must be preserved unchanged forever to allow sustainable life support of mankind or even reproduction of ecosystems, but the scale at which destruction occurs is of course critical for reproduction. An intermediate concept often used here is the 'critical natural capital' (Ekins *et al*., 2003), i.e. the natural systems and resources for which no or only poor substitutes exist. However, this does not mean that it is possible to characterise

particular elements of nature as always or intrinsically 'critical' or 'non-critical' (Ekins, 2003, p. 298).

This concept either considers that the relations between environment and the human society are flows (inputs and outputs), or considers that an ecosystem can not replicate above a given pollution level (load capacity). It does not consider a logic of system, where all the components are indispensable each other's, nor the quality of life or well-being aspects, which are not considered as environmental impacts, restricted here to the resources absolutely needed to life. In addition, Barkman (1997) as Skeffington (1999) show that the critical loads are mainly political compromises and not environmental limits to avoid impacts.

The conclusion could be that no absolute distinctions can be drawn from an environmental science point of view: If some critical loads exist and if some critical natural capitals can be considered, they do not appropriately address all the environmental issues that are of concern to human life or development (or all chains of causalities described in section 2.4.2). The environment aspects of sustainable development are clearly not reducible to 'critical natural capital' only, for conceptual as well as methodological reasons. Still notions like critical loads are of course essential to distinguish between different types of consequences.

## 2.2.5. Internal environmental substitutability

The debate between weak and strong sustainability (section 2.2.3) raises the question: Is-it acceptable to substitute the three pillars of the concept, for instance to replace without limit environmental quality by economic growth? In parallel, we can ask ourselves how substitutable are the components of the environmental pillar, such as water, air, noise, biodiversity, landscape quality, architecture heritage, resources etc. Is it for instance acceptable to irreversibly destroy vestiges or animal or vegetal species in return to a decrease of the greenhouse effect or of an improvement of the home water quality? Is it acceptable to compensate for the destruction of natural habitat with an improvement of the acoustic environment, or vice versa?

Irreversibility seems to be an essential aspect to consider: An impact, however minor, can in fact become extremely penalizing if it is irreversible. In this case, no irreversible damage of the ecosystems seems acceptable. On the other hand, we could admit the substitution of two reversible nuisances (noise and local air pollution for instance). An example on how to do this is provided by Joumard and Nicolas (2010), who categorized environmental impacts into three independent groups, two of them consisting of impacts considered to be irreversible (greenhouse effect, biodiversity), and the third group consisting of all other impacts together; Then economic, social, greenhouse effect, impact on biodiversity, and all other environmental impacts together are taken into account independently of each other.

But here two difficulties appear:

– There are different kinds of irreversibility, especially when it concerns species or individuals. The death of some humans or animals is of course a negative impact, but much less than the disappearance of the humankind or any animal or vegetal species. However, the difference between individual and species seems not applicable to all environmental issues (e.g. visual quality of landscape).

– A lot of environmental impacts are neither totally reversible, nor irreversible: The impact on landscape of intensive building of houses in the countryside (time scale of a century?), or the mid-long waste (time scale of several centuries), but also the greenhouse effect (time scale between a century and a millennium), etc.

# 2.3. Definition of the environment in the literature

There are several meanings of the expression 'environment'. The traditional one is 'the totality of surrounding conditions' or 'the remainder of the universe that lies outside the boundaries of the system'. The increase of what is called the environmental issue refers to something slightly different, the impact of the human activities on final targets. In this section we look at the meaning of the environment firstly within the concept of sustainability – it is more a top-down approach, then in terms of impacts considered – it is more a bottom-up approach.

## 2.3.1. Environment within the concept of sustainable development

The meaning of the environmental pillar of sustainable development is most often a vague term, referring sometimes to the quality of life, to the natural resources indispensable for life or economic activity, or to nature.

The strong and weak concepts of sustainable development differ especially by the content of the environment. The weak concept of sustainability developed in environmental economics considers mainly the living environment, i.e. local and reversible nuisances produced by the economic activity and potentially eliminated by a better management, although it defines also the natural capital. The strong concept considers rather global natural and non-renewable resources, which are necessary for our well-being, and irreversible and global nuisances. In other words, noise or oil.

Thus OECD (2001) makes a difference between on the one hand the development criteria whose environmental part deals with the environmentally conditioned welfare and the health for present generation trough air quality, noise, and water quality, on the other hand the sustainability criteria whose environmental part deals with the conditions of a long term development through critical natural resources, ecosystems, and climate stability. This last

type of criteria is often taken into account by economists in the form of a natural capital, or more precisely of a natural heritage or a resource, because a capital is managed to be increased and an heritage to be transmitted (Godard, 1990). However, the notion of "resource management" is specific to our western societies and is not inevitably understood in the same way by other societies, although sustainability is the core of their concerns (Rey, 2008). The pressure-state-response (PSR) and drive-pressure-state-impact-response (DPSIR) systems resp. from OECD and EEA seem well applicable to this meaning with a pressure representing a flow. It is the most common presentation of the environment, especially by economists, considering it as a resource used by the humans for producing economic goods. This resource is an ecosystem, i.e. the association between a physicochemical and abiotic environment and a living community characteristic of the latter (the biocenosis), including fossil resources. This resource is destroyed but can be renewed at a given extend: the environmental issue is a question of resource stock, resource flow and capacity of the biosphere to support the effects of the human activities (carrying capacity): It calls the 7th principle of the Rio declaration (UNCED, 1992): "...*to conserve, protect and restore [...] the integrity of the Earth's ecosystem [...] the pressures their societies place on the global environment*". The resources are sometimes described as inputs of the economic system, especially of the transport system.

Perret (2005) uses a similar approach, by differentiating the flow indicators (relative to the living conditions of the present generations: environmental quality) and the stock indicators (relative to the conditions of a future development: natural capital). The distinction flow / stock is nevertheless simplistic: For instance, the well-being and the environmental quality are partially transmitted and are conditions of future development; Above all this mechanistic view does not correspond always to a reality. In the same way, Derissen *et al.* (2009) uses, as a stock indicator, the concept of resilience as a measure of an ecological system to withstand external shocks without changing its structure.

In parallel, the environment is often understood as the quality of our physical environment or the quality of life: a calm area with pure air and pure water, a beautiful landscape, etc (Job, 2005; Gudmundsson, 2007 for instance). It calls the first principle of the Rio declaration: "*Human beings [...] are entitled to a healthy and productive life in harmony with nature*". It is here often difficult to consider only flows or pressures, although some authors, as Perret (2005), consider that the flows deal with the quality of life of the present generations. On the same line, the flows are understood as the physical or chemical outputs of the economic activity, e.g. transport, as noise, air pollution etc.

These two meanings of the environment correspond roughly to the external and internal territory sustainability defined by Wackernagel and Rees (1996): the internal sustainability consists in protecting its direct environment and living area, but the external sustainability consists in protecting the world.

The characteristic of all these definitions of the environment pillar of sustainability is to be synthetic, global, top-down, and not based on an explicit analysis of the environmental impacts, objectives or issues. Such definitions are

much too global and rough to be useful for describing the environmental issue or the impact on the environment of a human activity, and for designing environmental impact indicators. An exhaustive list of the environmental impacts or objectives is necessary to present a full picture, especially if the explicit aim is to identify the most important issues as made by Black (2000) or Borken (2003), and even to choose the issues of some importance for decision making as made by Ahvenharju *et al*. (2004), Nicolas *et al*. (2003) or Zietsmann and Rilett (2002): How to identify the important issues with a top-down approach without an encompassing assessment of all relevant issues?

When the environment is described in a detailed way, these descriptions are usually rather heterogeneous and structured in a often questionable manner.

Thus, the environmental objectives of sustainable development, as presented for instance by Swedish municipalities, according to Gudmundsson (2007, p. 37), merge primary objectives (e.g. environmental quality), secondary objectives which should be deduced from them (use less non-renewable resource for instance), and objectives in terms of solutions (less use of private vehicles, more use of public transport for instance), without differences being perceived and the objectives being logically organized into a hierarchy.

Very often, health, safety or land-use are considered in parallel to the environment, inferring that they are not part of the environment (see for instance Wolfram, 2004, or SSNC, 2006). As an example, Droulers *et al*. (2008) integrate health impacts into the social dimension and not into the environmental one, whereas the environmental dimension integrates an indicator of the concern to environment in general in comparison to other concerns, which should be rather used to weight the environmental item among others. The environmental dimension is limited to deforestation and biodiversity by lack of data (although health is taken into account otherwise), but the other aspects not taken into account are not presented: it does not allow to see if some other important items have not been left out without apparent reason. In the same way, Lardé and Zuindeau (2008) do not justify the choice of 12 criteria they use for designing the environmental profiles of 21 countries. These criteria are measured either by source parameters (emissions), or by parameters illustrating the environmental policies. But the output, the country typology, depends without doubt on the criteria used. The 12 criteria are considered from their definition as equally important, whereas the statistical tools used discard the well correlated parameters. Thus, CO and $CO_2$ emissions, which are surely not well correlated, play the same role in the definition of environmental profiles, although CO is today considered as a very secondary pollutant and $CO_2$ as an essential pollutant, and without doubt the most important source parameter. It builds undoubtedly a typology, but we do not see easily of what. If most of the papers deal actually with environment, they deal quite never with "the" environment, concept never defined explicitly and precisely, globally: Some impacts or concerns are taken into account, others are not, without this choice being touched on and even less justified.

In the absence of precise definitions, and all the more of an agreement on a given definition, the assessment of the sustainability of a situation, a project or a policy, the evaluation *ex-ante* or the looking for the causes of an *ex-post*

evaluation lend themselves to any adjustment. Everybody interprets the concept, adapts it as widely than it remains sometimes only a vague expression without any meaning, and at worse is used only to justify his project or his policy. We saw for instance, among many other cases, the concept of "natural performance indicator" of a territory, based on the number, the surface or the diversity of the natural areas easily accessible by a resident of this territory. It is presented (Poulit, 2008) as a measurement of the environmental pillar of the sustainable development, whereas it is only a measurement of the access to the transport infrastructures. Is-it necessary to specify that this indicator is widely used by the car and transport infrastructure circles?

Even if the three pillars of sustainability are not independent, even if sustainable development should be seen not like a final state, but as a *process* (WCED, 1987), we have to define quite precisely a concept when it is used so widely than today. Otherwise, we could almost believe with George Orwell that "Political language is designed [...] to give an appearance of solidity to pure wind".

Having now illustrated the difficulties and risks associated with seeking to define environmental impacts via 'simplistic' sustainability dichotomies like 'future / present' or 'stock / flow', we proceed in the next section to consider systematic attempts to identify environmental impacts more independently of the notion of sustainability.

## 2.3.2. Environmental impacts considered

The environment is taken into account often through the consideration of impacts. Here, we look at the impacts listed in the scientific and technical literature and at their classifications. Subsequently, we look at the role of culture in taking into account environmental aspects, in order to relativize the outputs of the Western literature.

Environmental or ecological impacts are often described in the literature (USEPA, 1996; OECD, 1996; Swedish EPA, 1996; EC, 2001a; OECD, 2002; EEA, 2002; Borken, 2003; Ahvenharju *et al.*, 2004; Goger, 2006a or Goger and Joumard, 2007; Calderon *et al.*, 2009; Joumard and Nicolas, 2010), as in public surveys at national (Boy, 2007) or international level (EC, 2008): See some examples in Annex 4. Their definition is neither clear nor precise. The lists are often heterogeneous, merging sources, intermediate states of the environment as local air quality, water quality, and final impacts on the environment as visual effects. For instance, USEPA (1996) or Ahvenharju *et al.* (2004) list mainly the pressures or the first consequences of the transport system on the environment (designed as impacts) rather than environmental impacts. Beside some impacts quite always mentioned as climate change, photochemical pollution or noise, some others are rarely mentioned as soil erosion, vibration, light pollution, hydrologic and hydraulic risks, odours, soiling, or low visibility. Dimming, fire risk or electromagnetic pollution are not mentioned at all in the 13 references studied. Some impacts listed are very wide, merging several impacts on the environment, as air pollution or protection of soil and landscape. Some lists, as

this one of the European directive (EC, 2001a), list the final targets but some are redundant as biodiversity / fauna and flora, population / human health. Goger (2006a) or Goger and Joumard (2007) give the most precise list but only due to atmospheric pollutant emissions: In this field, impacts are distinguished when they are due to different chains of causalities, taking into account the fact that the impact categories shall together enable an encompassing assessment of relevant impacts, which are known today (completeness), but at the same time should have the least overlap as possible (independence).

**Table 8. Hierarchy of objectives in the environmental field according to Rousval (2005) or Rousval and Maurin (2008)**

Master the environment
    At global scale
        Preserve an environment in favour of the human life
            Limit the greenhouse effect
            Limit the climate change
            Protect the ozone layer
        Preserve the natural resources
            Limit the extinction of natural species
            Limit the extinction of natural environment
            Limit the energy consumptions
        Limit the maritime pollution
        Limit the production of non-recyclable waste
    At local scale
        Concerning the natural environment
            Limit the soil degeneration
            Protect fauna
            Protect flora
            Preserve landscapes
            Limit the excessive concreting
        Concerning the human environment
            Concerning the public health
                Limit the effects of air pollution
                    Of the pollution peaks
                    Of the background pollution
                Limit the effects of the hazards
            Limit the health impacts of noise
        Concerning the quality of life
            Limit the annoyance
                Due to noises
                Dues to fumes
                Dues to odours
            Improve the townscape
        Preserve the cultural legacy
        Respect the areas « villages »
        Preserve habitats from soiling

In addition, the content of each chain of causalities depends on the society where it takes place. Esoh Elame (2004) for instance shows how the values and

beliefs of the cultural heritage of given African peoples determine in a large extend the items of the nature they want to protect; In Black Africa, the natural capital can not be dissociated from the cultural capital: To speak about nature means to speak about culture and vice-versa. Similar relationships had been shown by Roqueplo (1988) or Brüggemeier (2002) in the case of forests and acid rains in Germany. More generally Lammel and Resche-Rigon (2007) show how the concept of environment itself differs between holistic societies as Totonaque, Inuit or Badui and individualist / analytic societies as the Western ones.

In Western countries at least, the environment is basically a personal construct, based on the personal perception of its issues, through our perception by our senses (sight, smell, etc), completed by intellectual elements coming from technical or scientific news we receive through the education system and the media (Brüggemeier, 2002; van Staëvel, 2006). This personal construction is then structured by a long-term view. Thus for 65 % of the French people, in the 21st century, technical progress will need to be subjected to sustainable development (Maresca and Hebel, 1999), i.e. transmitting to the future generations a viable environment and a nature not deserted.

A survey made for the European Commission of 26 730 EU citizens face to face at the end of 2007 gives an overview of the meaning of the term environment and on the main issues for the citizens (EC, 2008). The meaning of the term and the issues depend on the country and change with time. The citizens of the new member States seem less sensitive to climate change than those of old ones, but distinctly more sensitive to nature issues. The French are noticeable by the importance they give to the using up of natural resources and the agricultural pollution. Globally, Europeans are more and more concerned with the climate change, which is now the main environmental concern.

One of the most structured description of the environment consists of streamlining the problem through objectives as proposed by Keeney (1992). Rousval (2005) and Rousval and Maurin (2008) applied this method to the environment, and got a hierarchy of goals by interviewing a limited number of local decision makers and environment specialists: See the output Table 8. This list is nevertheless rather heterogeneous, merging final targets (fauna, flora), processes (greenhouse effect) and intermediate impacts (soil pollution). It has the main advantage, as the approach of Van Assche *et al*. (2008) or Block *et al*. (2007), to use a systemic approach, with a clear logic (geographical scale / main targets / impacts).

## 2.4. Chain of causalities from transport to environmental impact

Van Assche *et al*. (2008) or Block *et al*. (2007), before defining almost 200 indicators of a sustainable city for the Flemish urban areas, stress with reason on the need of defining firstly a matrix view for a sustainable and viable city, giving a normative framework for the indicator choice. They indicate afterwards

that each indicator has to be connected very clearly with an item of the matrix view, what they call the pertinence criterion.

The DPSIR-approach (see section 1.4) is a causal framework for describing the interactions between society and the environment: driving forces, pressures, states, impacts, responses (EEA, 2009a: See Figure 2 on page 40). It is a first and rough attempt to describe the chains of causalities leading to the impacts on the environment, through i) pressures (all the sources can not be described as pressures), ii) a state intermediate between a pressure and an impact (in some cases it is impossible to distinguish pressure and state or state and impact: e.g. impact on the landscape of an infrastructure), and iii) a unique state: in some cases, the chain of causalities between a source and a final impact on the environment is a succession of state-impacts, as for the impact of greenhouse effect. A parallel distinction is made within the Life cycle impact assessment (LCIA: see Goedkoop *et al*., 2009) between the midpoint level (such as acidification, climate change and ecotoxicity) and the endpoint level (such as damage to human health and damage to ecosystem quality). A further attempt to describe the interactions between society and the environment is made by Niemeijer and de Groot (2008) by introducing the concept of causal network: It considers multiple parallel chains leading from driving force indicators to pressure, state, impact and finally response indicators, and includes the inter-relations between the various causal chains. It is a description of the DPSIR system.

A clear distinction has to be made between impacts, issues or objectives, on the one hand, and indicators on the other hand. Impacts, issues or objectives are criteria to be considered, but, according to Chapter 1, "*an indicator is a variable, based on measurements, representing as accurately as possible and necessary a phenomenon of interest. An environmental impact indicator is a variable based on measurements, representing an impact of human activity on the environment, as accurately as possible and necessary*." Therefore an indicator is the tool for measuring an impact, for taking into account an issue or to measure how an objective is achieved.

The selection or the building of indicators measuring environmental criteria requires that each process, each chain of causalities from the source to each final impact on the environment is described in detail: in terms of sources, intermediate and final targets, mechanisms between intermediate sources and intermediate targets. Such description allows us also to express clearly what a potential indicator does measure and what it does not measure, and on which scientific mechanisms an indicator should be based. For instance the global warming potential evaluates the global temperature increase and not really the final impacts of greenhouse effect as sea level increase, the amount of fauna, flora and human habitat destruction, the food chain changes, etc. The knowledge of the physical mechanism of the climate and temperature modifications as a function of greenhouse gas emissions allowed to build the shape of the indicator 'global warming potential'.

At the same time, the description of the chains of causalities allows us to define rather precisely the term 'environment': What are the impacts on the

environment? What are the issues, what could be the objectives? What are their characteristics or typical features?

## 2.4.1. The concept of chain of causalities

With the aim to use a systemic approach to environmental issues, encompassing all the environmental impacts and all the potential objectives of an environmental policy, we propose to enlarge the pressure-state-impact structure or the midpoint / endpoint structure to the concept of process or chain of causalities between a cause and a final impact, with possibly a succession of coupled cause-impact. A good example is the greenhouse effect with greenhouse gas emissions (GHG) as a first cause, which by physical phenomenon increases the infrared radiative forcing, which increases the average earth temperature, which modifies the global and local climates, then with impacts on the agriculture, sea level, with final impacts on all the biocenosis including the humans. If an initial pressure can be easily detected (GHG emissions), there are afterwards a lot of intermediate states and impacts.

Another advantage of the concept of process or chain of causalities is to be much wider than a stock or flow problem inspired by physics: any process can be taken into account, as cultural, psychological, psycho-physical, biological effect, and of course physical.

The concept of chain of causality is one option to interpret the concept of 'environmental mechanism' defined within Life cycle impact assessment framework by a 'system of physical, chemical and biological processes for a given impact category, linking the life cycle inventory analysis results to category indicators and to category endpoints' (ISO 14040, 2006: see section 6.2.2.2).

The chains of causalities have to describe all the impacts on the environment, but at the same time to avoid redundancy: a same process should not be part of two chains. For instance, if we consider the chain "odours" or a chain "health effects of photochemical pollution" (chains resp. 9 and 13 described in Annex 6), we can not consider a chain "health effects of air pollution", because the well-being is part of health as defined by the WHO and because photochemical pollution is part of air pollution. It the reason why we defined a chain called "direct restricted effects on human health of air pollutants" (chain 11): "Direct" excludes secondary pollutants, and "restricted" excludes well-being.

A chain of causalities can be described through:

- The element(s) of a field of human activity (the transport system or any other sector), which is at the beginning of the process, taking into account a life cycle perspective, i.e. considering all the processes needed for the considered activity all over its life cycle. When considering only the environmental impacts of the system under study (and not the economic or social effects), life cycle assessment or LCA follows typically this approach. LCA is a process to evaluate the environmental burdens associated with a

product system or activity, by identifying and quantitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of those energy and material uses and releases to the environment. The assessment includes the entire life cycle of the product or activity, encompassing extracting and processing raw materials, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal, and all transport involved. LCA addresses environmental impacts of the system under study in the areas of ecological systems, human health and resource depletion (Fullana *et al*., 2009; see section 6.2.2).

Transport consists of three main subsystems, including infrastructure, energy used, and vehicle. For each of them there are five types of activities, including production, existence, use, maintenance, and destruction. All together, there are 13 subsystems-activities, as the use of the infrastructure, final energy and vehicle is considered common to the three subsystems (i.e. the traffic): See Table 9. The 13 subsystems can be simplified into four, as coloured in Table 9 and used in Annex 5, by considering the three main subsystems but extracting the traffic. These transport subsystems do not cover all the materials used as made within the Life cycle approach, but the main ones. Thus the elements in the table are not necessarily absolute or final in this form, but provide an overview of the main elements at the source of the impacts on the environment.

**Table 9. Typology of the main transport subsystems**

| Infra-structure | | Energy | | Vehicle | |
|---|---|---|---|---|---|
| | Building (1) | | Final electricity production (5) | | Production (9) |
| | Existence (2) | | Electricity distribution (6) | | Existence (10) |
| | Maintenance (3) | | Fuel production (7) | | Maintenance (11) |
| | Destruction (4) | | Fuel distribution (8) | | Destruction (12) |
| Traffic = infrastructure - final energy - vehicle use (13) | | | | | |

- The final targets: Goger (2006a) and Goger and Joumard (2007) consider three targets (nature, humans, man-made heritage) and a pseudo-target, the earth. In addition the Eco-indicator approach (Brand *et al*., 1998; Goedkoop and Spriemsma, 2001) includes three types of endpoint damages: resources, ecosystem quality, and human health. The two first are subdivisions of the target "nature". The (human) health is defined by World Health Organisation (WHO, 1946) as "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*". Therefore it is useful to distinguish health in a restricted meaning (absence of disease or infirmity) and the complement so-called human well-being, because the processes are often very different. Finally we get the target structure presented Table 10, with six targets: the resources, the

ecosystems (both together the nature), the human health in a restricted meaning, the human well-being (both together the humans or the human health as defined by WHO), the man-made heritage, and the earth.

- The in-between elements, i.e. the chain of causalities between the human activity (as the transport system) and the final targets, to be described in detail. To design impact indicators, it is important to know the scientific milieu able to understand the process, and therefore to give the scientific disciplines involved. We propose a first and simple science structure: physics, chemistry, biology, psychology / sociology. This structure corresponds to the general university scheme, where the environment issues are usually treated per discipline, in worlds coming close but ignoring each other most of the time: world of the physico-chemists (photochemical smog), world of atmosphere physicists (greenhouse), world of biologists (health impacts), world of engineers and energy specialists (emissions), world of psychologists (sensitive pollution, annoyance), limited world of sociologists or environment historians, etc. It is important also to know if the process is linear or not, and if the human activity characteristics are major or minor explanation parameters, in order to know how these characteristics can be used for indicator building. Finally the reversibility is a major parameter from the sustainability point of view (see section 2.2.5), where we have to distinguish the reversibility for individuals and for species: The accidents have irreversible impacts for the humans who die, but for the society it is a reversible impact. The distance and time scales indicate who is concerned, if it is a local or global, short, medium or long term impact.

**Table 10. Typology of the targets of the impacts on the environment**

| Targets | | | Pseudo-target |
|---|---|---|---|
| **Nature** | **Resources** | | **Earth**<br>Covers all the targets: the three previous targets (ecosystems, humans and man made heritage) and physical environments such as the atmosphere and the oceans |
| | **Ecosystems**<br>Nature understood as ecosystems, i.e. the association between a physicochemical and abiotic (the biotope) environment and a living community characteristic of the latter (the biocenosis) | | |
| **Humans**<br>Humankind which we extract from nature and focus on its health as defined by the WHO | **Human health**<br>In a restricted meaning | | |
| | **Human well-being** | | |
| **Man-made heritage**<br>With a distinction is made between common and historic buildings | | | |

The concept of chain of causalities allows us also to give a precise definition to the expressions 'environmental impact' or 'impact on the environment'. The environment is defined by the targets (Table 10): the humans, the nature and the man-made heritage. Any modification of these targets due to one of the transport subsystems presented Table 9 is an environmental impact due to transport.

A chain of causalities can thus be defined as an "homogeneous process between the transport system and a final target of the impacts on the environment".

## 2.4.2. Description of the chains of causalities

According to this structure, a typology of the chains of causalities of the environmental impacts (especially due to the transport system) is proposed in Annex 5. 31 aggregated chains are distinguished, and 49 when taking into account differentiation in the last steps of the process corresponding to different final targets. The chains are independent because there is no double counting (for instance the restricted health effects of air pollutants are split into those due to primary pollutants – chain 11 – and those due to secondary photochemical pollutants – chain 13). In addition the chains encompass all the relevant impacts found in the literature in section 2.3. The 49 chains are briefly described in Annex 6.

We extracted in Table 11 and Table 12 two examples of chain description, whose references are given in Annex 6.

**Table 11. Description of the chain 13 'Health effects of photochemical pollution'**

The pollutants originating the photochemical pollution are the non-methanic volatile organic compounds), the carbon monoxide and the nitrogen oxides. The production of the tropospheric ozone and of other photochemical pollutants (aldehydes, ketones, nitric acid, peroxyacetyl nitrate or results from a non-linear chemical process. In particular, the ratio of VOC and NOx concentrations determines the conditions of production of the photochemical pollutants. Beyond the production of tropospheric ozone, the most important secondary impacts to be taken into account concern first the living beings, then the buildings.

Because ozone is considered as the main indicator of the photochemical pollution, the toxicity of this pollutant for the humans is far to be the most studied. The oxidizing properties of this gas lead after a short term exposure to an inflammatory reaction, with the release of various pro-inflammatory transmitters, which can lead negative effects especially on eyes and lungs. The impacts on the felt morbidity, i.e. the declared symptoms by the subjects, are eye irritation and nasal and throat irritation, and the appearance, especially after effort, of thoracic discomfort, breathlessness, cough, or also pains after deep inspiration. Ozone decreases for the asthmatic the reactivity threshold to allergens to which he is sensitive, and therefore favours or makes the clinical expression of the disease worse.

## Table 12. Description of the chain 35 'Loss of ecosystem health and biodiversity, due to habitat fragmentation'

Fragmentation involves dividing up contiguous ecosystems (or landscape unit) into smaller areas called "patches". The ecosystem fragmentation affects the habitat conditions:
• Larger and heterogeneous patches can sustain more species than smaller and homogeneous ones.
• Patch isolation difficult interchange between individuals, and contributes to extinction of stabilized species. The connectivity, enabling energy and material fluxes, which are basic in the ecosystem, is lost.
• Reduction of the patches size produces a higher perimeter-area ratio. It increases the permeability of the patches to external disturbances.
• Transport infrastructures are barriers to energy and material fluxes and alter the resources of a habitat, compromising the viability of the species.

These effects have far-reaching consequences for species survival. In particular, for area-sensitive species, the patches of suitable habitat may be too small to support a breeding pair or a functional social group, whereas species with low dispersal capacity are unable to recolonize the habitat patches.

The description of the chains could be more detailed, by dividing a chain into two or more chains, if it is considered as not homogeneous in terms of process or targets. In addition some chains can be missing.

## Table 13. Hierarchy of the 49 chains of causalities

**Noise and vibrations**
. Noise:
. Disappearance of quiet areas (chain 1)
. Annoyance and sleep disturbance to people due to noise (chain 2)
. Effects on human health (restricted meaning) of noise (chain 3)
. Noise and wildlife (chain 4)
. Vibrations (chain 5)
**Accidents**
. Effect of traffic accidents on human health (chain 6)
. Animal collision: Animal fatalities (chain 7)
**Air pollution**
. Sensitive air pollution
. Odours (chain 8)
. Soiling (chain 9)
. Visibility (chain 10)
. Direct (restricted) toxicity of air pollutants
. Direct restricted effects on human health of air pollutants (chain 11)
. Direct ecotoxicity on fauna and flora of air pollutants (chain 12)
. Photochemical pollution
. Health effects of photochemical pollution (chain 13)
. Loss of crop productivity due to photochemical pollution (chain 14)
. Ecotoxicity on fauna and flora of photochemical pollution (chain 15)
. Loss of cultural heritage due to photochemical pollution (chain 16)
. (Secondary effects: greenhouse gas, acidification)

. Acidification
  . Decrease of ecosystem health, loss of biodiversity due to acidification (chain 17)
  . Deterioration of historical buildings and other cultural assets due to acidification (chain 18)
. Eutrophication (chain 19)
. Dimming (chain 20)
. Ozone depletion
  . Health effects of ozone depletion (chain 21)
  . Ecotoxicity on fauna and flora of stratospheric ozone depletion (chain 22)

**Soil and water pollution**
. Pollution of soil, surface waters and groundwater
  . Effects on ecosystem health of pollution of soil, surface waters and groundwater (chain 23)
  . Health effects of pollution of soil, surface waters and groundwater (chain 24)
  . Recreational areas forbidden due to pollution of soil and surface waters (chain 25)
. Maritime pollution
  . Effects on ecosystem health of maritime pollution (chain 26)
  . Health effects of maritime pollution (chain 27)
  . Recreational areas forbidden due to maritime pollution (chain 28)
. Hydraulic changes and risks
  . Hydraulic changes (chain 29)
  . Hydraulic risk (chain 30)

**Impacts on land**
. Land take
  . Loss of natural habitats due to land take (chain 31)
  . Degradation of ecosystems due to land take (chain 32)
  . Modification of outdoor recreation areas, due to land take (chain 33)
  . Loss of cultural heritage due to land take (chain 34)
. Habitat fragmentation
  . Loss of ecosystem health, loss of biodiversity, due to habitat fragmentation (chain 35)
  . Reduction of living areas of people, due to fragmentation (chain 36)
. Soil erosion (chain 37)
. Visual qualities of landscape / townscape (chain 38)

**Non-renewable resource use and waste handling**
. Non-renewable resource use (chain 39)
. Non-recyclable waste (chain 40)
. Direct waste from vehicles (chain 41)

**Greenhouse effect** (chain 42)

**Other impacts**
. Electromagnetic pollution
  . Health effects of electromagnetic pollution (chain 43)
  . Effects on ecosystem health of electromagnetic pollution (chain 44)
. Light pollution (chain 45)
. Introduction of invasive alien species (chain 46)
. Introduction of illnesses (chain 47)
. Fire risk (chain 48)
. Technological hazards (chain 49)

## 2.4.3. Tentative aggregation of the chains of causalities

A first attempt to build a typology of the 49 chains of causalities is given Table 13, with the same type of output as Table 8 on page 65. The 49 chains are merged firstly into 27 aggregated chains, and then into 8 groups. This typology corresponds mainly to usual structures and allows a simpler presentation of the whole structure.

The aggregation of chains of causalities is conceivable. It could be useful in order to design impact indicators, for instance when the scientific knowledge necessary to build indicators of different impacts is similar and if the main characteristics of the corresponding chains are also similar. As, to be practical, the number of categories should amount to a not too high number, and considering the importance of each impact and the availability of indicators, some impacts could be merged, or chains considered as minor could be deleted. Because it is important to give the possibility to further users to perform such simplifications, the chain structure has to be as detailed as possible: It is easier to merge and delete than to add processes.

Another possible aggregation of the chains of causalities could correspond to the global or top-down descriptions of the environment pillar of sustainable development seen in chapter 2.3.1. These ones belong finally to two types:

- According to the axis life environment / natural resource, with two main sub-categories:
  A1 The well-being, the quality of life
  A2 the resources needed for life, the natural heritage, and the conditions of a long term development

- According to the axis present / future generations, with two main sub-categories:
  B1 Present generations
  B2 Future generations

When classifying our 49 chains of causalities according to A1/A2 or according to B1/B2, some chains cannot be differentiated according to such binary classification, belonging to both classes: for instance, most of the impacts on the ecosystems belong to the four subcategories, and the impacts on cultural heritage concern present and future generations. In the same manner, most of the 27 aggregated chains are aggregating detailed chains belonging to both categories. Therefore it is evident that these global classifications are not pertinent, because they cannot be used for characterizing some chains of causalities. The reality is really more complex than the globalising approaches.

**Figure 5. Order of magnitude of distance and time scales of the 49 chains of causalities, by increasing order of scale**
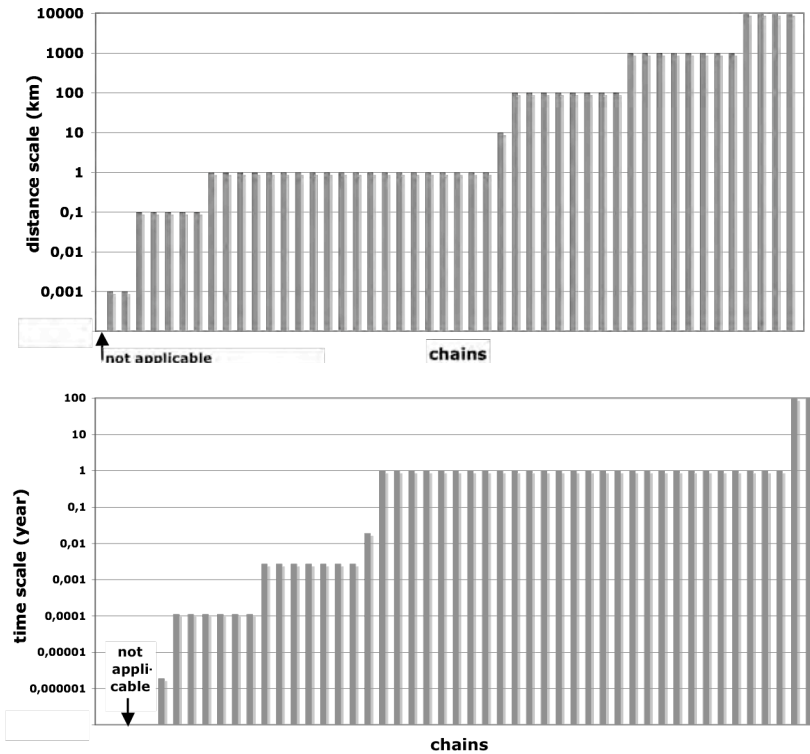


The chains of causalities can also be described according to their local or global character, or according to their time scale (short / long term), quite close to the reversible character (reversible / irreversible). But here again, as it can be seen Figure 5, these axes are rather continuous. Thus, the geographical scale goes from the very local (some hundred of meters for the odours) to the global level (the whole earth for the greenhouse effect), but with intermediate scales as for the photochemical pollution (a thousand of kilometres). We have the same picture for the time scale: Between the very short term (an hour for the odours or the hypoxic effect of carbon monoxide) and the very long term (some thousands of years for the impacts of some nuclear waste), we have impacts with middle time scales as the photochemical pollution (a day), the soiling or hydraulic risks (a year), etc. If we consider the irreversible character for the society, i.e. the definitive modification of our life conditions on the earth, here again the dichotomy reversible / irreversible is only apparent: Several chains of causalities, and not the least ones, are neither totally reversible nor totally irreversible. Thus the greenhouse effect is well reversible, but only after some centuries: It is totally reversible at the cosmic scale, but irreversible at the human scale.

# 2.5. Discussion

The aim of this chapter was to define what "environmental sustainability in transport" may mean for the use of indicators. Transport is defined as a system, consisting of fixed facilities, flow entities, energy carriers, and control units that permit people and goods to overcome the friction of geographical space. To fully consider the environmental impacts of the transport system or sub-systems, a life cycle perspective is necessary. However, this system is not independent from other systems such as land use, agriculture, leisure or more generally the production and consumption systems. It interacts with all other elements of the society and of the ecosystem. Hence a full disclosure of environmental impacts of transport always depends on drawing some system boundary.

The concept of sustainable development can be understood as an attempt to prescribe conditions for proper interactions within the society and not least between society and the ecosystem. The different concepts of sustainable development assume different degrees of substitutability between all the dimensions or 'pillars' of sustainable development. To discuss the interactions between the dimensions asks for a clear definition of each one, not least the environmental one. At the same time, 'sustainable' often refers to other dimensions and especially the long term.

"Environmental sustainability in transport" must therefore imply at least the taking into account of the impacts on the environment of the transport system within the concept of sustainable development, meaning that environmental impacts of transport system are looked at in a way that is comprehensive, adopts a life cycle perspective, and includes a long term perspective, and must be addressed together with a concern for the social, economic and other dimensions of sustainable development as well.

To describe the environmental impacts of an activity such as transport through a complete list of independent chains of causalities allows us therefore to give a precise definition of the term 'environment', while placing transport in the wider context of sustainable development and linkages to other systems, allows us to connect this definition to its full context. In the literature, the differences in the impacts considered translate often the research area of the author, and, when the work is more global, the local perception of the environmental or ecological issue. For instance the loss of visibility above the cities, due to air pollution, is often cited in North America, but never in Europe, although the physical situations are similar. It is especially important to define the term environment, because today the environmental issue is widely taken into account from local to international scale, but often without a precise knowledge of this field: In this case the environmental issue is very often reduced to greenhouse gases or to few well known impacts, or are reduced unconsciously to impacts for which simple to use assessment tools are available.

Environmental impacts, environmental issues, environmental objectives are not equivalent expressions. The chains of causalities we have defined and described deal clearly with environmental impacts. Following Keeney (1992),

environmental objectives are characterized by three features: a decision context (who does decide, what to decide?), an object (an environmental impact or an aggregation of impacts), and a direction of preference (decrease the environmental impact). Nevertheless, as shown by Rousval (2005) (see Table 8 on page 65), the environmental objectives can be quite easily linked to environmental issues, and then to environmental impacts, or to aggregations of impacts or of chains of causalities. A typology of chains of causalities can therefore be used as a basis to describe environmental issues and environmental objectives. However, in most of the cases, the list of chains of causalities we propose here is much too detailed to be used in a decision context: The chains have to be aggregated, or some of them have to be chosen and others left aside. The knowledge of a comprehensive list allows to aggregate and choose with full knowledge of the facts. It is also a comprehensive basis to study the social perception of the environmental issue by survey, whom outputs can be used to balance the quality of local air, of regional air, noise, greenhouse effect… according to the focus placed on each of these impacts, as made for instance by the Personal Security Index designed by the Canadian Council on Social Development (Tsoukalas and MacKenzie, 2003).

The framework of the chains of causalities should be an universally valid analytical framework. It is surely not the case, because some generally marginal but possibly locally important impacts can be forgotten and should be added. In concrete assessment situations, this overarching concept can be adapted by leaving explicitly some impacts out, for instance because they are not pertinent or by lack of data: The most important is to do that explicitly. The main limit of the framework is cultural: it is certainly adapted to Western societies, but could be not adapted to Eastern, African or other societies, where the concept itself of environment can be fundamentally different or does not exist in this shape.

Possibly the frame of chains of causalities presented here is quite arbitrary in the level of detail or aggregation for chains. For example, the chain 'Direct ecotoxicity on fauna and flora of air pollutants" could cover a chain for flora and a chain for fauna, because flora and fauna could have completely different behaviour. It could be also the case for the chain 'direct restricted effects on human health of air pollutants', where the carcinogenic effects, mutagenic ones, the effects on the reproduction etc. could be differentiated. Therefore the list of chains should not be considered as a definitive one, but more as a first attempt to exemplify the concept of chain.

To make chains of causalities more applicable for practical transport assessments, it is useful to deepen the descriptions of the chains, and also to identify more specifically how the intermediate impacts (pressures, etc) depend on individual and combined variables or decision parameters of the transport systems (such as transport volumes, vehicle speeds, transport supply, fuel prices etc). Disaggregate descriptions can provide more guidance for the selection of appropriate indicators in practical applications. Such disaggregation is nevertheless quite out of the scope of this report and is anyway made elsewhere (for instance in the research field on sources).

The chain of causality approach does not deal with interactions between chains although in practice interaction could occur. For instance, we know that all the psycho-physical impacts are not independent (between impacts due to odours, noise, landscape quality etc.). More generally, the processes leading to the different impacts but on a same final target (the humans, or the ecosystems) react each other. Nevertheless to consider 'independent' chains is a first step before describing more in depth the possible synergies.

The social context plays therefore a role in the construction of the framework of the chains of causalities. This context is also especially important when taking into account the three pillars of the sustainable development. What is our concern to environment in comparison to the social or economic issue? Public inquiries or inquiries specific to a given circle allow to answer such questions, but the meaning of each pillar has to be clear: The detailed description of the environmental chains of causalities should be of some help, possibly after aggregation or simplification, to make explicit the meaning of the environmental pillar.

The precise description of the environmental processes constitutes then a powerful tool for indicator assessment, similar to but more completed than that done by USEPA (1996). *A priori*, it can be stated that the nearer to the final target the indicator is, the more precise the final impact is estimated. It is mainly a tool to define what precisely an indicator does represent: Does it represent the final impact, or an intermediate one? How accurately is the process translated into the indicator function? Which relevant impacts are not taken into account by existing indicators? Isn't it possible double counting? When the business is not only, in the name of the pragmatism, to reorganise already existing information, but to build the tools necessary to measure really the environmental impacts, the encompassed description of the impacts is the first step of the process. When the aim is to design new indicators for instance of environmentally sustainable transport, the knowledge of the process indicates which scientists should be asked about the best way to represent the impact.

# 3. The dimensions and context of transport decision making

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Chapter 3 aims at shedding light at two important aspects of environmentally sustainable transport policy, plan, programme and project (PPPP) decision making, namely (a) the different dimensions of transport decision making, and (b) the overall context within which transport decision making is happening. The hypothesis underlying this chapter is that a good understanding of these two aspects can support the choice of environmental indicators in transport PPPP making. An analytical rather than descriptive approach is taken (see e.g. Cobb and Rixford, 1998) and recommendations are given on how the transport decision making situation might help to prescribe the choice of specific environmental indicators.

Whilst this chapter is based on the assumption that it may be possible to identify indicators that are suitable for use in specific decision making situations, the authors acknowledge that certain indicators may be collected and reported on more continuously over years at different administrative levels (e.g. national, regional and local), and across PPPPs. Performance documents that, for example, report on the conditions of the road network and sustainability indicator reports may have this character. These continuous indicator systems may actually lead to fewer conflicts over facts and values in a specific decision making situation than might be the case otherwise. As a consequence, at times, knowledge may be in existence before a specific decision making situation is discussed. This means that indicators may contribute to structuring knowledge for a decision making situation, rather than being the outcome of that situation.

The chapter is divided into five parts. Firstly, processes, conflicts and the importance of the decision making context for transport policy, plan, programme and project making are discussed. Secondly, some basic models are introduced that can be used to explain how decision making works. Thirdly, the potential role of indicators in supporting environmental sustainable transport PPPP making is elaborated on. This section makes a link between the more conceptual sections 3.1 and 3.2 and the empirical evidence for indicator selection and usage, provided in section 3.3. The evidence presented in section 3.4 is based on a survey of European practitioners on the requirements of environmentally sustainable transport indicators from the planning and decision making point of view. Finally, section 3.5 provides for some overall conclusions and recommendations.

Whilst the focus in this chapter is on decision making processes by public administrations, it is important to acknowledge that transport decisions are also made by other actors, not least individuals. These include e.g. the users of transport means, who may look at standardized fuel consumption or $CO_2$ emissions; This is similar to the way energy levels (A++ to F) are calculated for a lot of many domestic appliances, providing the potential consumer with an idea of their environmental impacts.

Furthermore, an indicator is also a way to synthetize knowledge. Therefore, it can be used by anyone who is interested, for example schoolchildren, students, newspaper readers, journalists, scientists, consultants, policy makers. A good example for a popular indicator, used by a wide range of people is the ecological footprint, which represents a simple and easily understandable approach, which has a concrete meaning, not just for experts, but also for lay persons .

# 3.1. Transport policy, plan, programme and project making – the importance of the decision making context

In democratic societies, transport policy, plan, programme and project (PPPP) making is often normally happening within the context of publicly accountable decision making processes. These are political activities, which can be portrayed as (Daft, 1992, p. 403):

> *"process[es] of bargaining and negotiation that [...are] used to overcome conflicts and differences of opinion"*

As a consequence, these processes are usually highly complex and often marked by controversy. Complexity is enhanced by issues of multi-layer governance, with transport decisions normally affecting different administrative levels (e.g. national, regional, local), systematic tiers (i.e. policy, plan, programme, project - PPPP) as well as sectors (e.g. transport, land use, energy). Here, a policy is understood to represent a long-term course of direction (why and what), a plan a medium term course of spatial action (where), and a programme a medium to short term course of temporal action (how and when)[1]. Transport policies that explicitly include an assessment of various impacts mainly date back to the 1990s, where this approach had been widely used in certain countries. More recent policies, particularly those prepared after 2000 do not tend to explicitly include an assessment of effects. Assessment inclusive policies include e.g. the city of Hamburg transport vision from 1995, in which effects of 16 pricing / administrative measures, 14 infrastructure development measures and 10 organisational measures were assessed on overall transport volumes (Fischer, 2006). Another example

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[1] Note that the terms 'policies', 'plans' and 'programmes' are provided with a specific meaning here. In practice, these terms are often used more loosely, and as a consequence what may fall into eg the 'plan' category here may in fact be called a 'programme'.

includes the Dutch national Transport Infrastructure 'Plan' of 1989 in which policy measures for reducing anticipated transport growth were assessed (taking into account e.g. taxes and parking management). Transport plans include e.g. the 'North-East Triangle' road infrastructure improvement study from 1995 for the area between Hamburg, Hannover and Berlin (Fischer, 2006), in which a comprehensive assessment of various spatial options in terms of economic, social and environmental criteria was provided. Transport programmes include e.g. the local transport plans in the UK (Fischer, 2006). A further explanation of what constitutes to the different tiers is provided in section 4.3. Here the policy tier will also be referred to as the 'strategic' tier, the plan tier as the 'tactical' tier and the programme and project tier as the 'operational' tier. In addition, decisions frequently have multi-modal implications, requiring co-operation and co-ordination of activities of different administrations, agencies and authorities.

Due to the high degree of complexity, in order for transport PPPPs to stand a chance of subsequent implementation – which may occur in different ways[2] - communication and participation in decision making processes is of crucial importance. Furthermore, within this context, in the interest of environmentally sustainable outcomes, the existence of formal, commonly agreed upon objectives is crucial, providing for normative and prescriptive guidance. However, as in practice, different economic, social and environmental objectives are frequently not entirely compatible, processes need to be conducted in a way that make ensuing conflicts transparent and that allow to identify best possible environmentally sustainable solutions.

Conflicts in transport PPPP making are the main reason for why in practice decision making processes do not frequently end up being as clearly structured within distinct steps as initially planned (see e.g. Dalkmann and Bongardt, 2004). However, this does not suggest they are entirely unstructured and random. Rather, processes are directed by legislation and guidelines in e.g. development consent procedures. Examples are environmental assessment (EA) type processes. These consist of several distinct stages (see e.g. Gazzola and Fischer, 2008). It is now commonly accepted that there may be numerous feedback loops and that the process may have iterative elements.

Whilst conflicts arise in basically all transport PPPP making situations, they tend to be particularly pronounced in situations of (following Daft, 1992):
1   structural change (e.g. at times of innovation or crisis);
2   extensive inter-departmental / inter-authority coordination requirements;

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[2] Wallagh's (1988, p. 122-123 in Faludi, 2000, p. 310), for example suggested that effective policy implementation may take the following forms:
- an operational decision conforms to the policy and explicit reference is being made to it, demonstrating that conformance has not been accidental;
- arguments are being derived from the policy for taking non-conforming decisions, ie departures are deliberate;
- the policy provides the basis for analysing consequences of an incidental decision which happens to contravene the policy, thus bringing that decision under the umbrella of the policy;
- if and when departures become too frequent and the policy must be reviewed, the original policy may still be said to have worked for as long as the review takes that policy as its point of departure.

3 involvement of different management bodies / management succession; and

4 concrete resource allocation to different institutions / bodies.

It is important that in situations where consensus on norms and values is greater, arising conflicts may be less pronounced. Processes may therefore end up being more structured than in situations where consensus is low (see e.g. Hilden *et al*., 2004; Lehtonen, 2009). Resulting decision processes may therefore be of a more rational nature, e.g. when deciding on how to proceed with infrastructure maintenance.

Figure 6 provides for a visual representation of these relationships, also looking at the extent to which there is consensus on knowledge. The ensuing 'structuredness' of the issues to be addressed in PPPP making can be used as the basis for identifying acting strategies for managers of PPPP processes. The hypothesis is that this can also be used to support the choice of appropriate environmental indicators.

For example, in a situation where consensus on values and knowledge is high, the PPPP maker (or 'manager') may act as a problem solver, as opposed to only functioning as a problem recogniser. The latter may need to be necessary when consensus on both, values and knowledge is low. 'In-between' acting strategies include advocacy and mediation (see Figure 6).

**Figure 6. The 'structuredness' of different types of transport decision making and associated acting strategies**

**Types of policy problems**

**+      Consensus on knowledge      -**

| Consensus on values | | |
|---|---|
| + | *structured problem* <br><br> *road maintenance* <br> **Problem Solver** | *moderately structured (consensus of goals) problem* <br> *particulate matter* <br> **Advocate** |
| − | *moderately structured (consensus on means) problem* <br> *abortion, euthanasia* <br> **Mediator** | *unstructured problem* <br><br> *climate change* <br> **Problem recogniser** |
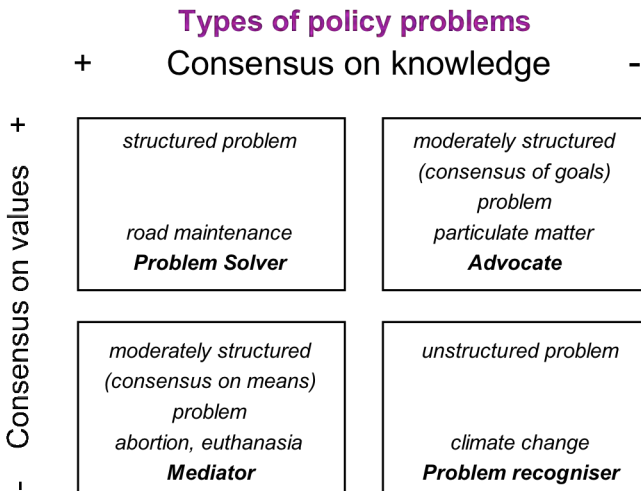
Source: Runhaar and Driessen, 2007; de Ridder and Petersen, 2008

Similar suggestions have also been made in the environmental assessment literature, in what has been referred to as the establishment of a 'communication based acting strategy' for different assumed tiers of strategic decision making (see Figure 7, following Fischer, 2003). Here, what is described in Figure 6 as a 'problem solver' for structured problems is translated

into a 'technician' in a programme situation. Furthermore, a problem recogniser is described here as an advocate in situations of moderately structured problems where there's consensus on goals. Finally, a mediator in a policy situation can be related to the problem recogniser in totally unstructured or moderately structured problem situations where there's no consensus on values.

Ultimately, these acting strategies can be connected with the contingency model of organisational decision making, as first developed by Thompson and Tuden (1959). This is further elaborated on in the next section on how decision making works. Here, decision making models were charted in terms of means and ends uncertainty (uncertainty about how and why to take a course of action). As a consequence of the observed levels of uncertainty, they made suggestions for how organisations may want to act, ranging from computation over judgement / bargaining to inspiration.

**Figure 7. Identifying a communication based acting strategy for Strategic Environmental Assessment**
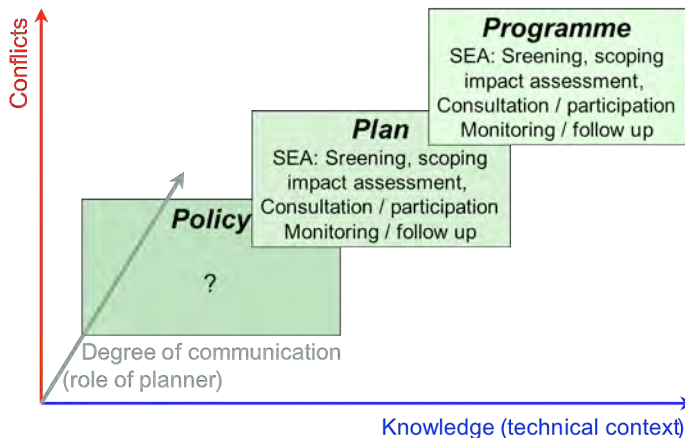


Source: Fischer, 2003

Finally, very similar suggestions were also made in the environmental indicator literature. Lehtonen (2009), referring to the energy sector, connected the purpose of indicators with the stage of policy making. For the first three policy stages (i.e. at the strategic levels 'emergence of the problem', 'legitimisation' and 'mobilisation of the public for action'), he suggested that the role of indicators would be of a discursive nature. At the following two (tactical and operational) stages 'formation of an official plan of action' and 'implementation of the plan', he suggests that whether the role of indicators is more of an instrumental / rational or 'political' nature depends on whether there is overall consensus (the former) or controversy (the latter).

In the context of this report, understanding the specific requirements of various transport PPPP making processes is suggested to be crucial for being able to 'design a harmonised set of methods for the construction of enhanced and optimised environmental indicators'.

# 3.2. How does decision making work?

Section 3.1 focused on various aspects of transport PPPP making, revolving around its processes and arising conflicts. The specific decision making situation was said to potentially give raise to certain acting strategies, which in turn was said to potentially enable identification of situation specific indicators.

This section provides for some theoretical underpinnings of different decision making situations. In this context, the focus is on a few basic decision making models that can help to explain why and how a specific situation (as outlined in the previous section) may arise. Models introduced include the rational model, the bounded rational model and the garbage-can model of decision making (following Posas and Fischer, 2008). In addition to these three basic models that are able to explain the acting strategy identified in section 3.1, political aspects of decision making are also discussed, referring to the political or coalition approach to decision making. Finally, reflecting on the recent mainstream planning debates (see e.g. Elling, 2008) communicative planning theory is also outlined.

## 3.2.1. Rational model of decision making

In the rational model, decision making is a rational, linear process, which will produce rational outcomes. It is used to explain microeconomic behaviour and is the accepted model in many disciplines up to the present. The steps in rational decision making (which are similar to the stages of the traditional 'policy cycle'; see Figure 9 on page 90) can be described as follows (Brooks, 2003, p. 36):
  1  identifying a problem that requires a decision;
  2  gathering information and materials that will help solve that problem;
  3  generating potential solutions to the problem; and
  4  making a rational choice, selecting the best solution, and then implementing it.

This is a logical normative model, and the main difficulties with it lie not with the model's process, but rather with its underlying assumptions. Thus, the model implies that a person will:

> *"always make a rational decision based on the ability to evaluate all the alternatives and effectively calculate the potential success of each alternative (Brooks, 2003, p. 36)."*

In addition, it suggests that the decision is being made in a stable, slow-moving environment and that the decision maker has ample of time to gather all the information, reflect on all the alternatives, and reach a rational solution. This implies that there would also be ample of space and time to identify appropriate indicators that may be used at the different stages of the policy cycle. The main function of indicators (see section 1.2) would therefore be to inform decision making. Indicators therefore fulfil an important role and can potentially effectively influence outcomes. In practice, routine decisions where consent on norms and values is high and uncertainties are low may nearly follow this

rational process (Butler, 1991). However, many decisions, particularly at higher tiers (see Figure 6 and Figure 7) face more pressures and unknowns than this model's assumptions allow for.

## 3.2.2. Bounded rational model

In 1959, Simon introduced the concept of bounded rationality to address the rational model's potential weaknesses and incongruence with many decision making contexts, which are not benefiting from unlimited time and perfect information, i.e. referring to Figure 6 and Figure 7, decisions at higher tiers that are marked by greater uncertainty and less consensus on norms and values.

Bounded rationality is not based on an alternative concrete normative process, similarly to a rational process. Rather, it suggests that a rational process does not realistically describe real decision making in many situations. However, there have been attempts to model bounded rationality. These models are at time highly complex (e.g. computer models). Rubinstein (1998) proposed to model bounded rationality by explicitly specifying decision-making procedures. These vary, depending on the specific context of application.

The bounded rational model has been shown to be much more consistent with the way e.g. managers of enterprises behave (Brooks, 2003), in that they are faced by time pressure and imperfect information which causes them to find a solution that will 'satisfy' rather than what might have been the best one. While the rational model can be said to still have some relevance for more routine decisions (i.e. referring to Figure 6, decisions with a high consensus on values and knowledge), the bounded rational model is more appropriate for unfamiliar, non-routine, and potentially contentious issues (Butler, 1991). Its six explicit assumptions are listed in Table 14. Here, indicators would be identified on an ad-hoc basis, depending on how the decision process pans out, probably with no direct link to specific goals and targets. Whether certain indicators could be consistently used is rather questionable.

**Table 14. Features accepted in the bounded rational model**

- Managers respond to problems rather than going out of their way to find them.
- Cognitive limits exist in the search process (human mind is limited in comprehension of problem).
- Time pressures frequently apply (decisions have to be made with incomplete information).
- Disjointed and incremental decision making often occurs, not a smooth continuous rational process.
- Intuition and judgment may have to be the basis for making a decision rather than computation.
- Satisfying (satisfactory and 'will do') solutions rather than optimal solutions are arrived at.

Source: adapted from Butler (1991, p. 47)

## 3.2.3. Garbage can model

Cohen, March and Olsen's (1972) 'garbage can model' is different from the two rationality based models just discussed, in that it is not a sequence of steps that start with a problem and end in a solution. Rather than steps, this model proposes four independent streams (problems, solutions, participants, and choice opportunities). An organisation acts as a 'garbage can' in which these streams flow. A decision will be made when problems and solutions can be connected during a time when there are choice 'opportunities' (to be made by individuals). This model is more random and likely to be relevant to organisations operating in a volatile business environment (Brooks, 2003). Butler (1991) notes that organisations following this model exhibit several features, including:
−  ambiguity in the decision process;
−  difficult to determine cause and effect relationships; and
−  fluid participation (i.e. turnover of participants).

While not particularly efficient in organisations (Butler, 1991), the garbage can model can represent an apt description of public policy making (Kingdon, 1995), convergence of problem, policy, and politics. In this context, indicators are likely to mainly fulfil a generic measurement function (see section 1.2.1). To what extent indicators can fulfil an effective role is rather questionable.

## 3.2.4. Political or coalition approach to decision making

Whilst the three basic decision making models introduced above underpin the various possible PPPP making situations introduced in section 3.1, this paragraph briefly deals with what has been described as the political or coalition approach to decision making. This may provide for a useful additional explanation for how transport PPPP making may happen. It also hints at the necessity to be cautious when approaching transport PPPP making in an overly rational way. Subsequently, three related models are introduced; (a) the political or coalition model; (b) the contingency model and (c) the contingent institutional model.

(a) The political or coalition model of organisational decision making was put forward by Cyert and March in 1963. In it, the process of organisational decision making is portrayed as

> *"involving shifting coalitions of interests and temporary alliances of decision makers who can, for the purposes of a decision, come together and sufficiently submerge their differences to make a decision" (Butler, 1991, p. 51).*

A coalition may be formed for just one decision, though some quid pro quo and bargaining is likely to be involved. This kind of decision making has been known to occur in government contexts.

**Figure 8. Contingency model of organisational decision making**

Means uncertainty

| | |
|---|---|
| **Computation**<br>rational<br>*crisp* | **Judgement**<br>bounded rational<br>*fuzzier* |
| **Bargaining**<br>coalition<br>*fuzzier* | **Inspiration**<br>garbage can<br>*fuzziest* |
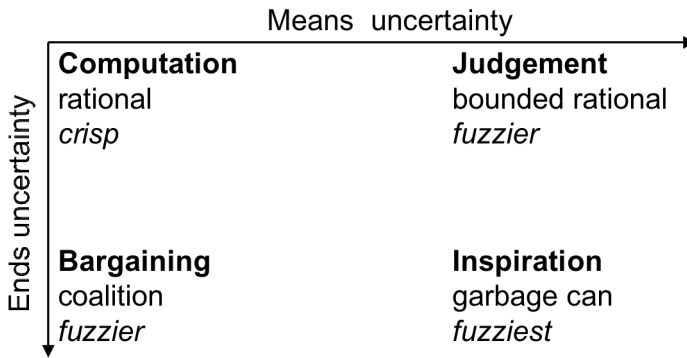
Ends uncertainty

Source: Butler (1991, p. 59), adapted from Thompson and Tuden (1959)

(b) The contingency model of organisational decision making, developed by Thompson and Tuden (1959), charts the decision making models in terms of means and ends uncertainty (uncertainty about how and why to take a course of action). It positions the three theoretical models discussed above in relation to one another, and adds a 'coalition' dimension. Furthermore, it suggests the type of organisational context for which they might be appropriate (Figure 8). Here, ends uncertainty can be seen as being equivalent with certainty on values and means uncertainty with certainty of methods. This complements the suggestions coming out of Figure 6 and Figure 7. This model can be connected with those introduced in section 3.1 regarding a communication based acting strategy for different decision tiers.

(c) In the third model, the contingent institutional model of organisation, Butler (1991) links the institutional model of organisation (consisting of context, structure and ideology) to the decision models. He sees decisions in terms of their interactions with the areas of context, structure, and ideology in a given organisational context. The variables associated with each aspect are shown in Table 15.

**Table 15. Variables associated with three aspects of organisation**

| **Fuzzy v Crisp** | **Complex v Simple** | **Robust v Focused** |
|---|---|---|
| Implicit v Formal<br>Expert v Local<br>Differentiated v Demarcated<br>Interactive v Parametric<br>Active v Analytic<br>Collective v Individualistic<br>Decentralized v Centralized<br>Supportive v Punitive<br>Symbolic v Literal | Unique v Comparable<br>Open v Concentrated<br>Ambiguous v Clear<br>Variable v Stable<br>Disparate v Agreed<br>Heterogeneous v Homogeneous<br>Independent v Autonomous | Plural v Singular<br>Tolerant v Particular<br>Moral v Efficiency |

Source: Butler (1991, p. 255)

While the exact meaning of some of these terms may not be apparent without further reading, they suffice to illustrate Butler's observation that there is a constant tension between these dialectical aspects in an organisation. These variables also fuel a tension between inner loop learning (pushing an organisation towards efficiency) and outer loop learning (which helps it adapt). In this context, Butler (1991, p. 255) explains that the

> *"phenomenon appears in organizations when short term expediency leads organizations to tighten up structures, with apparent immediate return achieved through greater efficiency, centralization, and the like, but leads the organization into a vicious circle of decline as the ability to adapt to future exigencies decreases."*

In crisp decision making situations, indicators are likely to fulfil a decision making function, informing actors on the best outcomes. The fuzzier a decision making situation the more likely the role of indicators will be limited to generic measurement.

# 3.2.5. Communicative planning

Since about the mid 1990s, communicative planning has been widely promoted as the way to reach decisions in societies that are increasingly marked by fragmentation and individual lifestyles (see e.g. Healey, 1996; Innes, 1998). In this context, societal problems were said to have become too complex to be solely managed by the 'classical' model of representative democracy (Innes, 1995). Based on observations that planners are not often able 'to deliver unbiased, professional advice and analysis to elected officials and the public, who in turn make the decisions' (Innes, 1998), but instead spend a lot of their time communicating with various stakeholders and actors, communicative planning is widely seen as an alternative approach to the rational model, introduced in section 3.2.1. In communicative planning, the function of indicators is likely to be reduced to generic measurement for informing actors, rather than for making decisions.

The concept is based on Habermas' notion of communicative rationality, arguing that people inevitably searches for and accepts rational arguments in open and fair debates. The ensuing idea is that policy, plan and programme making should develop as an arena for conversation among equals in what has been called an 'ideal speech situation' which, in turn, should lead to consensus decisions. Several principles underlie the concept of communicative rationality. These are shown in Table 16.

Whilst communicative rationality is likely to be able provide some good guidance in unstructured or fuzzy situations, it is doubtful whether it is equally useful in situations, which are structured and crisp (see Figure 6 and Figure 8).

In this context, the underlying assumption that communicative spaces could be created that are free of power has been criticised as being unrealistic in many decision making situations (Tewdwr-Jones and Allmendinger, 1998).

**Table 16. Principles of communicative rationality as a process
of deliberation**

- − Individuals representing all important interests must be at the table
- − All the stakeholders must be fully and equally informed and able to represent their interests
- − All must be equally empowered in the discussion
- − Power differences from other contexts must not influence who can speak or who is listened to
- − The discussion must be carried out in terms of good reasons, so that the power of a good argument is the important dynamic
- − The discussion must allow all claims and assumptions to be questioned
- − Within the process, it must be possible for participants to assess the speakers' claims in terms of four tests
  - • Speakers must speak sincerely and honestly
  - • They must be in a legitimate position to say what they do, with credentials or experience to back them up
  - • They must speak comprehensively (jargon and technical language communicates poorly)
  - • They must be factually accurate
- − The group should seek consensus

# 3.3. Towards the development of a situation-driven approach for the selection of indicators

Following on from what was said in section 3.1, this section discusses how different decision making situations may be categorised further and explores the possible implications on the use of indicators. It is suggested that indicators' selection may, at least in parts, be situation driven, and that a range of variables may constitute to a specific decision making situation. In order to demonstrate that different decision making situations may require different kinds of indicators, requirements along the strategic – tactical – operational dimensions of decision making are discussed and exemplified.

Niemeijer (2002) called the use of criteria for selecting indicators the theory-driven approach. He contrasted this with a data-driven approach, which applies when the selection of indicators is based on data availability. A third approach was described by Lehtonen (2009; see also section 3.1) who suggested that there is also a politically-driven approach wherein indicator selection is motivated by politics and legal requirements.

In this section, a fourth approach is developed, following on from what was discussed in the previous section. This may be called 'the situation-driven approach' which is based on the hypothesis that indicators are used (or not used), depending upon the nature of the decision-making situation. If this was true, a decision maker could take advantage of the knowledge about a situation for selecting indicators. For example, if the situation was a bike path or transport

corridor plan situation, the decision-maker would potentially be able to select indicators, or narrow down the set of choices, based on this simple situational information. Therefore, the situation-driven approach says that indicator selection criteria are a function of the decision making situation.

**Figure 9. Some dimensions characterising decision making situations**
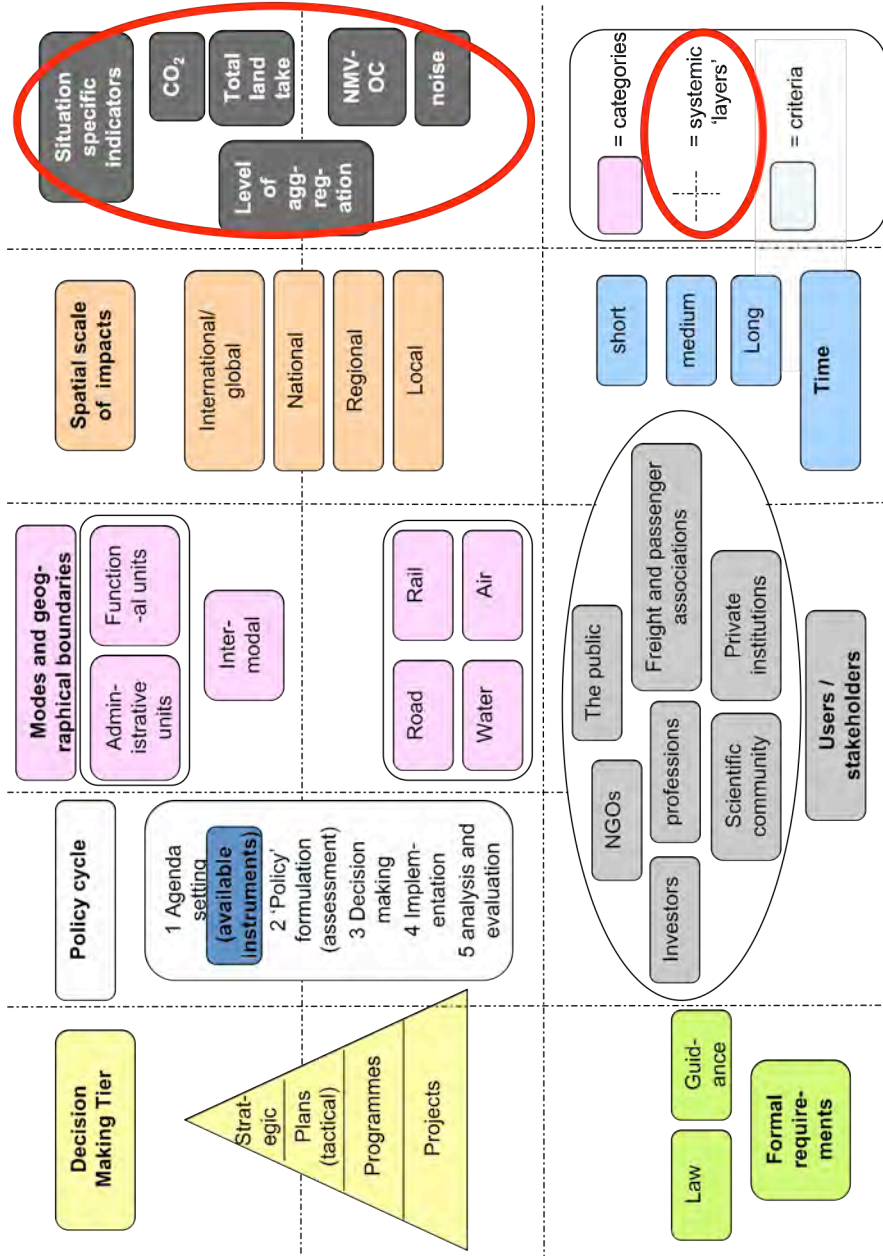
A number of variables characterising the differences in decision making situations have been discussed in the previous two sections. Some of them are included in Figure 9, depicting seven overall groups of variables that may influence the choice and formulate criteria of situation specific indicators. The seven groups include (1) the decision tier (i.e. whether it is a policy / strategic decision, a plan / tactical decision, programme or project / both operational decisions that is being prepared). Furthermore, and related to this, they include (2) the stage in the policy cycle, i.e. whether the policy agenda is set, the policy is formulated, concrete decisions are made and implemented or post decision evaluation is conducted. Also, (3) the transport modes to be considered, the administrative and functional geographical boundaries as well as the (4) spatial scale of impacts (from local to international) may play a role. (5) The type of formal requirements, as well as (6) the affected users / stakeholders and (7) the timescale of the policy, plan programme or project that is being prepared may influence the choice of situation specific indicators.

There are other related variables which could also be used to describe a decision making situation, including e.g. the legal framework within which a decision is made, whether objectives are agreed, whether knowledge exists, whether the decision rules are fuzzy or crisp, whether the problem is simple or complex, or whether uncertainties are large or small (see previous sections).

Due to the budget and time limits of this research project, trying to describe decision making situations so that all variables constituting the context of concrete decision making situations are fully considered is not possible, even though it may be desirable. In this chapter, instead, an attempt is made to characterise certain differences in indicator requirements related to the specific decision making situation along the strategic – tactical – operational dimensions. This is not randomly selected, as a number of decision making systems are organised along these dimensions, e.g. land use and planning acts are often organised in this way (national guidelines, municipal land use plans, zoning plans). The same could also be said about sector plans (National transport plan, regional transport planning, local transport plans). Furthermore, these tiers are related to what has been described as the 'structuredness' of different types or transport PPPP making and associated acting strategies in section 3.1.

Decisions made at the strategic level are long-term decisions about what to do in order to achieve something. This could be generic decisions about how to e.g. reduce GHG emissions from transport, or more specific decisions about how to solve a traffic and environment problems, like congestion on major roads or health problems caused by transport at the municipal level. Tactical decisions are of a more medium term nature and consider how to achieve what is decided on at the strategic level, including decisions on alternatives. Operational decision making, finally, is more short term and concerns the actual implementation in ways that maximize the positive outcomes and that minimize and mitigate negative effects and impacts (see also the policy, plan and programme examples provided in section 3.1).

Decision relevance is a criterion common for the selection of indicators. Decision relevance revolves around the question what the decision is relevant

for. For example, climate change is an important environmental issue for which various indicators have been proposed (e.g. "Global Warming Potential" (GWP) or $CO_2$ emission: see section 5.6.1). Yet the relevance of climate change depends on the decision-situation. If the decision concerns whether or not to build a new road (strategic), then climate change may be considered as being extremely relevant and associated indicators should be used in the decision-making. However, if the decision to build the road has already been made and if the situation revolves around the alignment of the road (i.e. whether tactical or operational), then climate change can be expected to be less relevant and other issues, such as noise pollution and habitat fragmentation, may be of greater importance. This does not mean that the global warming potential can not be reduced further, by e.g. choosing a different alignment. However, compared with other impacts, this is likely to be less significant and would probably be more appropriately covered under the heading reduction and mitigation of impacts. This point is discussed further in section 6.1.1.2. In a similar manner, other criteria may be a function of the situation, such as "Representativity" and "Data availability" (for the discussion of criteria for indicator selection see Chapter 4).

There are also some generic differences between decision making situations. In strategic decision making, the aim is often to select *few* indicators, which represent main differences between strategic choices related to *main objectives and main thresholds*. In operational decision making, on the other hand, frequently the aim is to seek to develop a comprehensive knowledge about the impacts of the action to be implemented, and to bring in indicators representing most types of impacts.

There will be differences in the knowledge of the details of future situations. Strategic decisions are often made without detailed knowledge, for example when dealing with the question whether to improve public transport services or building a new road. Operational decision making often happens on the basis of detailed information about the future situation, e.g. what will be built or done. This also means that the certainty of impacts and of indicators representing these impacts will differ between strategic (i.e. policy), tactic (i.e. plan) and operational (i.e. programme and project) decision making situations. Taken together, the differences in detail and certainty about what will happen in the future represent a main difference between criteria for indicators to be used. It could be argued that the more strategic a decision making situation is, the more *robust the indicators* should be. Robustness here refers to the ability to represent differences in impacts related to the main objectives and thresholds. Robustness also often relates to the existence of general knowledge about the interrelations between the decision and its implementation and how this will affect what is understood as the most important variables in each case. Frequently, this means that the precision of the knowledge is not very good, even if there is certainty about roughly what the main impacts of different decisions are. The more operational a decision making situations becomes, on the other hand, the more comprehensive and detailed it is and appropriate indicators are needed. Among the main differences of indicator requirements for different decision making situations along the strategic – tactic – operational

dimensions could thus be said to be representativeness (few) versus comprehensiveness (many), and robustness versus certainty and precision.

This is illustrated here through a few virtual examples. If a city or a region has a problem with growing traffic volumes, causing increasing GHG-emissions, local pollution, health problems, traffic accidents, congestions and delays, a number of strategies may be chosen in order to improve the situation. At the strategic level, detailed planning of the different alternatives will often not be carried out. Instead, main variables to consider will be defined, based on their importance and on whether they are decision relevant (such as GHG-emissions, number of people affected by noise and local pollution, costs, accidents). Based on general knowledge about how implementation of the different strategies will affect these variables and about informed assumptions about possible solutions, knowledge will be produced (often as rough predictions) about what will happen in the future if each of the strategies is carried out, and how this will affect the most important variables. Indicators may be selected, representing the impacts on these variables.

At the tactical level, a decision may have been made to improve the situation by increasing road capacity or to build new roads. This can be done in several ways. Existing roads could be considered, new roads could be built, or tunnels be constructed. How and where this is done may have very different impacts. If it is supposed to be built in an environmentally sensitive area, then the impacts ensuing would make certain indicators particularly useful (vulnerability of nature, species etc., landscape aesthetics, effects on biodiversity etc.). If it was built in a populated area, it would have other impacts and a need for other indicators (number of people affected by noise and pollution, barriers etc.). What impacts we are talking about depends on the context and on the road (its size, speed limits, traffic load etc.). When it comes to decision making at the tactical level, the different alternatives would be defined in more detail (e.g. route alignment), which improves the possibilities to know what may happen in the future (what may be built) and what concrete impacts could be expected. This means that the knowledge needed in a specific decision making situation is defined by the context. Since there are a number of alternatives to consider, the focus will often be on trying to find the most important impacts. The number of variables, and thus the number of indicators, increases. At the same time, knowledge becomes more detailed and certain. Cost-benefit analyses are often used in programme situations to aggregate the positive and negative impacts of various alternatives into an index that is supposed to tell which is the "best" alternative, or what proposed projects should be given priority for investment (see a presentation of economic approaches in section 6.2.5).

When a decision is made about how and where to build a road, very detailed plans must be made. Detailed knowledge about the environment in which the road is to be built will be gathered. Together, this can provide decision makers with some good knowledge about what will be built and what consequences this will have on nature, society and economy. In this phase, an important task will often be to try adjusting the project, in order to maximize the positive effects and to minimise the negative effects. Severe negative impacts should always be mitigated.

# 3.4. An investigation into indicator selection and usage

There is currently a lack of empirical evidence regarding the use of situation specific indicators. In this section, therefore, results of a survey into situation specific indicator selection and usage are presented, which was conducted in 2008. Here, in order to explore the situation-driven approach, various transport planning case studies were covered. For each case study, the following three questions were asked.

1. What were the situational factors?

2. Why were indicators used or not used?

3. How were indicators used?

The first question assesses the situation. In this context, in the survey, a framework of five situational factors that were suspected to exhibit a relationship with indicator usage were used, which are able to describe most transport planning situations. These are shown in Figure 10. Whilst factors 1, 2, and 3 consist of mutually exclusive categories, factors 4 and 5 have categories that are potentially overlapping. Other factors and categories could be considered, such as time frame (short term, long term), audience (private, public, government), government level (city, county), extent of impacts (transport only, more than just transport), and severity of impacts (minimal, grave). However, the factors chosen achieve a concerted focus.

**Figure 10. Five situational factors and their categories**

| **1. decision-making tier** | **2. decis.-making cycle** | **3. administrative level** |
|---|---|---|
| • strategic (policy)<br>• tactical (planning)<br>• project selection (programming)<br>• project design | • ex-ante assessment<br>• continuous monitoring<br>• ex-post evaluation (auditing) | • international / global<br>• national<br>• regional (network level)<br>• corridor<br>• neighbourhood<br>• site specific |

| **4. instruments** | **5. transport mode** |
|---|---|
| • fiscal incentives<br>• regulation<br>• technological innovation<br>• information programmes<br>• infrastructure<br>• land use planning | • walking<br>• cycling<br>• automobile<br>• public bus<br>• light rail or subway<br>• train<br>• boat, ferry, etc.<br>• airplane, etc. |

The second question asked in the survey was why indicators were used / not used. The following reasons for using an indicator were considered:
− legal requirement

- data already exist / can be acquired easily
- political reasons
- public request
- the indicator represents an important issue (theoretical reasons)
- it is common practice to use the indicator for this situation
- it is easy to communicate the indicator to the public and decision-makers.

  Furthermore, the following reasons for not using an indicator were used:
- it is not necessary or doesn't make sense to use indicators for this situation (theoretical reasons)
- it is too expensive to collect data
- the time frame does not permit the use of indicators
- political reasons: there isn't a reliable way to measure (or forecast) an indicator in this situation.

**Figure 11. Questionnaire flow chart**
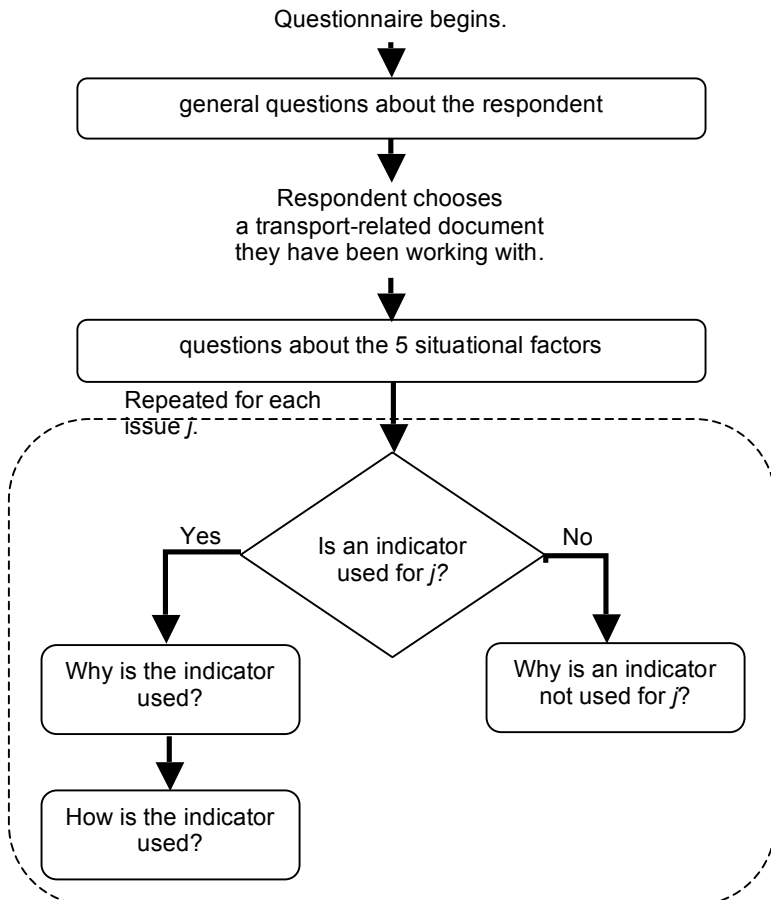
The third question concerned how the indicators were used. In this context, various characteristics that could be framed in a dichotomous manner were chosen, as follows:
− descriptive / predictive
− quantitative / qualitative
− refers to the cause of a problem / refers to symptoms
− standalone / composite or component
− target / no target

## 3.4.1. A survey to answer the three analytical questions

The three questions were at the heart of an online questionnaire that was administered to various European experts. It was sent to members of the COST Action as well as to various transport-related email list-serves.

Figure 11 shows the flow chart for the questionnaire. A respondent was supposed to begin the questionnaire by answering a few questions about themselves (e.g. contact information, job position).

Next, he or she was asked to choose a transport planning document with which they had been recently working. This is followed by questions about the situational factors surrounding the document. They are then asked about the use of indicators for various environmental issues. These questions are repeated for each issue. Here, four issues were chosen, namely climate change, air pollution, noise pollution, and habitat loss. If an indicator was used for one of these issues, the respondent was asked why it was used and how it was used. If an indicator was not used, they were asked why indicators were not used.

## 3.4.2. Description of the results

In total, 21 responses were received. These were subsequently analysed. This section presents the main results found.

### 3.4.2.1. The situational factors

Overall, the analysis shows that there is a link of indicators for the four environmental issues climate change, noise pollution, air pollution and habitat loss with situational factors, albeit only weak. It is most strong for the decision tiers (i.e. policies, plans, programmes, projects).

Figure 12 shows the frequency with which four environmental issues were considered in assessments at strategic (i.e. policy), tactical (i.e. plan) and operational (i.e. programme and project) tiers of decision making. Overall, indicators related to 'habitat loss' was found to be consistently considered to a lesser extent than 'climate change', 'air pollution' and 'noise pollution'. In addition, Figure 12 suggests that assessments at different decision tiers indeed give some preference to the consideration of certain implications. Here, this is

particularly evident when looking at 'noise pollution', which is considered to a lesser extent at the higher policy and plan tiers than in more project oriented assessments, confirming what was said earlier in section 3.3. Whilst, according to the hypotheses formulated earlier, climate change should have been considered particularly at higher tiers, here it was found to be given similar attention at different tiers. Based on the results from other questions in the survey, it appears that the consideration of climate change is frequently politically driven, i.e. it is not really looked at whether it may be appropriately considered in a certain situation. What is very surprising here is the low rate of consideration of habitat loss, air and noise pollution at the project level.

**Figure 12. Percentage of documents that use an indicator for the different tiers**
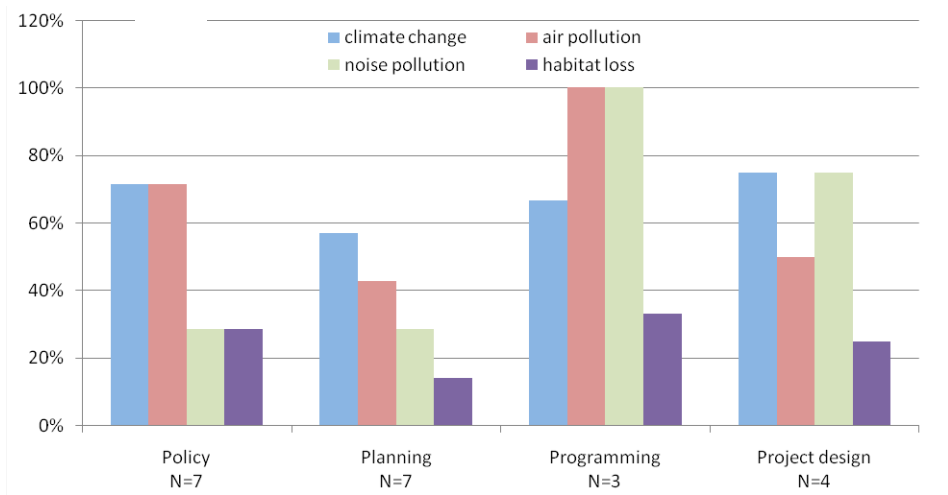


**Figure 13. Percentage of documents that use an indicator for the different cycles**
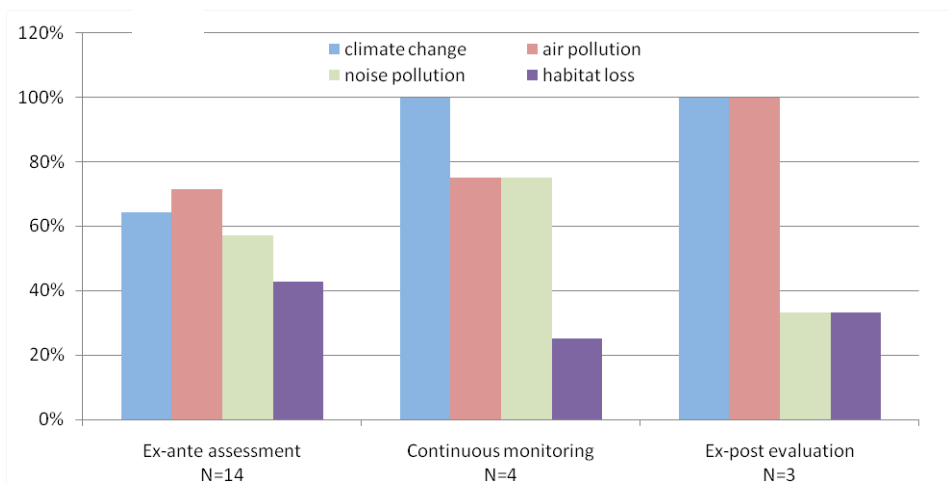
Figure 13 shows the extent to which policies, plans programmes and projects considered indicators for the four environmental issues at different stages of the decision cycle, namely in ex-ante assessment (e.g. SEA / EIA), within continuous monitoring and in ex-post evaluation. Climate change, together with air pollution were considered most frequently at all stages, which may, as indicated above, reflect in particular political pressures. Somewhat surprisingly, noise pollution and habitat loss received the poorest attention in ex-post evaluation.

**Figure 14. Percentage of documents that use indicators for the different administrative levels**
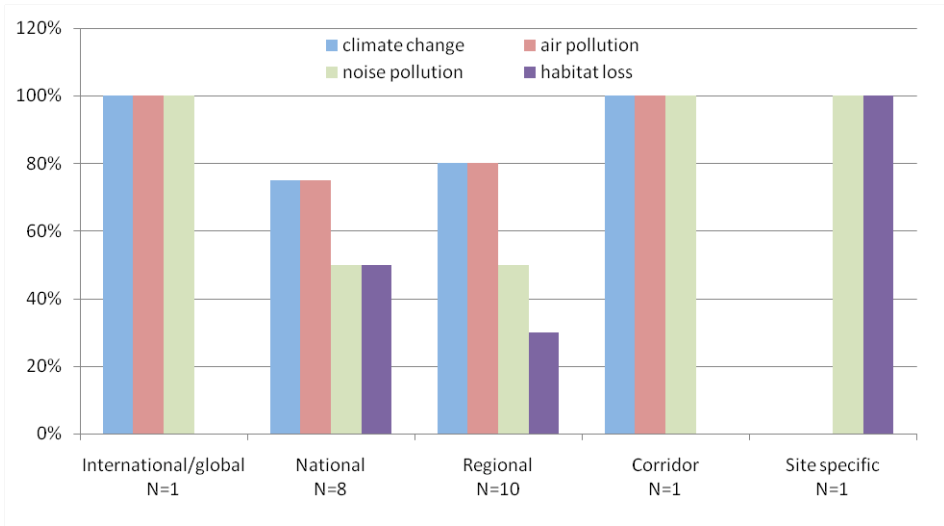


**Figure 15. Percentage of documents that use indicators for the different instruments**
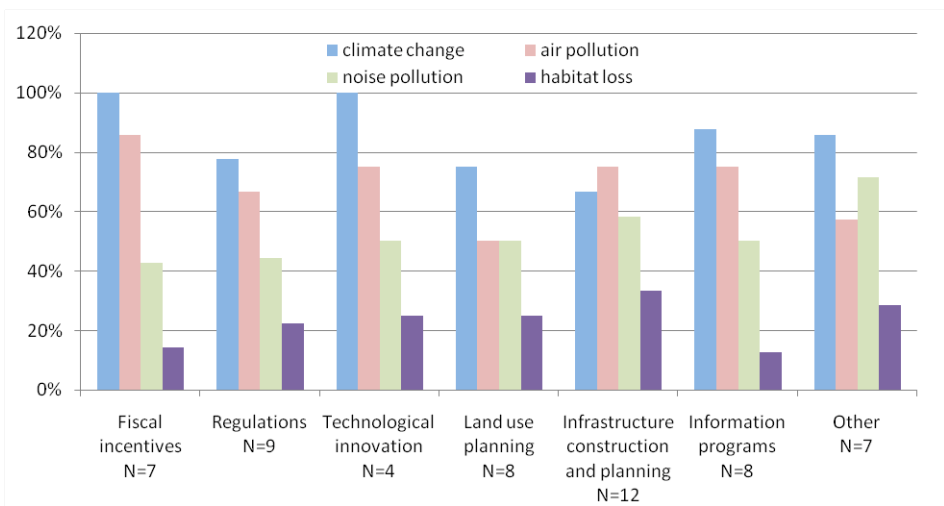
Figure 14 shows the extent to which indicators for the four environmental issues are used at different administrative levels. Interpretation of international, corridor and site specific levels is not possible, as these represent only one case each. National and regional levels show similar pictures with climate change and air pollution considered by 80 % / nearly 80 %, noise pollution by 50 % and habitat loss at national level also by 50 %, but at regional level only by 30 %. Again, it is somewhat unclear why habitat loss is comparatively poorly considered at the regional level. Here, similarly to e.g. noise pollution, this should become more relevant the closer you come to the project level.

Figure 15 shows different types of measures suggested in policy, plan, programme and project making and the use of indicators for the four environmental issues. Differences are only small. Within this context, it doesn't come as a surprise that climate change plays a more important role when fiscal incentives and technological innovation are discussed than when concrete transport infrastructure construction is considered and vice versa for habitat loss.

Finally, Figure 16 makes the link between the use of indicators for the four environmental issues and the consideration of different transport modes in PPPP making. Here, generally speaking, when cycling and walking are considered, indicators are considered to a lesser extent than when motorized transport is considered, including individual and public transport. However, again connections of transport modes and indicators are weak.

**Figure 16. Percentage of documents that use indicators for the different modes**
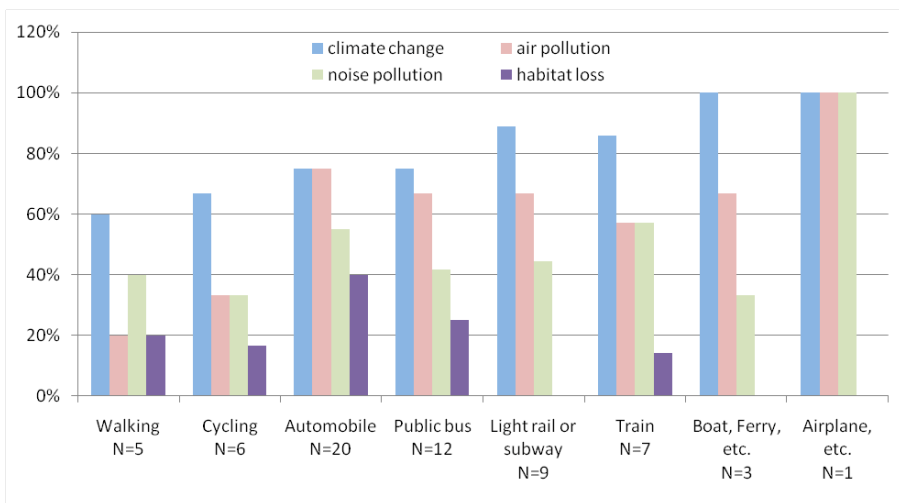


### 3.4.2.2. Why were indicators used or not used?

Our initial analysis reveals interesting results concerning why the respondents believed indicators were used or not used. The percentage for each response is shown in Table 17 and Table 18.

It is apparent that most respondents believed that indicators were used primarily because of theoretical / situational reasons. On the other hand, only about half believed that indicators were used for legal, political, or data availability reasons. This supports the idea that whilst indicators may be selected based on theoretical (and situational) reasons, political considerations and data availability may also play an important role. This same conclusion can be drawn based on the results shown in Table 18. It appears that most respondents did not feel data availability was a key reason for excluding an indicator; instead, most of the time they felt it was due to theoretical reasons.

**Table 17. Why do you think indicators were used for climate change, air pollution, noise pollution, and habitat loss?**

|  | N | Legal reasons | Data exists | Political reasons | Public request | Theoretical reasons | Common practice | Easy to communicate | Other |
|---|---|---|---|---|---|---|---|---|---|
| climate change | 16 | 36 % | 50 % | 50 % | 36 % | 79 % | 57 % | 43 % | 21 % |
| air pollution | 16 | 62 % | 38 % | 38 % | 46 % | 85 % | 62 % | 38 % | 15 % |
| noise pollution | 12 | 50 % | 50 % | 50 % | 70 % | 100 % | 80 % | 30 % | 10 % |
| habitat loss | 8 | 60 % | 20 % | 60 % | 20 % | 100 % | 40 % | 20 % | 20 % |

*Note:* The respondents could choose more than one reason.

**Table 18. Why do you think indicators were *not* used for climate change, air pollution, noise pollution, and habitat loss?**

|  | N | Theoretical reasons | Too expensive to get data | Not enough time to get data | Political reasons | No way to measure or forecast | Other |
|---|---|---|---|---|---|---|---|
| climate change | 5 | 50 % | 0 % | 0 % | 25 % | 25 % | 0 % |
| air pollution | 5 | 50 % | 0 % | 0 % | 25 % | 0 % | 0 % |
| noise pollution | 11 | 20 % | 0 % | 0 % | 20 % | 20 % | 20 % |
| habitat loss | 13 | 50 % | 13 % | 13 % | 38 % | 38 % | 13 % |

*Note:* The respondents could choose more than one reason.

## 3.4.2.3. How were the indicators used?

Another interesting result of our initial analysis concerns how the indicators were used. Table 19 shows the responses to the five dichotomous questions concerning indicator use. It seems from this table that most of the time the indicators were used prescriptively, quantitatively, as a standalone, and with a target.

**Table 19. How were indicators used?**

|  | N | Descriptive \ prescriptive | Quantitative \ qualitative | Cause \ symptom | Standalone \ composite | Target \ no target |
|---|---|---|---|---|---|---|
| Climate change | 16 | 6 \ 9 | 14 \ 2 | 9 \ 5 | 9 \ 5 | 8 \ 5 |
| Air pollution | 16 | 6 \ 10 | 13 \ 3 | 9 \ 7 | 10 \ 6 | 11 \ 4 |
| Noise pollution | 12 | 4 \ 8 | 9 \ 3 | 8 \ 4 | 9 \ 3 | 8 \ 4 |
| Habitat loss | 8 | 2 \ 6 | 6 \ 2 | 3 \ 5 | 4 \ 4 | 1 \ 7 |

*Note:* The respondents could choose only one of the two choices or "I don't know".

# 3.5. Conclusions

In this chapter, the question was raised as to whether the dimensions and context of decision making may provide for a suitable basis for choosing environmental indicators. This was said to potentially give rise to a 'situation driven approach' to selecting indicators (in addition to data driven and politically driven approaches).

Firstly, the contexts within which transport policy, plan, programme and project making is happening were discussed. Conflicts were said to be a 'normal feature' of transport decision making, which were, however, more or less strong, depending on the overall consensus on values and solutions. The application of structured processes for channelling and managing conflicts was suggested to be of great importance. Indicators were suggested to have different functions in different contexts. Whereas in situations with little or no conflict they may serve as decision makers, in situations of great conflict they are likely to only inform actors.

Secondly, basic decision making models were introduced that may be used to explain how decisions are made. Depending on the specific context within which decision making is happening, these were said to include the rational model, the bounded rational model and the garbage can model of decision making. Furthermore, political or coalition approaches to decision making were identified as being of importance. Finally, the normative concept of communicative planning was discussed. Authors from different research fields were found to make similar suggestions regarding the structuredness of different types of transport situations and associated acting strategies. These appeared to be connected with different stages of the policy cycle and the strategic, tactical and operational decision tiers (as reflected in policies, plans, programmes and projects; PPPPs). Consensus on norms and values, certainty in a PPPP situation and the degree of communication all appear to be closely connected. All of these aspects were said to be potentially related to the choice of appropriate indicators, with indicators potentially taking the role as *quasi* decision makers in concrete project situations that are with little or no conflict, and as more generic informants in more uncertain of conflict laden policy or tactical situations.

Possible functional criteria for selecting suitable indicators were introduced next. These were identified in several working group meetings. These were said to include the decision making tier and related to this the stage in the policy cycle at which decision making is happening. Furthermore, the transport modes covered and the administrative as well as functional boundaries were said to be potentially of importance. Other possible factors for defining functional criteria were said to include the spatial scale of the impacts, the type of formal requirements, the users and stakeholders involved as well as the timescale of the policy, plan, programme or project.

Results of a survey on 21 transport policies, plans, programmes and projects were presented, using five situational factors, including the decision making tier, the stage of the decision making cycle, the administrative level, as well as the instruments and transport modes covered in decision making, indicators for four environmental issues were considered; climate change, air pollution, noise pollution and habitats loss. Here, it was found that only the decision tier appeared to play a clear role in indicator selection. The more geographically limited impacts of noise and air pollution were more frequently considered at programme and project levels than at policy and plan levels of decision making. However, this wasn't the only factor able to explain the choice of indicators and there appeared to be an overlap with other factors. It was suggested that these may include in particular the political dimension, as climate change was an issue consistently considered at all levels. At the time when the survey was conducted, climate change had been high on the political agenda. Somewhat worryingly, habitat loss was considered only occasionally and there didn't appear to be any obvious connection with a particular decision tier.

# 4. Criteria and methods for indicator assessment and selection

**Authors: H. Gudmundsson, A. Tennøy and R. Joumard**

As representative tools (see Chapter 1), indicators may help to measure, manage and mitigate environmental impacts of transport. But how to identify appropriate indicators or choose well among possible ones?

Many examples of transport assessment using environmental indicators exist. However, according to several reviews (e.g. Jeon and Amekudzi, 2005; May *et al*., 2007; Litman, 2008; Goger *et al*., 2009) often only a narrow range of indicators are used, and limited justification for the particular indicators chosen is typically given. Few systematic guidelines for choosing appropriate indicators across the area of environmentally sustainable transport systems and policies exist.

This chapter will address ways to identify, assess and select specific indicators, using *criteria* of indicator quality and appropriateness and associated methodologies to apply and interpret the criteria. 'Criteria' refers to the general notion of a principle, or standard on which a judgment may be based. The aim of the chapter is to devise basic elements for choosing indicators of transport and environment impacts using indicator criteria.

A general description and definition of indicators has been provided in Chapter 1 of this report. Chapter 2 has identified the environmental impacts for which transport indicators are generally needed while Chapter 3 has discussed general contexts of application of indicators.

Building on these foundations this chapter will seek to review and define a set of criteria and a general method to apply criteria to review potential indicators of transport and environmental impacts. These elements will be built from an extensive compilation of existing literature combined with internal working group contributions. The method will be applied for selected environmental impacts of transport in the subsequent Chapter 5. Recommendations to further work are given.

A more detailed account of the work is given in a working report (Gudmundsson, 2010).

# 4.1.  Methodology of the work

The methodology has involved two directions of work. One direction is a top-down approach, with compilation and review of general literature on indicator criteria and assessment methods. The other direction is a bottom-up approach involving internal working group contributions to identify key questions and criteria of particular interest for indicators in the area of environmentally sustainable transport. The principal emphasis in this chapter is on the results of the top-down approach, where criteria and methods are proposed with a basis in the literature. The bottom-up approach provides necessary framing and context to direct, interpret and ground the general literature in the area of transport and environment. Therefore the bottom-up approach is described first in the following brief account of the two elements of the work method.

Several authors note that indicator selection should primarily be driven by *the questions that the indicators are supposed to answer* (e.g. Lenz *et al*., 2000; Jeon and Amekudzi, 2005; and USEPA, 2006); The bottom-up process identified the following overall questions for this work:
− To what extent are transport systems or transport flows having a negative effect on the environment?
− How are potential or actual transport policies, programs, plans, projects or choices influencing such effects in a positive or negative way?
− How significant are the environmental impacts of transport with regard to sustainability or other notions of acceptability?

These questions encompass a variety of situations with differing information requirements, from the measurement of specific environmental impacts to the comprehensive evaluation of transport policies. In Chapter 1 it is emphasized that indicators will have to serve measurement as well as decision making functions, with the former being the basis of the latter.

As established in previous chapters, the scope of the work should not be limited to any particular environmental impact, selected transport mode, special policy level, or sustainability concept.

This suggests a need to review a wide range of literature to identify indicator criteria across the domains of environment, sustainability, health, transport etc. To guide the review the working group initially proposed a long list of potentially relevant types of criteria; This list was refined and improved during the work.

The working group also discussed tentative definitions and groupings of criteria (e.g. according to measurement versus decision making functions of indicators). This allowed the identification of a number of additional important issues where guidance from the literature was needed:
− clear definitions of criteria (rather than intuitive ones)
− dealing with overlaps and possible redundancies among criteria
− grouping and distinguishing among criteria relevant for different situations
− considering if special criteria are relevant in the context of environment and transport
− designing methods to apply the criteria in actual indicator selection processes.

The working group was involved in steps along the literature review to consider the results and to discuss criteria and methodology for assessing indicators.

An extensive search of literature was conducted. The search involved both general literature of indicator selection, and more specific reviews of indicator studies in various areas, such as environmental sciences, ecosystem management, sustainability assessments, health monitoring and performance management. Special care was taken to identify work on indicator criteria applied to the area of environmentally sustainable transport, such as Goger *et al*. (2009). Around 150 articles, papers, books and reports were retrieved.

In the remaining sections of this chapter the results of the literature review is reported and used to devise a general methodology. Section 4.2 has a focus on the criteria as such and how to organize them, while section 4.3 reviews the methodological aspects of applying the criteria in practice.

# 4.2.  Indicator criteria in the literature

The identified literature includes a wide variety of contributions. Most of the references were found in the area of environment, sustainability, or public health assessment (key examples are Dale and Beyeler, 2001; Eyles and Furgal, 2002; OECD, 2003; NCHOD, 2005; WHO, 2006; and Niemeijer and de Groot, 2008;). Indicator criteria selection methodology seems particularly advanced in areas like marine science (e.g. Rice and Rochet, 2005), agricultural research (Bockstaller and Girardin, 2003), and forestry management (Mendoza and Macoun, 1999). Performance management literature addresses criteria to derive indicators at the level or organisations (e.g. Keeble *et al*., 2003). Some useful references in the transport area were also found (e.g. Zietsman and Rilett, 2002; Marsden *et al*., 2005).

The majority of the publications discuss indicator criteria, and provide *lists* of such criteria for use in the selection of indicators in various domains such as environmental assessment or sustainability. The lists include anything from 4-5 to over 30 criteria. Many criteria are commonly mentioned even across domains. Some studies report actual indicators that were selected based on the criteria lists, while others provide the lists as more general reviews or guidelines. It is not so common to find detailed accounts reporting how indicators were actually assessed and selected by using criteria (but see EEA, 2004c; or NCHOD, 2005).

Most references provide some kind of *definition* of each criterion, but very often the definitions are limited to only a headline or some informal comment. The definitions often appear similar but are not at all fully corresponding across references, For example, a criterion like 'measurability' is defined in one reference simply as whether the indicator is measurable in qualitative or quantitative terms (Niemeijer and de Groot, 2008); in another with regard whether the measurement process is possible within the available budget and

resources (NCHOD, 2005), while in a third more specifically if variance and potential bias of the indicator can be estimated (Rice and Rochert, 2005).

Only few studies of the 'criteria list' type refer directly to more rigid definitions from for example basic scientific literature, although some studies do discuss selected criteria definitions in some depth (as for example Boyle *et al*., 2001).

Interestingly, few if any sources define exactly what they understand by a 'criterion' in terms of indicator selection, although usually it is clear from the context what is meant. The main idea is to evaluate indicators with regard to some capacity expressed by the criterion. It is most often done in a qualitative way, or by using ordinal scores, rarely with more sophisticated numerical procedures (but see. e.g. Mendoza and Macoun, 1999). In a few cases minimum scores are set to exclude indicators below some threshold for some criteria (exclusive criteria).

It is characteristic that almost all identified references seek to *distinguish and group* criteria according to various functions of indicators, similar to those defined in section 1.2, such as measurement and decision making related functions. A typical distinction is between 'scientific' versus 'policy related' criteria. However, the groups are most often distinguished in a way that is quite unique to each particular reference.

A limited number of studies present systematic *methodologies* for the assessment and selection of indicators. In such studies application of indicator criteria is often included as a distinct step in a multi-stage process. Examples of this include Hardi and DeSouza-Huletey (2000), Jackson *et al*. (2000), NCHOD (2005), Rochet and Rice (2005), Cloquell-Ballester *et al*. (2006). Such references are particularly valuable for this work, even if they address different fields than transport and environment (see further in section 4.3).

A few *meta-reviews* of indicator criteria literature were found, such as Boyle (1998) for environmental monitoring, Niemeijer and de Groot (2008) for environmental assessment more generally, NCHOD (2005) for human health, and (more limited) Marsden *et al*. (2005) for sustainable transport in the UK. These references do typically not provide more in-depth analysis of individual criteria than the 'criteria list' references mentioned above, but they tend to come up with more reflective or at least longer lists. Some encyclopaedic articles provide conceptual reviews of indicator criteria (e.g. Bollen, 2001; Leviton, 2001), but even these are typically focussed on a limited set of criteria in a certain domain, such as of indicators for 'health' or 'social reporting'. No completely universal review of 'indicator criteria' literature was identified.

What follows is a compilation of selected contributions from the literature review. First comes an overview of criteria as presented in a number of general references in the areas of environment, sustainability and health assessment (section 4.2.1) and then follows a more detailed review of criteria within three levels of indicator applications (called measurement, monitoring and management levels - section 4.2.2) This is followed by a review of criteria in the area of transport indicators research (section 4.2.3). On this basis the identification of key criteria is discussed together with problems with overlaps and redundancies among criteria (section 4.2.4). The conclusion of this section

is a long list of potentially relevant, but partially overlapping criteria (see Annex 7), and a more restricted, selective and detailed list of criteria proposed for practical application in subsequent chapters of this report (found in the main text and Table 25).

The development of a method to apply the proposed criteria for indicator assessment is addressed in the following section 4.3.

## 4.2.1. Overview of criteria

There is not a full agreement in the literature about which criteria that are needed to sufficiently assess indicators, or how to categorize the criteria with regard to the which functions the indicators are to serve; each reference has its own list of criteria and categories, although there are of course many similarities and overlaps.

Table 20 provides a quick and quite comprehensive example of some of the most frequently occurring types of criteria in the literature generally. This is the list of criteria used by the National Health Service in the UK to quality review indicators for public health assessment (NCHOD, 2005). The criteria were derived from 18 independent sources, and grouped into 4 categories: scientific criteria, policy criteria, methodological criteria, and statistical criteria.

**Table 20. Comprehensive list of clinical health indicator criteria
(see NCHOD, 2005, p. 427 ff)**

| Scientific criteria | |
|---|---|
| Explicit definition | Is the indicator explicitly defined by appropriate statistical units of measurement and clinical terminology? |
| Indicator validity | Will the indicator measure the phenomenon it purports to measure i.e. does it makes sense both logically and clinically? |
| Scientific soundness | How scientific is the evidence / selection process (systematic / non-systematic) to support the validity of the indicator? |
| **Policy criteria** | |
| Policy-relevance | Does the phenomenon under measurement represent significant public interest, disease burden or cost? |
| Actionability | Can the factors which influence the phenomenon be positively influenced to induce a future health / cost benefit? |
| Perverse incentives | Will the measurement process encourage undesired behaviours by those under measurement? |

| Methodological criteria | |
|---|---|
| Explicit methodology | Are measurement tools / procedures explicitly defined, understood and monitored? |
| Attributability | Are the factors which influence the phenomenon likely to be identified e.g. patient risk factors, practitioner procedure etc? |
| Timeliness | What is the average time (months) between measurement and results? |
| Frequency | What is the average time (months) between reporting of results? |
| Sensitivity to change | Do the measurement tools and timing of results allow changes to be observed over time? |
| Confounding | What is the risk that variations between organisations and changes over time may be influenced by confounding factors? |
| Acceptability | What percentage of stakeholders accepts the process of measurement and the reasons for it? |
| Measurability | Is the measurement process possible within the available budget and resources? |
| Cost-effectiveness | Does the likely output represent a cost-effective use of budget / resources? |
| Statistical criteria | |
| Specificity | Does the measurement appropriately capture the level of detail required e.g. subgroup analyses, accurate diagnosis? |
| Comparability | Is the measure comparable between relevant subgroups e.g. are age / sex / geography-specific data standardised and consistent? |
| Representativeness | Are sample sizes representative across all required subgroups? |
| Data quality | Data quality % of the information missing from the records? |
| Data reliability | % agreement (kappa coefficient) between measured records and those collected by an independent source? |
| Uncertainty | Have appropriate techniques been selected to demonstrate the effects of variation, dispersion and uncertainty? |
| Interpretability | Can understandable, meaningful and communicable conclusions be drawn from the results? |

Table 21 lists a range of indicator criteria review publications. It shows that the number of criteria listed varies from 34 and downwards, and that the categories used to group them range from 6 and downwards.

The question of criteria, categories and how they relate to one another is addressed in the following sections.

**Table 21. Selected indicator criteria publications**

| Reference | Area | Categories | Number of criteria |
|---|---|---|---|
| Niemejier and de Groot, 2008 | Environmental assessment | Scientific dimension<br>Policy and management<br>Systemic dimension<br>Intrinsic dimension<br>Historic dimension<br>Financial and practical dimensions | 34 |
| NCHOD, 2005 | Public health assessment | Scientific criteria<br>Policy Criteria<br>Methodological criteria<br>Statistical criteria | 18 |
| Jackson *et al.*, 2000 | Environmental assessment | Conceptual Relevance<br>Feasible Implementation<br>Response Variability<br>Interpretation and Utility | 14 |
| Boyle *et al.*, 2001 | Environmental monitoring | Conceptual model<br>Issues framework<br>Knowledge base<br>Data<br>Reporting | 13 |
| OECD, 2003 | Environmental performance review | Analytically sound<br>Policy relevant and useful<br>Measurable | 11 |
| WHO, 2006 | Public health assessment | (none explicit) | 10 |
| Rice and Rochet, 2005 | Fisheries management | (none explicit) | 9 |

# 4.2.2. Structuring the criteria

The categorisation of indicator assessment criteria with regard to indicator functions is not an irrelevant consideration, it has to do with how to build a systematic approach where relevant indicator functions are addressed to the appropriate degree and time, while irrelevant ones may be skipped or downplayed.

There are quite large differences among the publications with regards to which categories are used, and how individual criteria are organized under them. In other words there appears to be limited consensus about why or in which situations a particular indicator selection criterion might be important. For example the same criterion 'responsiveness / sensitivity' is classified under completely different categories in a number of references, hence under 'policy

relevance' (OECD, 2003); 'systemic dimension' (Niemeijer and De Groot, 2008); 'methodological' (NCHOD, 2005) or its own category 'Response variability' (Jackson *et al*., 2000). It seems clear that simply picking one reference could lead to rather arbitrary lists and categories. These differences could be due to different characteristics of the fields of indicator applications considered in the selected publications (public health, environmental assessment, sustainability, transport), but when considering the diversity across several references (see Table 21), it appears more to be a result of a lack of common understanding about indicator functions.

However, further review of the literature has allowed to structure assessment criteria into three different intended functions of indicators:

- Level 1: Indicators treated as units measuring particular system properties or endpoints, for example, using criteria of validity and sensitivity to assess 'hospital admissions' as an indicator to represent occurrences of non-fatal road accidents (Cryer *et al*., 2002)

- Level 2: Indicators considered as reporting units in monitoring programs, for example using criteria related to effective data collection methods to evaluate indicators like Dissolved Oxygen Concentration as indicator of hypoxia in aquatic environment (Strobel, 2000)

- Level 3: Indicators treated as decision making units in policy or management strategies, for example using the relevance for European transport policy objectives as a criterion to evaluate indicators for transport policy assessment (van der Loop, 2006)

This distinction corresponds well to ones proposed by e.g. Walz (2000), Dale and Beyeler (2001) and Cloquell-Ballester *et al*. (2006). As will be shown it is possible to assign criteria more uniquely to this structure.

Level 1 criteria should emphasise basic requirements of accurate representation, disregarding practical and political concerns. One problem of this category is that indicators are approximations, that cannot always be expected to be verifiable with standard scientific methods (see e.g. Bockstaller and Girardin, 2003).

Level 2 criteria involve practical concerns if indicators are to be actually used for reporting, for example across territories or over time. This is obviously not possible for example if the indicators are not measurable in practice, or if there are no data available (see discussion in Chapter 1). Such aspects can of course not be ignored if indicators are to make sense from an analytic point of view.

Level 3 refer to criteria that are important for decision making. Added concerns at this level are ones related to possibility of interpretation, transparency to provide legitimacy of the information, relations to policy or management objectives, and possibilities to draw implications for action (e.g. to choose among alternatives, or to proceed or stop along a given trajectory).

A common critique of level 2 and 3 approaches is that "…management and monitoring programs often lack scientific rigor because of their failure to use a defined protocol for identifying ecological indicators" (Dale and Beyeler, 2001).

In other words, level 1 criteria can be considered as basic level criteria that always have to be considered if indicators are to be accepted from a scientific point of view, while systematic application of criteria on level 2 or 3 must be added if indicators are to used in monitoring or decision support or management respectively, which will usually be the case for indicators of transport and environment.

The following subsection will review literature that seek to define criteria, in accordance with such a logic. The selection of references is limited to eight reports and studies that were deemed to represent some of the most thorough or otherwise significant accounts for each level. A detailed consideration of the criteria definitions is not undertaken here but in section 4.2.4.

## 4.2.2.1. Criteria from a scientific point of view (level 1)

Approaches concerning criteria for indicators as units of scientific measurement (level 1) typically emphasize how to ensure that an indicators validly represent system properties in a particular system or point of interest (e.g. how to select appropriate indicators that describe eutrophication of lake ecosystems). Examples of references adopting this approach include e.g. Cameron *et al*. (1998) for soil quality, Breckenridge *et al*. (1995) for rangelands, Franceschini *et al*. (2005) for air quality index, and Babisch (2006) for noise.

The three sources cited in Table 22 below each attempt to summarize 'scientific' indicator criteria, although other concerns are sometimes mixed in, as indicated by grey colouring in the table.

Jørgensen *et al*. (2005) provide a large scientific compendium over indicators and indices for measuring 'ecosystem health'. Five general scientific criteria suggest a summary of what ecosystem health scientists should be most concerned with when selecting indicators. The criterion 'ease of handling' could be considered as more practical concern for monitoring or management (levels 2 and 3).

Eyles and Furgal (2002) propose a set of criteria to select indicators of human health effects of ecosystem changes. They distinguish between 'scientific' criteria and 'use–related 'criteria (the latter not shown in Table 22). The criteria have been established in a scientific consensus process, and are widely cited by other authors. The proposed criteria for 'indicator validity' consist of elements that have been established mainly in psychology and social sciences as will be discussed in more detail later. Some of the criteria (such as 'data availability') belong more to the monitoring level.

The World Health Organization (WHO) has several indicator programs for health monitoring. In WHO (2006) indicators for reproductive health are established. The criteria for selecting indicators that should be 'scientifically robust' are cited in Table 22; In this case WHO does not mix in criteria types (no grey colouring added) related to the other levels; these follow in Table 23.

**Table 22. Level 1 - Scientific measurement criteria proposed in selected references**

| Jørgensen *et al.* (2005) (Ecosystem health) | Eyles and Furgal (2002) (Human health / ecosystem) | WHO (2006) (Reproductive health) |
|---|---|---|
| Ease of handling | Data availability, suitability and representativeness - with respect to sampling of populations. | Valid. An indicator must actually measure the issue or factor it is supposed to measure. |
| Independence of reference states | Indicator validity: | |
| Sensibility to small variations of environmental stress | - 'face validity' (is it reasonable?) <br> - 'construct validity' (does it behave as expected?) <br> - 'predictive validity' (does it predict outcomes?) <br> - 'convergent validity' (different measures react in same way?) | Reliable. An indicator must give the same value if its measurement were repeated in the same way on the same population and at almost the same time |
| Applicability in extensive geographical areas | Reliability (repeatability across times and sources). | Sensitive. An indicator must be able to reveal important changes in the factor of interest |
| Possible quantification | Responsiveness to change | |
| | Disaggregation capability -across personal and community characteristics. | Specific. An indicator must reflect only changes in the issue or factor under consideration. |
| | Comparability across populations and jurisdictions. | Representative. An indicator must adequately encompass all the issues or population groups it is expected to cover |
| | Indicator representativeness | |
| | Coverage of important dimensions of concern | |

Grey shading of a criterion suggest it could better belong to one of the other levels, according to the present review.

The examples illustrate only a partial consensus about what the 'scientific' measurement criteria for indicators are. A basic problem is that indicators in many cases are substitutes for actual scientific models or methods. Hence their 'scientificness' will always have some limitation; the 'validity', 'reliability' etc can typically not be established with the same rigor as in a fully developed 'scientific' model.

## 4.2.2.2. Criteria from a monitoring point of view (level 2)

Publications about indicators as elements in monitoring systems (level 2) often do include some level 1 aspects, and then adds various operational criteria related to actually collecting, continuously monitoring, and communicating indicators in a monitoring context. Examples of questions include: Is it feasible to monitor the indicator? Are data available or can they be obtained? Is it cost-effective?

The three sources cited in Table 23 each attempt to summarize which indicator criteria are particularly important in a monitoring context.

**Table 23. Monitoring system related criteria from selected references**

| Boyle (1998) (Ecosystem monitoring) | Dale and Beyeler (2001) (Ecosystem monitoring) | WHO (2006) (Monitoring reproductive health) |
|---|---|---|
| Sustainable Management goals and objectives: provide information that is timely. | Be easily measured: the indicator should be straight-forward and relatively inexpensive. | Useful: at national level, an indicator must be able to act as a "marker of progress"… the data should also be useful locally, i.e. follow-on action should be immediately apparent. |
| Conceptual model of the system: clearly relate to a specific societal or environmental concern. | Anticipatory, i.e. signify an impending change in key characteristics of the ecological system: Change in the indicator should be measurable before substantial change in ecosystem integrity occurs. | Understandable. An indicator must be simple to define and its value must be easy to interpret. |
| Issues framework: be clearly relevant to articulated goals and objectives. | Predict changes that can be averted by management actions: The value of the indicator depends on its relationship to management actions. | Accessible. The data required should be available or relatively easy to acquire by feasible data collection methods that have been validated in field trials. |
| Knowledge base; be scientifically valid, statistically and analytically sound, demonstrated to be practical through case studies. | Are integrative: the full suite of indicators provides a measure of coverage of the key gradients across the ecological systems. | Ethical. An indicator must be seen to comply with basic human rights and must require only data that are consistent with morals, beliefs or values of the population. |
| Data: use data that are available and accessible, accurate, comparable over time, complete with historical information and covering sufficient geographic area. | Have a known response to disturbances, anthropogenic stresses, and changes over time: The indicator should have a well-documented reaction to both natural disturbance and to anthropogenic stresses. | |
| Reporting: provide information that is understandable to potential users, unambiguous, easy to use; provide information that is at the appropriate scale for decision making. | Have low variability in response: Indicators that have a small range in response to particular stresses allow for changes in the response value to be better distinguished from background variation. | |

Grey shading of a criterion suggest it could better belong to one of the other levels, according to the present review.

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Boyle (1998) did a large study about different indicator sets and systems for monitoring the state of ecosystems in Canada. The study is remarkable because it is based on an extensive literature review covering the indicator selection criteria literature rather broadly. The entries in Table 23 are those monitoring concerns that Boyle conclusively believes should guide criteria application to indicators. The three first entries of Boyle all deal with the need to devise an appropriately comprehensive framework, not individual indicators. One of them (conceptual model) rather belongs to the measurement category described above.

Dale and Beyeler (2001) propose a procedure for selecting indicators for comprehensive monitoring of ecosystems in the US. They note: "In general, ecological indicators need to capture the complexities of the ecosystem yet remain simple enough to be easily and routinely monitored" (Dale and Beyeler 2001, p. 6). The 'integration' criterion addresses the need for an appropriate suite of indicators to allow comprehensive measurement of a system. The Dale and Beyeler criteria are rather widely cited by other references.

WHO (2006) is the same source as in Table 22 above, but here is only listed the criteria additional to the 'scientific robustness' ones above. An interesting addition here is ethical concerns which are of course highly important if indicators concerning personal issues like human health conditions, or unhealthful behaviour are to be monitored.

These examples illustrate how practical and communication issues enter strongly when the purpose shifts from basic measurement issues to regular monitoring programs.

## 4.2.2.3.  Criteria from a policy point of view (level 3)

Publications about indicators as elements in policy or management strategies (level 3) usually include some level 1 and 2 aspects, but emphasize in addition criteria related to broader communication aspects as well as to decision making, reflecting to what extent indicators address policy relevant issues, and to what extent they allow an assessment of policy responses or management interventions (Segnestam, 1999; OECD, 2003; EEA, 2004b; Kusek and Rist, 2004).

The sources cited in Table 24 are widely used or cited as standards for selection of indicators for policy or management in the area of environment.

The OECD (2003) criteria have been used for more than a decade in connection with assessment of environmental policy performance in OECD member states. It is among the most well known criteria sets. It does however mix scientific, monitoring as well as management aspects (all levels), in a somewhat peculiar combination. Several of the criteria are addressed above under level 1.

## Table 24. Policy or management criteria (level 3)

| OECD (2003) | EEA (2004b) | Segnestam (1999) |
|---|---|---|
| **(Environmental performance)** | | |
| Policy relevant and useful indicators should:<br><br>• provide a representative picture<br>• be simple, easy to interpret and able to show trends over time<br>• be responsive to changes<br>• provide a basis for international comparisons<br>• have a threshold or reference value against which to compare it<br><br>Analytically sound indicators should:<br>• be theoretically well founded in technical and scientific terms<br>• be based on international standards and international consensus about its validity<br>• lend itself to being linked to economic models, forecasting and information systems | • Be policy relevant - support EU policies' priority issues<br><br>• Monitor progress toward the quantified targets<br><br>• Be based on ready available and routinely collected data within specified timescale at reasonable cost-benefit ratio<br><br>• Be consistent in space coverage and cover all or most of EEA countries<br><br>• Time coverage – sufficient / insufficient time trends<br><br>• Primarily be national in scale and representative for countries<br><br>• Be understandable and simple | • Direct relevance to project objectives<br><br>• Limitation in number. It is most effective to be selective and use smaller sets of well-chosen indicators<br><br>• Clarity in design<br><br>• It is important that the indicator is clearly defined to avoid confusion in the development or interpretation<br><br>• Realistic collection or development costs<br><br>• Clear identification of causal links<br><br>• High quality and reliability |
| Measurable indicators based on data that should:<br>• be readily available or made available at a reasonable cost / benefit ratio<br>• be adequately documented and of known quality<br>• be updated at regular intervals in accordance with reliable procedures | • Be conceptually and methodologically well founded and representative; and based on consultation with countries<br><br>• EEA priorities in management plan<br><br>• Be timely (be produced in reasonable and "useful" time)<br><br>• Indicator well documented and of known quality | • Appropriate spatial and temporal scale<br><br>• Targets and baselines<br><br>• To measure the environmental problem at three points in time: before the project begins, during project implementation, and after the project has ended |

Grey shading of a criterion suggest it could better belong to one of the other levels, according to the present review.

The European Environment Agency (EEA, 2004b) used the shown criteria to establish its 'core set of indicators' for reporting on the European environment. The purpose was to identify the best available indicators for a number of key issues, taken from several large indicator sets already existing, and presumable already validated according to level 1 criteria. Still a few criteria link to levels 1 and 2 (most directly the criterion 'indicator well documented and of known quality').

Segnestam (1999), proposed the criteria listed for use in the World Bank's assessment of the environmental performance of projects in developing countries. The role of the indicators in project assessment is strongly highlighted, e.g. measuring 'fulfilment of project objectives', while some measurement aspects are also considered important for this function (e.g. 'design clarity' and 'reliability). The need to limit the range of an indicator set for the management context is an important consideration also noted.

**Figure 17. Tentative linkage of criteria to categories**



### Management

- Policy relevance
- Usefulness
- Threshold connected
- Relevance to objectives
- Comparability across jurisdictions
- Linkable to economic models etc

### Monitoring

- Measurability
- Quantifiability
- Applicability across geographical areas
- Ease of handing
- Data availability
- Integrativity
- Accessibility
- Understandability
- Ethical acceptability

### Measurement

- Validity
- Reliability
- Sensitivity / responsiveness
- Specificity
- Representativity

## 4.2.2.4. Summary of the three levels

The review of selected references found that it is rather common to make distinctions among criteria according to broad categories such as measurement / science related, monitoring related, and policy or management related criteria. However, even when such references are used, it does not lead to a common typology across several references, since each one interprets the connection between overall categories and individual criteria independently.

In the review an assessment was made (indicated with grey shading) to suggest in which cases it could be argued to link a criterion to another category than the one proposed by the cited authors. In the Figure 17 a summary is made of these assessments, so that most of the proposed criteria are tentatively re-allocated according to the logic of the three categories as defined above. The summary suggest that the categories can be seen as cumulative, in as much as monitoring and management ones assume, absorb or depend on measurement related ones (see Figure 17). Hence it is not an exclusive distinction, but one of overlaps and partial interdependence. The categorisation is tentative as it does not yet consider more specific contents or definitions of the criteria, or their relevance for the context of assessing transport and environmental sustainability.

Before a more detailed discussion of individual criteria is undertaken, a review of literature in the area of the transport indicators will therefore be undertaken, in order to reveal if some of the general criteria could be considered as less relevant or if any additional criteria emerge as important.

## 4.2.3. Criteria in transport references

In total 11 studies and reports were identified where criteria with regard to indicators for the area of transport, environment and sustainability were addressed more or less extensively (USEPA, 1999; EEA, 2000; Gilbert *et al*., 2002; Zietsman and Rilett, 2002; Batalle *et al*., 2004; Marsden *et al*., 2005; Farchi *et al*., 2006; van der Loop, 2006; Dobranskyte-Niskota *et al*., 2007; Litman, 2008; and Goger *et al*., 2009).

The references cover indicator usage domains from traffic management, to infrastructure planning, to transport policy and a range of indictor topics from traffic flows, to safety, to environment, to sustainability.

Most of the transport references adopt or propose very similar criteria to the general ones in section 4.2.2. However some additional criteria are proposed, including general ones, and ones considered particularly important or specific to the transport context. This section will concentrate on the works where this is the case, followed by a general summary across the transport references.

Goger *et al*. (2009) defined nine overall criteria to be used in the selection of indicators for strategic assessment of environmental impact of traffic and transport infrastructure. Five of them are 'general', while four are 'strictly linked to the goals' of the research (on transport assessment).

The list represents a mix of measurement related issues, policy making issues, and practical considerations. An interesting contribution at the general level is the notion of 'significance' criteria, This is not an actual criterion, but really a frame for a set of subcriteria such as:
− the importance of an indicator
− how well indicators provides an early warning of potential problems
− how well it demonstrates a move towards or away from sustainability
− how well it detects long term effects

The transport assessment specific criteria proposed by Goger *et al*. includes the following questions:
− 'how the responsibility of the transport sector is in the considered impact evaluated by the indicator' and
− 'how well the indicator shows the contribution of the transport sector in the considered impact'

The report does not suggest any general methodology to apply these criteria.

The United States Environmental Protection Agency conducted a major review to identify potential indicators on transport and environment (USEPA, 1999), even if no indicators in the end were actually proposed. The report notes that indicators of transport and environment should be reasonably certain, should be stated in meaningful units, and should allow isolating *transportation's share of the impact*. Indicators should thus identify the effect of transportation rather than providing an estimate of environmental quality that may depend on numerous sources (USEPA, 1999). The latter concern is fully parallel to the position of Goger *et al*. (2009) above, although again not specified as an operational criterion.

Zietsman and Rilett (2002) suggest a set of sustainable transportation performance measures, which have been applied in transport planning at the corridor level in the US. The indicators were derived using an extensive list of criteria combining general, and more transport assessment specific concerns. The latter ones can be seen as contributions to help the interest in detecting transport's share of impacts, including:
− ability to differentiate between the individual components that are affecting the performance of the system
− not influenced by exogenous factors that are difficult control for, or that the planner is not even aware of
− ability to detect a certain level of change that occurs in the transportation system.

A criterion not mentioned in the general literature is 'acceptable'. The criterion suggests that the community who will be affected must assist in identifying and developing the performance measures. 'Ability to integrate' refers not to individual indicators but to the need to combine several indicators in joint consideration in a context like transport and sustainability.

Marsden *et al*. (2005) develop indicators for sustainable transport at the local level in the UK. The report includes a review of indicator criteria in five previous studies which cover transport applications of indicators This review generally yields the same types of criteria as seen in previously cited references, although adding two new ones namely 'avoids perverse incentives / corruption', and 'allows innovation'. Both criteria aim to help avoid indicators that can mislead policy action or management. The criterion 'controllable / attributable' again highlights the need to be able to separate out specific (in this case transport) effects from general ones. Criteria like 'limited in number' is a criterion for composing a whole set, contrasting the needs to be comprehensive suggested by Goger *et al*. and Zietsman and Rilett.

Summing up transport references as noted generally suggest similar criteria for assessing indicators as found at levels 1, 2, and 3 in the general literature are reproduced in this context.

However, the studied transport reports all belong to levels 2 and 3, including always criteria related to usefulness and relevance of indicators in particular monitoring or management contexts (suggesting criteria such as policy relevance, links to targets, timeliness, links to relevant legislation, avoidance of perverse management incentives, etc). It seems the transport indicators are always applied as part of project, program or policy assessment. Some measurement related criteria are usually included as well.

The most significant feature is the emphasis in some references on criteria to reflect *the contribution of transport* to the overall impact (Goger *et al.*, 2009), or, to what extent an indicator is able to identify the specific transport part of the general impacts, and thereby how to separate the transport parts from other parts of the problem (USEPA, 1999; Zietsman and Rilett, 2002; Farchi *et al.*, 2006). This could be phased as a criterion of 'transport attributability' or 'sensitivity' to the general list of criteria, not only as a part of policy or management concerns (level 3), but as also measurement concern (level 1).

As examples one could think of the degree to which changes in impacts or concentrations of a pollutant vary with the transport contributions, or the degree to which an indicator can be disaggregated easily to show contributions from different transport modes, vehicle types, travel purposes, etc. If it is possible to add such dimensions to an indicator, then this criterion would suggest (ceteris paribus) selecting such indicators rather than ones where such a distinction is not possible, as it would allow better understanding of transport impacts and better directions for management actions.

This highlights another issue brought forward by the transport references, namely the tension between indicators with a clear 'transport' focus versus ones with a clear 'impact' focus. In transport planning, transport focused indicators (e.g. Vehicle Kilometres Travelled) are typically chosen because they are easy to measure but also responsive to transport policies or projects, as opposed to e.g. measures of air pollution health impacts. Hence, in the examples above, it is typically easier to identify a 'transport' part of the problem by using a 'pressure' type indicator (e.g. emissions) than by using 'state' indicators (e.g. concentration in air) let alone a direct 'impact 'indicator' (e.g. number of people with health damage from transport pollutant x). In the latter case sophisticated calculation or modelling may be needed to identify the 'transport share', and data or models to ensure this may not always be available. Conversely, in the former case, transport specific data may be available (e.g. emission values per vehicle type or speed class), but such data do not indicate very accurately the actual health impacts. Indicators or both types may be needed.

There may be some examples where it is clear that more or less all of an impact arises from transport because transport is the only source contributing to a particular impact. Examples could perhaps be noise disturbance indicators for people living near roads, or health effects of drinking water contaminated by Methyl Tertiary Butyl Ether (MTBE) leaked from underground gasoline storage

tanks. But even in those cases there would be other sources affecting the final impact target (e.g. human health).

There may also be examples where alternative transport projects are compared, and in this case, the 'share' of transport in the total problem is less relevant, only the differences in impact between the two cases. If only relative performance is of interest, a 'transport attributability' criterion is less relevant, but if an absolute level is of importance (e.g. with regard to passing a threshold) the distinction of the transport share or contribution may be important. Hence, a 'transport attributability' criterion for indicators may sometimes, but not always be needed.

# 4.2.4. Discussion and development of criteria

A large number of possible indicator selection criteria have been identified generally and for transport applications, and a tentative structure of criteria with three levels have been defined.

It is now possible to proceed to populate each level with specific criteria and associated definitions. Considering the many possible criteria, and their often overlapping meaning it is necessary to discuss their content, relations and which criteria are the most important ones

There are basically two ways to use the literature review:
− to look at which criteria are mentioned most frequently in the reviews
− to see if some criteria are generally considered as more fundamental or important than others

Both options will briefly be discussed before specific criteria are addressed.

## 4.2.4.1. Frequency of mention

The two studies with the longest lists of criteria, are both based on a number of underlying studies. NCHOD (2005) is based on 18 references, and Niemeijer and de Groot (2008) of nine. Both count the occurrences of criteria. In the NCHOD review the seven most frequently applied criteria in the cited literature are: 'validity', 'policy-relevance', 'measurability', 'comparability', 'data quality', 'data reliability', and 'interpretability' (mentioned by more than 10 of the 18 sources). 'Scientific soundness', 'actionability', 'explicit methodology', 'timeliness', 'frequency', 'sensitivity to change', and 'representativeness' were listed by more than 5 sources.

In the Niemeijer and de Groot study the most frequently cited criteria found are 'analytical soundness', 'time-bound', 'measurability', 'resource demand', and 'relevance'.

In the more limited review of four transport indicator studies conducted by Marsden *et al*. (2005) the most frequently cited criteria are 'timely', 'scientific validity', 'relevant to organisation', 'transparent' and 'consistent over time'.

A more cursory skimming of additionally around 20 references reviewed in the background report to this chapter (Gudmundsson, 2010) indicates that frequently mentioned criteria include 'validity', 'reliability', 'representativity', 'theoretical basis', 'sensitivity', 'data availability', 'cost-effectiveness', 'timeliness', 'understandability / transparency' and 'policy relevance'.

Even if the limited compatibility and overlaps of criteria definitions across references is a barrier for making a clear assessment, it can be seen that criteria at all 3 levels are represented among the most cited ones, and that some themes are particularly frequent, such as 'validity' / 'analytical soundness', 'timeliness', 'measurability', 'policy relevance', 'reliability' / 'consistency over time', and for transport, transport 'sensitivity / attributability'.

## 4.2.4.2.   Importance of criteria

In the context of this report the measurement functions of indicators are considered as inherently foundational and fundamental to the others even if they do of course not stand alone. This corresponds with much of the literature, which even for the policy (such as OECD, 2003; EEA, 2004b) and monitoring (e.g. Boyle, 1998) oriented references tend to include and emphasize the measurement level. Hence notions such as validity, conceptual foundations, representativity and reliability, belonging to this level must be addressed.

Still, it is clear that other criteria need to be considered just as well, since indicators of transport and environment are almost always connected to functions with regard to monitoring and/or management. However exactly in those cases, the more specific context is likely to determine which are the more pressing concerns (e.g. timeliness, or cost-effectiveness, or target relevance). This means that a generally valid ranking for importance cannot be made.

In the following some of the more fundamental, but also complex, and partly overlapping criteria concepts are discussed in more detail.

## 4.2.4.3.  Validity

Most prominent among all the criteria is 'validity', a concept widely used in the indicator literature, and often put forward as the most fundamental requirement for indicator quality together with reliability (Innes de Neufville, 1978; Bollen, 2001). WHO (2006) defines validity most simply: 'An indicator must actually measure the issue or factor it is supposed to measure'.

NCHOD (2005) adds a bit more substance: "Will the indicator measure the phenomenon it purports to measure i.e. does it makes sense both logically and clinically?" Hence the distinction between logical (conceptual) validity and some form of empirical, or practical (clinical) validity is introduced.

Eyles and Furgal (2002) mention 'Coverage of important dimensions of concern' in their discussion of validity, and then goes further to introduce distinctions between various types of validities that have been identified and applied in research such as 'face validity', 'construct validity' and 'predictive validity'. Each of these notions have specific definitions and associated

assessment methodologies in the technical measurement literature in e.g. psychology and the social sciences (e.g. Crocker, 2001; Leviton, 2001; Bollen, 2004). 'Face validity' for example means an immediate (non-scholarly) assessment of plausibility. 'Construct' validity, on the other hand, reflects the degree to an indicator is actually measuring variations of the phenomenon (construct) it is supposed to relate to - and not ones it is expected not to (Bollen, 2001, p. 7285). Several other dimensions of 'validity' are defined and reported in the literature.

Innes (1990, p. 215) suggest that validity is the most important criterion for an indicator, but unfortunately also an elusive concept to test for because of the many aspects involved. George and Bennett (2004, p. 19) use the notion of 'conceptual validity', which they define as "...indicators that best represent the theoretical concepts the researcher intends to measure", hence is it is relation between a theoretically conceived notion and the measurement. Cloquell-Ballester *et al*. (2006) use the related notion 'conceptual coherence', which has three elements 1) The definition of the indicator and the concepts that comprise it up is suitable; 2) there is correspondence between the indicator and the factor to be quantified; and 3) the interpretation and meaning of the indicator are suitable.

No more in depth review will be made of the complex validity concept here, but we simply note that it is an important notion that must be incorporated, even if simplifications may be needed. Procedures for *validation* are discussed in section 4.3.1.

## 4.2.4.4. Reliability

A companion concept to validity is reliability. The working group described it initially as the ability of an indicator to perform its pre-defined functions in routine circumstances, as well as hostile or unexpected circumstances. According to Bollen (2001) in social science reliability concerns the consistency or stability of an indicator with regard to capturing an underlying latent variable. However while validity seeks to find indicators that mirror the concept, reliability is more concerned with indicators that produce the same results in repeated situations, even if they are not necessarily valid. Reliability is often especially a problem for qualitative indicators that are not measured in a rigorous way.

A number of additional ways to conceive 'reliability' exist in the referenced literature. Eyles and Furgal (2002) mention 'Repeatability across times and sources'. NCHOD (2005) more technically talks about 'Data reliability' defining it as 'agreement [...] between measured records and those collected by an independent source'. Farchi *et al*. (2006) and Goger *et al*. (2009) a bit confusingly mixes it into validity. Niemeijer and De Groot (2008) simply equates reliability with 'a proven track record'. Kusek and Rist (2004) have the following definition 'Reliability is the extent to which the data collection system is stable and consistent across time and space. In other words, measurement of the indicators is conducted the same way every time'.

We consider reliability to refer to a measurement method that yields the same result under similar conditions. If validity is poorly known, high reliability of

a measure may be illusive, but it may also help to identify more valid explanations and indicators. It is clear that reliability must be key concern for indicators.

## 4.2.4.5.  Sensitivity and specificity

Yet another basic criterion is 'sensitivity' (or 'responsiveness') – the ability of indicators to reveal important changes in the factors of interest. One may see this as a further specification of validity and reliability; an indicator must respond correctly when the phenomenon to be indicated changes, and it must do so in a consistent way.

This is particularly important here in combination with 'specificity' – or 'attributability' – the ability to reflect only changes in the issue or factor under consideration (Marsden *et al.*, 2005; NCHOD, 2005; WHO, 2006). The opposite is 'confounding' - the risk that variations in the indicator may be influenced by confounding factors (NCHOD, 2005), or, stated otherwise, indicators should not be influenced by '…exogenous factors that are difficult control for, or that the planner is not even aware of' (Zietsman and Rilett, 2002).

These qualities are important for the ability of indicators to 'isolate transport's share of the impact' (USEPA, 1999), which should be a key concern for environmentally sustainable transport indicators. The proposed term to use here is 'transport sensitivity'.

## 4.2.4.6.  Representativity

A widely used term, which appears in several lists of criteria is 'representativity'. Hauge *et al*. (2005) defines it as 'correlation between an indicator and the issue for which it is supposed to be a proxy'. Representativity is of course fundamentally important, but it seems to be quite inoperational considered as an indicator criterion and overlapping with several other more specific ones. It may equate with validity (does the indicator measure - represent - what it is supposed to?); reliability (is it reliable – representative - under different circumstances?); 'theoretical foundation' (has a cause-effect relation between the indicator and the phenomenon it indicates - represents - been theoretically established and accepted?), and 'sensitivity' (does the indicator reveal – represent - important changes in the factor of interest?). 'Representativity' can also refer to indication of a wider phenomenon than the variable being measured, which brings it close to the notion of 'external validity' which means generalisability of the indicator beyond the entity it directly measures (Leviton, 2001). Moreover 'representativity' can be considered beyond the context of objective measurement to mean an indicator being perceived or accepted as appropriate - representative – of a problem by those involved in using the indicator. Some authors in fact (mistakenly?) place 'representativity' as a criterion related to policy relevance (Hauge *et al.*, 2005, p. 552).

In sum it is not easy to operationalise 'representativity' as a criterion without risking considerable overlap with, or redundancy, of other important criteria. The

outcome of this analysis is not to consider representativity as a criterion, but as a category for the measurement related criteria, as will be demonstrated below.

## 4.2.4.7. Transparency

Transparency is often mentioned in connection with indicator selection methodology, but surprisingly, it has not been possible to find a distinct definition of 'transparency' as a criterion in the indicators literature. However, Hauge *et al*. (2005, p. 552) provide the following useful reflections:

"To judge the quality and relevance of an indicator, users need a transparent presentation of the scientific background and of the uncertainties involved […]. Knowing the underlying assumptions, simplifications, and other scientific judgements is useful, as is knowing how they affect the indicator and the objective to be agreed upon, and how well-founded is the underlying knowledge. [...] We regard four aspects as important for ensuring indicator transparency: a clear description in the context of associated knowledge, its scientific foundation, the robustness of its value, and its performance in a management context."

In this sense transparency could perhaps – like representativity – be understood more as a composite of a number of underlying aspects or criteria, rather than as a criterion in itself. Some of the same elements are covered by other references with terms such as 'theoretical foundation', 'explicit methodology' or 'measurement' (Rice and Rochet, 2005; NCHOD, 2006). In contrast, the OECD (2008) defines transparency very generally as "access to information". The EEA (2004b) has defined transparent indicators also in a simplified way: "Indicator well documented and of known quality". In this way it can be a more restrictive notion, which embody the need for rigorous definitions and procedures that allow an indicator to be objectively assessed.

Moreover is it seems necessary to distinguish 'transparency' from 'interpretability'. While the former concerns the possibility to explain exactly how each an indicator is built, the latter refers to the user's ability to make correct inference and interpretation from the result, regardless of how it is produced. This is not a measurement concern, but one of communication, another crucial aspect of indicators (Innes, 1998; Morrone and Hawley, 1998). The recommendation here is to retain and distinguish these two notions as separate criteria

Several other criteria treated in the literature may be relevant for the assessment of indicators of transport and environment (such as measurability, data availability, policy relevance, actionability etc), but generally these are either less controversial conceptually than the main ones discussed above, or their further specification is likely to depend significantly on contextual factors, such as the precise policy goals, or the intended scope of an indicator program (or costs); Hence a further review is considered redundant here.

# 4.2.5. A selective list of criteria

From the above analyses two outcomes emerge.

One is a long list of all the criteria that were found potentially relevant for the assessment of indicators of transport and environment and found to have some form of operational definition in the reviewed literature or otherwise. Such a list can be found in Annex 7 and used with caution. The long list suffers from partial overlaps among criteria and lack of guidance for interpretation and application. It can be used as a gross list to start from.

The second outcome is a more selective and consistent set of criteria, which is further detailed and specified in its application. The aim of this main list is to allow a more immediate and manageable assessment of candidate indicators. The selective list has been designed to minimize ambiguity with regard to definitions, and overlapping or redundant criteria, which can be found in many other lists, including the 'long' list in Annex 7.

The following considerations have gone into the design of the consolidated list:

1) The three categories of criteria or 'levels' used to structure the literature review (measurement, monitoring and management) are retained but rephrased as criteria related to a) Representation (or representativity), b) Operation and c) Policy application These are parallel in content to the former labels in terms of the distinctions they offer, but have broader scope.

2) The number of criteria has been kept to a minimum to reduce work load of application, and each criterion has been defined in a way to minimize overlaps and redundancy, following the results of the discussion in section 4.2.4.

3) To assist in the application and interpretation of the criteria, each one has been provided with a definition, inspired form literature as well as added explanatory text and commentary. In addition examples are given for each criterion, in the form of indicator cases that fulfils the criterion, versus counter-examples (in italics) of indicators that fail to fulfil the criterion.

It should nevertheless be kept in mind that even the selective list is tentative, and mainly devised to allow application in internal working group efforts reported the subsequent Chapter 5, before recommendations about criteria for the use in sustainable transport assessment can be given.

Moreover the criteria are only forming a list, and are not yet considered in the context of a procedure for application. This is to be discussed in the following section 4.3.

## Table 25. Selected list of criteria

| Category | Criteria | Definition and commentary | Examples of agreement ----------------- *Counterexamples (disagreement)* |
|---|---|---|---|
| REPRESENTATION | Validity | **A valid indicator must actually measure the issue or factor it is supposed to measure** (WHO, 2006). A valid indicator must be based on a conceptual model that justifies how the indicator and the issue are causally connected. The model should be well accepted by the scientific community involved in the particular field (conceptual validity). The indicator should be defined explicitly by a standard international terminology and should identify clearly its input parameters and causal mechanism. The validity of indicators can be reinforced by statistical tests of the agreement between a prediction obtained from the indicator and other, more direct or 'objective' measurements of the same phenomenon (predictive validity). Predictive validity without conceptual validity can however be misleading and should not be considered a substitute. | A large number of scientists from a range of disciplines work on the greenhouse effect, aided by strong internal cooperation, particularly within IPCC. This organisation provides an indicator known as global warming potential (GWP), which is the subject of widespread international agreement (IPCC, 2001). This indicator establishes a simple relation between the emission of gases and the heat energy given to the climate system over a period of time. ----------------- *Chemists have developed a global potential odour indicator (PO), built in the same way as the GWP, that establishes a relation between an intensity of odour annoyance and a quantity of pollutant emitted (Guinee et al., 2002). The global odour is given by the total emissions of pollutants weighted by a coefficient corresponding to an olfactory perception threshold. However, this indicator has not achieved consensus since many specialists underline the fact that sensitive pollution is characterised by annoyance, which is not directly related to the intensity of an odour, but far more to its variation through time.* |
| | Reliability | **A reliable indicator must give the same value if its measurement were repeated in the same way on the same population and at almost the same time** (WHO, 2006). If a scale is used 10 times to measure something that weights 100 kg, and it reads "100" each time, then the measurement is reliable and valid. If the scale consistently reads "150", then it is not valid, but it is still reliable because the measurement is very consistent (after Wikipedia). Reliable indicators allow different people to obtain the same results when operating the indicator. Reliability is therefore often more difficult to obtain for qualitative indicators that involve interpretation as part of the measurement process. Reliability also refers to the consistency of the indicator results when it is applied across the domain (e.g. subgroups, time periods) of the phenomenon it is supposed to represent (representative reliability). | An indicator based on a mathematic formula using measured (or estimated) variable as input parameters is reliable and replicable if it produces the same results every time the same data are entered, with little influence of random error. The formula used to calibrate quicksilver thermometers allows to make a reliable prediction of the temperature because the expansion of the material does not vary randomly but only with temperature (and, to a negligible extent, air pressure). ----------------- *Eksler et al (2007, p. 57) review a range of potential indicators to characterize accident protective measures, including the function of airbags. As they observe using a qualitative indicator such as the very presence of airbags in cars would not adequately reflect the great variety of airbags present on the market and within the vehicle fleet. It would hence not be a reliable indicator of the effectiveness of in-vehicle protective systems.* |

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|---|---|---|---|
| **REPRESENTATION** | **Sensitivity** | **A sensitive indicator must be able to reveal important changes in the factor of interest** (WHO, 2006).<br><br>Indicators should generally react clearly and promptly to significant changes in the phenomenon being indicated.<br><br>The main concern here is transport sensitivity meaning how well the indicator shows the contribution of transport changes in the considered impact evaluated by the indicator (Goger *et al*., 2009). A transport sensitive indicator should identify the effect of transport rather than providing an estimate of environmental quality that may depend on numerous sources (USEPA, 1999).<br><br>Transport sensitive indicators would be ones that could be broken down to subcomponents of the transport system to allow detailed assessment of the cause of the change (e.g. measured by transport mode, vehicle type, speed level etc). | Drivers sometimes suffer from fatigue, which is a potential traffic hazard. Systems to detect fatigue must use indicators that are sensitive to be able to rapidly diagnose signs of fatigue. Fairclough (1997) found some measures of car driving such as measured variation in short term steering adjustments to be sensitive indicators of driver fatigue, while others (like standard deviation of speed) were sensitive to other factors.<br><br>-----------------<br><br>*Black (2002) found that variations in Vehicle Kilometres travelled (VKT) could to a very high degree explain variation in a set of nine other transport variables. However, Black also noted that VKT ignores differences in fuel efficiency. For example, if California would shift completely to zero emission vehicles, it would have (almost) no influence on VKT and we would misinterpret the state's transport sustainability using VKT only. In this regard VKT suffer from low sensitivity as an indicator of transport sustainability.* |
| **OPERATION** | **Measurability** | **A measurable indicator should be straight-forward and relatively inexpensive to measure** (Dale and Beyeler, 2001).<br><br>Measurability is an operational concern. I It is important that indicator can be measured or calculated using easy tools and using simple data that are easily achievable and at a raw level (non elaborated) (Goger *et al.*, 2009).<br><br>Indicators can be measured in different ways using nominal, ordinal, interval or cardinal scales. Qualitative (nominal) indicators may be easier to observe than some quantitative measures but more difficult to measure in an accurate (reliable) way if it involves interpretations. Indicators on a cardinal quantitative scale are typically the most measurable, and able to provide the most information through measurement. Simple indicators are easier to measure than aggregate ones combining several data streams. | The number of motor vehicles in a country is measurable rather exactly via the legally required vehicles licensing and registration. Other ways to measure the number of motor vehicles include manual or automated traffic counts, satellite and area cameras, or surveys and interviews. Each method may allow different degrees of accuracy and different attributes of the vehicles to be measured together with the simple numbers.<br><br>-----------------<br><br>*The 'average' degree of satisfaction with the public transport service in European cities cannot be measured in studies where the satisfaction is expressed on an ordinal Likert scale (Ferrari and Salini, 2008). Likert scale typically has categories such as allowing to 'agree', 'strongly agree', 'disagree', 'strongly disagree', named after psychologist Rensis Likert.* |

| | | | |
|---|---|---|---|
| **OPERATION** | **Data Availability** | **Data available indicators are Indicators based on (input) data that should be readily available or made available at reasonable cost and time** (OECD, 2003).<br><br>The data have to be accurate, comparable over time, complete with historical information and covering sufficient geographic area (Boyle, 1998).<br><br>Time, cost, ownership or work required could be considered as parameters in the assessment of data availability for an indicator. Some data are readily available immediately (e.g. on www). Some are less available while some could potentially become available with the use of new technology.<br><br>Timeliness is a particular concern associated with data availability. Timeliness can be defined as the degree to which data values or a set of values are provided at the time required or specified (Batalle *et al.*, 2004). An operational measure proposed by NCHOD (2005) is the average time (months) between measurement and results. | Comparable data for urban traffic systems in Europe are often lacking through the work in the so-called 'European Common Indicators' and the 'Urban Ecosystem Europe 2007' report (Ambiente Italia, 2007). Comparable data on a number of indicators have become available, via a coordinated effort of data collection and reporting involving 32 cities. Hence it is now possible to compare e.g. the average length of dedicated cycle lane per inhabitant, as one indicator for 'better mobility'.<br><br>------------------<br><br>*The TERM indicator set contains an indicator (TERM 39) 'Uptake of environmental management systems by transport companies'. The indicator has been defined conceptually but is has only been produced once (in EEA, 2000). The indicator has been omitted from all subsequent annual TERM report since data have not been collected since 1999.* |
| | **Ethical concerns** | **An indicator must comply with fundamental human rights and must require only data that are consistent with morals, beliefs or values of the population** (WHO, 2006).<br><br>The criterion has been introduced in the human health assessment context to ensure that health data collection does not violate privacy or other ethical concerns of people. Similar concerns might be appropriate with regard to other aspects of human and social activity (e.g. transport behaviour, criminal records, property exposure to environmental pressure, etc). An indicator should not be based on data that are offensive for people to report or could be used against them. | In travel surveys such as the Danish TU (DTU Transport, 2009) information is collected about travel activities including 'private' information about people's choice of destinations, travel purposes, timing of trips, etc on a certain day. The use of the data is restricted by privacy safeguards. Users have to sign up to confidentiality agreements.<br><br>------------------<br><br>*Collecting data to produce performance indicators on drunk driving as a cause of accidents is hampered by a number of factors, one of which are privacy concerns, which in some countries disallows for example police to collect blood alcohol data from test made at autopsies. It is an ethical question if privacy of deceased persons should be violated to improve data quality for accident reporting.* |

| | | | |
|---|---|---|---|
| **POLICY APPLICATION** | **Transparency** | **A transparent indicator is one which is feasible to understand and possible to reproduce for intended users.**<br><br>The conceptual model must describe in an understandable way how the indicator is constructed. Input data, assumptions, methods, models and theories must be accessible. Transparency allows the user to check the calculation and therefore to trust in the figures. Transparency is associated with but not identical to simplicity. A simple indicator may be more attractive because it easier to show how it is produced. However, complex indicators may also be transparent if the methodology is well justified, well defined and well explained. | Innes describes a process involving an environmental management plan being developed for the San Francisco Bay in California in the 1990s. A number of stakeholder organizations formed a consensus about how to measure water quality in the Estuary. Transparency of the process in which the indicator emerged contributed to create trust in and acceptance of the result, as opposed to measures predefined by external experts (Innes, 1998).<br><br>-----------------<br><br>*Sager and Ravlum (2005) report a case where the cost-benefit ratio was used as an indicator to inform political decision about a rail freight terminal in Norway. The results were based on assumptions about the benefits of transferring freight from road to rail transport. However these assumptions were not documented in any of the underlying reports. The politicians had no way to control how the results were produced. It is not the method, but how it is applied that fails.* |
| | **Interpretability** | **An interpretable indicator allows an intuitive and unambiguous reading.**<br><br>It must be possible to draw clear conclusions from reading the indicator. Interpretability depends on how well the indicator varies with what it represents (the phenomenon in focus), and how it is influenced by uncertainties. It should move in an analogue fashion to the phenomenon. | Number of people killed in traffic is an intuitive and unambiguous indicators of traffic safety. Few people could dispute or misinterpret that it is negative when the number increases.<br><br>-----------------<br><br>*The Lyon conurbation developed some years ago an indicator of air pollution, based on pollutant concentrations (Rousseaux, 1994). As this indicator is a decreasing function of the concentrations, it is easy to misinterpret its outputs.* |
| | **Target relevance** | **A target relevant indicator must measure performance with regard to articulated goals objectives, targets or thresholds.**<br><br>If the environmental impact concerned is quantifiable (quantitatively), an indicator should make possible a comparison with any relevant threshold or reference value (standard, political target...). If there are no quantified targets or thresholds the indicator should be considered in terms of its relevance for non-quantified policy objectives or goals.<br><br>Indicators that do not or cannot measure performance with regard to any goals or targets are less supportive of management and decision making function of indicators. | The European Commission has established the European Road Safety Observatory. In the Basic Fact Sheet Main Figures (ERSO, 2007) we find the number of road accident fatalities in Europe 1990-2006. This figure is comparable to the road safety target for Europe of a 50 % reduction in the number of annual fatalities from 2001 to 2010. The report provides the indicator together with an assessment of target fulfilment.<br><br>--------------<br><br>*"The lack of targets for some of the indicators (e.g. all-cause mortality and childhood poverty) may be a deterrent to monitoring"* (Zucconi and Carson, 1994, p. 1645). |

<table>
<tr><td rowspan="2" style="writing-mode: vertical-rl;">POLICY APPLICATION</td><td rowspan="2" style="writing-mode: vertical-rl;">Actionability</td><td><strong>An actionable indicator is one which measure factors that can be changed or influenced directly by management or policy action.</strong><br><br>Actionability refers to the role of indicators as tools to support decisions and management. The indicator can be directly actionable by measuring a parameter that is also a policy variable (e.g. number of police controls to check vehicle emission control equipment), or indirectly by measuring something that can be influenced by policy (e.g. population exposure to air pollution above limit values). An indicator directly measuring the parameters of decisions (e.g. funding decision) are more actionable than indicators measuring the general environmental conditions (e.g. temperature rise of the atmosphere). The point of actionability is that follow-on action to the indicator should be immediately apparent (WHO, 2006).</td><td>Road construction has significant negative impact on habitats. The US Federal Highways Administration has adopted a performance target measuring the number of so-called Exemplary Ecosystem Initiatives (EEI), which are actions or measures that will help sustain or restore natural systems and their functions and values. Each EEI is counted and the results compared with an annual target value of 50 projects, which was just reached for 2007 (US DOT, 2007). The measure is actionable considering that the FHWA can control the number of initiatives initiated.<br><br>------------------<br><br>*"In the context of European road safety, variables describing differences in weather conditions in different countries might help an understanding of why accident rates differ across Europe. However, such variables are not "actionable" in the same sense that variables describing variations in infrastructure quality, for example, would be."*<br>*(Rackliff, 2008).*</td></tr>
</table>

# 4.3. Frameworks and methods for assessing indicators

This section will consider how criteria sets can be applied to assess or develop indicators, beyond simply listing individual criteria as discussed in section 4.2. The consideration of methodologies and procedures for indicator assessment and validation represents an important step in the work on indicator development, as noted in another context by the US National Commission on Science for Sustainable Forestry (NCSSF):

*"The bottleneck in effective selection and use of indicators is not a lack of good indicators or good science, but rather the lack of [...] a clear process for electing indicators. [...] The reliability of identified measures is frequently questioned, at least in part because selection of indicators often has lacked transparency, social inclusiveness, and/or a logical structured process of selecting indicators."* (NCSSF, 2005, cited from Niemeijer and de Groot, 2008)

Although there may be several 'bottlenecks' for the identification of appropriate indicators (including lack of both good candidate indicators and science), this section will follow this line of reasoning by seeking to review and establish procedures for indicator assessment and selection.

At the most general level three different pathways to the development of indicators have been described: so-called theory-driven, data-driven, policy-driven approaches (Niemeijer, 2002; Hanafin and Brooks, 2005; Niemeijer and

De Groot, 2008). A *theory-driven* approach is defined as one that focuses on selecting the best possible indicators of a particular system or problem from a theoretical or scientific point of view (Niemeijer, 2002). A *data-driven* approach means that indicators are mainly selected on the basis of the availability of data that are suitable as input data for indicators. Existing data sets are exploited inductively to develop a range of potential indicators. In a *policy-driven* approach indicators are developed for issues that are currently on the political agenda and for which indicators are politically in demand, for example based on policy objectives and targets. Hanafin and Brooks (2005) suggest that all of the three approaches should be combined in order to arrive at appropriate sets of indicators that would be measurable, representative, and useful.

The three approaches roughly correspond to the three types of criteria for selecting indicators that have been identified in this report, namely as criteria related to representation / measurement ('theory driven'), to operation / monitoring ('data driven') and to application / management ('policy driven'). Each group of criteria could thus support primarily one part of a process towards the identification of broadly acceptable indicators. Ultimately the aim of this report concurs with the idea of combining the approaches, as in the attempt to connect 'measurement' and 'decision making' aspects of indicator selection. The starting point has been taken in the measurement or 'theory driven' dimension, with the question of how well existing or possible new indicators describe individual impacts of transport activity or policy interventions on the environment. Monitoring and in particular management aspects have been considered as additional important concerns. The question here and now is how to make the approaches operational, and possibly combine them.

Meanwhile, authors like Hoppe (2005) and Turnout *et al.* (2007) suggest that the different 'approaches' are not randomly chosen and that harmony between them is not a given opportunity. The acceptance of scientifically based indicators in policy and decision making may for example depend on the degree of consensus about the basic underlying knowledge, and also about the degree of shared values involved in decision making. In cases of conflict or uncertainty policy and theory driven approaches may never meet. Where to start the process, and which type of criteria to build on may well depend on the status of the knowledge in each particular area to be measured by proposed indicators. The problem will be addressed later again in this section.

The section will first consider a number of frameworks and procedures proposed in the literature and will then consider ways to apply and adapt them for application in the present context.

## 4.3.1. Validation frameworks and selection procedures

In the indicator literature can be found a number of more or less elaborate methodologies for how to perform the identification, evaluation, selection and application of indicators using criteria in various ways. The references identified

all roughly follow the general logic proposed by Boyle (1998) involving three main steps:

− Generation of indicator selection criteria
− Generation of potential indicators
− Selection of indicators.

A number of contributions seek to establish logical frameworks and general procedures to undertake these steps. Three examples are Innes de Neufville (1978), Bockstaller and Girardin (2003), and Cloquell-Ballester *et al*. (2006) who all refer to the need for indicator *validation*. By validation they generally mean procedures and criteria to ensure acceptance of indicators as appropriate by scientists, but also by indicator users. A few works reported in the literature define more specific practical step by step approaches for using criteria with associated guidelines or sub methods for each step. Examples include (again) Cloquell-Ballester *et al*. (2006), Jackson *et al*. (2000), Kurtz *et al*. (2001), NCHOD (2005) and not least Rice and Rochet (2005), who in an accompanying paper (Rochet and Rice, 2005) even reports a test of their methodology.

Below a number of these references are reviewed moving from general to more detailed, practical and reflective approaches. It should be noted that the examples are from the prescriptive literature about somewhat idealised methodologies. The text does not pretend to describe or critique how indicator selection processes normally or generally are conducted in practice.

Bockstaller and Girardin (2003) propose a framework for validation of environmental indicators. The authors understand indicators as variables having dual functions: as information tools for complex systems, and a decision support function. Even if indicators are not exact models, their development and assessment should follow somewhat similar scientific standards. However, procedures to ensure this are rarely specified in the literature.

Bockstaller and Girardin suggest three steps of indicator validation inspired from model validation, namely 'design validation', 'output validation', and 'end-use validation'. Design validation is concerned with confirming the conceptual quality of the indicator, how well founded in theory the representation of the indicator is. This is typically done in expert's reviews of proposed indicators.

Output validation focuses on the information function of indicators, and if the indicator produces reliable results (values). This is where the parallel with model output validation may be most appropriate. However, Bockstaller and Girardin recognize that indicators are often difficult to test like models, as sufficient studies may not be available. Again 'expert validation' will often be the only method to assess the output of an indicator.

Finally the end-use validation concerns the usefulness of the indicator for decision making. According to Bockstaller and Girardin, such a validation requires the input from users. An axample could be whether planners need average or marginal data for each environmental impact. Summing up, validation is divided into design, output and end user processes. The starting point is design validation, and the output validation should be done by thinking in parallel to models as far as possible. Which methods to use for output validation depends on whether there is (only) casual assumptions, or a

simulation model behind the indicator, and what kind of data are available. Users are bought in as part of end-use validation.

Cloquell-Ballester *et al.* (2006) build on the ideas of Bockstaller and Girardin but provide more detail about the procedures and groups involved in the different validation steps. They term the method '3S validation', 'Self-validation', 'Scientific validation', and 'Social validation'. They add a multi-criteria methodology to systematize the criteria based indicator scoring involved. The assumption is that '3S-validated' indicators will not only guarantee quality and reliability but will also support public participation and broader consensus in the use of indicators for assessment (Cloquell-Ballester *et al.*, 2006, p. 81).

The starting point for the methodology is a new proposed indicator design. Then follows a series of steps to describe and evaluate the indicator(s). First a basic 'indicator report' is drawn up with available documentation. Next a set of criteria for assessment are defined. Cloquell-Ballester *et al.* propose 12 criteria, organised in three groups, 'conceptual coherence', 'operational coherence' and 'utility' (closely corresponding to the ones proposed in this report, see section 4.2.5).

The indicators are then assessed by three different groups representing the three 'S's. The first S refers to 'self validation', which involves the working group undertaking the indicator development itself (similar to internal working group efforts in the present report). The second S is 'scientific validation' where a group of external experts undertake the same assessment in a Delphi setup. For the third S 'societal validation', groups of stakeholders are invited to take part in a similar process. A 'process-controller' is engaged to assist and encourage the work. The assessment process uses a similar methodology for each group involving a number of steps. First the indicators are scored according to the individual criteria on a five-point Likert-scale. Then the results are aggregated to the level of the three categories to reach an overall assessment for each category using weights suggested by evaluators and a multi-criteria methodology. This leads to a judgment of the indicators in four categories, from 'validated' (high scores and low deviation in all categories) to 'unacceptable' (the opposite).

A case is described where four indicators relevant for assessing the location of industrial facilities are tested with the 3S method. The three teams give rather similar scores to the indicators. Their relative weights of the three categories differ strongly however, where 'scientists' place great emphasis on 'operational' criteria, while stakeholders not surprisingly emphasize 'user' criteria. They agree on the importance of 'conceptual' criteria. The aggregate scores are found to differ significantly depending on the multi-criteria method used to reach a result on the level of the category. The validation of indicators is partly achieved. The subsequent practical legitimacy of the assessment (to confirm if the method actually supports consensus etc) is not addressed.

In summary the '3S' method provides a rigorous framework and procedure for indicator assessment. Its core methodology is a qualitative (expert and stakeholder based) assessment of pre-defined indicators using individual criteria combined with multi-criteria methodology. The method as such is not

dependent on the exact criteria or categories used in the case. It is assumed but not verified if application to all three groups enhances the overall legitimacy.

Rice and Rochet (2005) provides one of the most detailed reports of approaches to the selection of indicators, as applied in the context of fisheries management. It involves a procedure with eight steps, as shown in Table 26. The potential indicators to be assessed in the case example measure either the conditions of the fish stocks or the environmental conditions for fishing. After deriving the method, two of the critical steps are tested using trial groups of experts assessing candidate indicators for a range of marine ecosystems.

**Table 26. Framework for selecting indicators
(Rice and Rochet, 2005)**

1. Determine user needs
2. Develop a list of candidate indicators
3. Determine screening criteria
4. Score indicators against criteria
5. Summarize scoring results
6. Decide how many indicators are needed
7. Make final selection
8. Report on the suite of indicators

In summary the work specifies practical steps involved in indicator assessment, and suggests specific approaches and methods for each step, from definition and weighting of criteria, to assessing available knowledge, to scoring, to reporting results for a suite of indicators. Like in the previous studies, it acknowledges the different perspectives of various groups (experts, decision makers, etc) although here this is addressed by experts assigning presumed criteria weights for each group. The method is considered useful and applicable overall, but does not guarantee elimination of subjectivity or personal perspective from the selection of indicators. Parts of the guidance are specific to the area of fisheries management (e.g. the ranking of types of evidence, and conclusions regarding specific indicators).

Finally to review is the guidance for indicator assessment provided by the National Centre for Health Outcomes Development (NCHOD) in the UK. The guidance is based on assessment of a range of criteria and methods found in 18 different references. Criteria are divided into four groups: scientific criteria, policy criteria, methodological criteria, and statistical criteria.

As a unique element among the studies considered here, the NCHOD report suggests a distinction among criteria according to which state of development the indicator is in, whether it is under development, whether it is in the measurement phase, or whether the results are to be interpreted. These stages are to be considered consecutive and exclusive, meaning that an indicator should not proceed to the next stage (e.g. 'measurement') if it does not score sufficiently in the previous one (e.g. 'development').

## 4.3.2. Summary discussion of criteria methods and frameworks

The following points can be drawn from summarizing the review of criteria based methods.

First of all there is more to the selection of indicators than simply to assess them using a set of universal criteria. A universal list of criteria for assessing indicators does not exist; the set has to be composed in relation to the needs.

Secondly, criteria are themselves often composed of several concepts or subcriteria, which may disallow fully objective application of a criterion. An option is to break down criteria into sub-components, leading to more, and possibly more unique criteria. According to Rochet and Rice (2005) longer criteria lists may be less controversial to apply than more condensed ones. However they could also increase the risk of overlap, excessive workloads, and missing ability to score some criteria.

It is generally recognized that the relevance and applicability of criteria vary according to a range of aspects, such the purpose of the indicators, and who is doing the assessment. One way to approach this is to let indicator users apply weights to each criterion before the indicators are scored. In the framework of Rice and Rochet (2005) this is performed by experts assuming different usage positions. In other approaches like the ones proposed by Bockstaller and Girardin (2003) and Cloquell-Ballester *et al*. (2006), the assessment of the indicators is undertaken in consecutive rounds involving different groups e.g. from scientists, to epistemic communities, to end users. Generally it is assumed that scientists and experts are the ones most concerned with criteria for accurate representation, such as validity, reliability and sensitivity, but these criteria are not irrelevant or generally disregarded by other groups.

The application and weight of each criterion may also depend on what kind of evidence is available. Different types of evidence may be used, depending partly on which type of phenomenon the indicator is supposed to measure (e.g. if it measures a physical dose-response relation, or if it measures the satisfaction with a given condition). In some research areas (like fisheries management), a hierarchy of methods may be established, allowing a transparent assessment of the strength of the evidence behind the indicator scoring, while this is not necessarily the case in all areas (or a hierarchy may have to be established). As pointed out by Innes de Neufville (1978), the types of evidence is likely to affect the trust that policy makers and other users bestow on the indicators, where generally indicators based in theory as well as confirmed by statistical correlation is likely to be most easily accepted. However, in many cases evidence in the form of 'expert judgement' seems the only feasible approach. According to NCHOD (2005) the stage in the development of the indicator can also be a consideration in connection with choice or weight of criteria.

The actual assessment of indicators is typically done by individuals or groups, using simple scores with a limited number or ordinal levels, and sometimes criteria weights. Some methods apply mathematical tools to reach

aggregate scores and ranks of indicators, as exemplified by the multi-criteria approach of Cloquell-Ballester *et al*. (2006). However Rice and Rochet (2005) strongly warns that this may assume too much homogeneity in the knowledge available for each indicator, and mask subjective interpretations of criteria. In short overly sophisticated methods may belie the ambiguousness of the underlying knowledge.

A general observation is that explicit criteria are useful or even essential for the rational assessment and selection of indicators, but application of criteria is sensitive to purpose, type of problems addressed, users applying them, available knowledge, stage in the process, and other factors, and the processes should in no way presume to be neutral or objective. Systematic approaches may eliminate some of the randomness, and in any case help to increase transparency and dialogue, but are not developed to prescribe 'secure' methods to find the best possible indicators.

# 4.4. Proposed approach and recommendations

In this section a general approach to assess indicators for transport and environment is proposed, and then more specific next steps to be conducted within the context of this report are submitted.

## 4.4.1. General approaches for the assessment of EST indicators

Indicators for environmental impacts and sustainability of transport could be assessed, developed or selected using quality criteria and systematic methods to identify and apply appropriate criteria as discussed in this chapter.

As demonstrated in Chapter 2, transport is a contributor to a wide range of environmental impacts. For some impacts many indicators exist, while for others there may be few or none. In principle a review of potential indicators should be conducted for each impact, using such an approach. The purpose should be to identify good indicators as well as areas where indicator development is needed. The work to review indicators per impact should primarily be conducted by researchers and advisors, with limited involvement of policy makers and stakeholders.

In addition it could be a possibility to apply a similar systematic approach for the identification, assessment and selection of indicators for a range of more specific policy, planning or decision making situations. This could allow to take into account how criteria should be combined and weighted in order to reflect specific needs or situations. Some short term planning situations could for example require that emphasis is put on criteria like data availability, while other areas where there is high controversy over facts, criteria of scientific validity and reliability could be emphasized. These procedures and templates should be

worked out in collaboration between researchers, advisors, policy makers, external users and stakeholders.

## 4.4.2. Approach and guidelines for subsequent internal work

The work in this report seeks to construct or select 'indicators per environmental impact' using criteria and methods as identified here. The context of the continued work fits with the main approach suggested above, even if time, capacity and expertise to assess indicators in depth for all environmental impact chains identified in Chapter 2 is limited compared to literature such a Rice and Rochet (2005). Potential Indicators for a small set of impact chains will be analysed. Key objectives of this work are to identify and review indicators per impact, to try out the proposed assessment approach, and to discuss how indicator availability and quality vary across selected different impact areas.

The process can resemble the first step, 'sui validation' (or 'self' validation by a working group), as described in the three stage methodology of Cloquell-Ballester *et al*. (2006), or the 'research team' efforts of Rice and Rochet (2005). It should be emphasized again, however, that the effort here is more limited due to limited capacity to assess several impacts. Therefore the outcome cannot be finally recommended indicators, but rather a first review of them and an appraisal of the method.

The following guidelines refer to the literature review and discussions in this chapter and in particular using the list of criteria presented in Table 25. The aim is to support the assessment of indicators for a limited number of environmental impacts of transport selected among those identified in Chapter 2. The approach is intended to be simple, manageable and comparable.

### 4.4.2.1. Consider what is to be indicated

For the assessment of each selected impact, its title and main contents should be given to clarify 'what is to be indicated'. This involves a reflection of whether the chain or impact is clearly defined or not in terms of causes and effects. If it is not clearly defined it is more challenging to suggest good indicators. If the role of transport in the impact is unclear, it is also more difficult to suggest good indicators. If there are several dimensions involved in the impact itself (e.g. different endpoints for the impact, such as simultaneous short term and long term effects for the health impact of a particular air pollutant), this may also challenge the identification of adequate indicators.

### 4.4.2.2. Consider situation(s) where the indicators are needed

Assumed need and purpose of the indicators can further help to specify what the indicators are supposed to describe and evaluate. The basic option is to imagine that the indicator is assessed as a generic descriptor of the causal chain without any particular purpose in mind (as generic types of assessment

are considered here). Reviewing the specific appropriateness of the indicator could however be helped by imagining different application situations.

### 4.4.2.3. Weights and aggregations of criteria / categories

In this limited approach it is not proposed to rank the criteria. In a more realistic setting weighting of criteria according to their importance or significance for a particular policy application could for example be considered.

### 4.4.2.4. Describe the candidate indicators

Potential or 'candidate' indicators are described. The indicator descriptions cannot avoid reflecting the specific character of indicators for each unique impact type. However the descriptions should be to some extent harmonized. Some key elements to consider (if not necessarily copy) for each candidate indicator include:
− definition
− formula (if applicable)
− single or multiple dimension (ex index) indicator?
− location in DPSIR type chain
− amount of documentation available, e.g. 'multiple scientific sources' / 'few scientific sources'
− example of use in practice e.g. for transport assessment, monitoring, evaluation

### 4.4.2.5. Score each potential indicator with all ten criteria

The candidate indicators can be scored using the criteria in Table 25. It is proposed to use a simple four level ordinal ranking, 1) 'Poor', 2) 'Limited', 3) 'Good', 4) 'Excellent'. The assessor (author) will have to use his/her own best judgment, and possibly consult literature. In realistic settings a team of assessors per impact should be involved.

There will obviously be different ways to use and interpret the scoring. The meaning of the 'quality' of an indicator and the associated score have to be considered individually for each criterion. It should be noted to what extent an assessment score refers to the actual quality of the indicator, or to the degree of available knowledge about it. Scores 'good' or 'excellent' should only be given to indicators that are well established in research or otherwise well documented.

### 4.4.2.6. Summary assessment

A summary assessment should be made for the set of indicators considered per impact taking into account scores on all criteria. Generally, a summary assessment could aim to
− Optimize: rank the indicators according to performance on all criteria to choose the best indicator

−  Satisfy: allow to identify one or more indicators that are passing some defined threshold and become 'recommended' (e.g. hypothetically: "at least 'good' or 'excellent' for 6 out of 9 criteria, and none with 'poor' ")
−  Reject: allow to discard some indicators
−  Fuzzy optimization: allow a qualitative distinction between 'better' and 'worse' ones to choose

The suggestion here is to seek only a fuzzy or qualitative type of summary assessment, pointing out

−  If the candidate indicators score differently or are more or less the same level
−  If there are indicators which appear to be good or excellent with regard to all or most criteria
−  if the indicators score differently in the different hypothetical situations (if applied)
−  If there appears to be a need for building new better indicators

# 4.5.  Conclusion

A process to derive criteria and methods for the assessment and selection of environmentally sustainable transport indicators has been undertaken. It has emerged through a combination of literature review and working group discussions. The review has included general indicator literature in areas like environmental assessment, health, resource management, sustainability, as well as literature more specifically on transport and sustainable transport indicators. The working group discussions have addressed particular indicator needs and criteria of relevance for measurement and assessment of environmentally sustainable transport.

It was found that there are many similarities in the criteria applied throughout the literature, although not a full consensus. The transport indicator literature is not always explicit about criteria but tends to import similar criteria as used in other fields, while stressing a special concern for the transport sensitivity of environmental indicators. The general literature also reports a number of methods and frameworks for how to apply the criteria when indicators are to be assessed. No examples of this were found in the transport area.

An important aspect of the methodologies is the relative sensitivity or importance of indicator criteria with regard different contexts such as different indicator purposes and functions, different development of the knowledge, or different user groups. Many attempts are made to categorize criteria into types that reflect such contexts with low agreement over the exact categories to use. In the present work a distinction of literature into 'measurement', 'monitoring' and 'management' oriented indicator criteria literature was adopted, and a corresponding distinction of the criteria themselves into the three related groups of 'representation', 'operation' and 'application' was used.

10 criteria were highlighted and equipped with interpretation and examples. However the partly arbitrary character of such a list must be recognized, and a

potential need to draw in additional or other criteria (as listed in Annex 7) if relevant must be retained.

It is common for published methodologies to suggest differentiation or weighting of criteria according to various contexts. However several studies also assume connections between contexts, which mean first, that most types of criteria are prone to play some role in the process at some time, and second, that the final indicator selection is likely to depend on many other factors than formal criteria.

The scoring of indicators themselves is often made with simple ordinal scales administered by experts or sometimes wider groups of stakeholders. Sophisticated multi-criteria methods to allow ranking of candidate indicators have been applied in some cases while other scholars warns that this may mask underlying inherent ambiguities and subjectivity, making the results difficult to interpret clearly.

Based on the review, it was recommended to promote further work in the area of indicator assessment for the environmental impacts of transport. A general, simplified approach for assessing indicators was proposed, along with a suggestion to undertake more specific indicator assessments where concrete planning situations or needs are taken into account.

# 5. Assessment of some indicators within an impact

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A thorough presentation and discussion of principles for the selection and building of indicators was given in Chapter 4. Chapter 4 also discussed the role of different kinds of criteria for the selection or building of indicators. A procedure applicable for the selection or building of environmental indicators for transport was arrived at in section 4.4.2. The procedure, including the use of ten criteria listed in Table 25, is brought further in the present Chapter 5. This is done by presenting how the suggested procedure can be applied to seven of the chains of causalities described in Annex 6: direct toxicity of air pollutants (section 5.1), natural habitat fragmentation (section 5.2), non-renewable resource use (section 5.3), loss of cultural heritage due to land take (section 5.4), noise as annoyance to humans (section 5.5), greenhouse effect (section 5.6), and waste (section 5.7). The seven chains have been selected so as to

− be of value for European-level policy makers
− be of value for national government policy makers
− be of value for regional planners and policy makers
− be of value for researchers and other academics
− be pedagogic
− include causality chains that are qualitatively different
− include chains that are well described and well known

For three of the chains, the application of the different steps of the procedure has been outlined. For six of the chains, examples of existing indicators for a limited number of chain steps are presented and discussed. The chapter also illustrates how the procedure could be applied for the building of an indicator where there is a lack of indicators (section 5.4).

# 5.1. Example chain: Direct toxicity of air pollutants

## 5.1.1. Health indicators

Among primary pollutants originating in direct restricted health impacts on humans (see the description of the corresponding chain of causalities 11 in Annex 6), the particulates (and especially PM10) are considered in most of the epidemiologic studies as the indicator of the pollution responsible for restricted direct health impacts according to WHO (1987; 1999a), Künzli *et al*. (2000) – see also Deloraine and Ségala (2001), Cassadou *et al*. (2002) and Goger (2006a) – or in a more accurate wording, as the cause of the impacts. The impact indicators consider for example:

– the short term impact through:
  - short term mortality (all causes)
  - short term mortality (non-accidental)
  - short term mortality (cardiac)
  - short term mortality (pulmonary)
  - hospital admissions for respiratory reason
  - hospital admissions for cardio-vascular reason
  - hospital admissions for acute bronchitis
  - hospital admissions for children asthma attacks
  - hospital admissions for adult acute asthma attacks

– the long term impacts through:
  - long term mortality
  - chronic bronchitis
  - lung cancer

Long and short term extra-fatalities can be aggregated into the number of lost life years.

All these health indicators can be linked with ambient PM10 level: an increase of each of these indicators is defined for a unit increase of PM10 concentration and per population unit. These functions are determined mainly through epidemiologic studies. Their input data are not a source or pressure (P) factor (pollutant emission) but a state (S) factor (pollutant concentration) in the DPSIR system.

## 5.1.2. Evaluation of health indicators

The evaluation of health indicators presented in section 5.1.1 according to the criteria defined in Table 25, summarized in Table 27, shows that:

– Validity: All the indicators are based on PM10 concentrations but take into account the health impacts of other pollutants only if these pollutants are statistically strongly correlated with PM10. This is usually the case but

exceptions occur. For instance, the relationship may vary between sources, and further research is needed. All the indicators do not represent the health impact. Aggregated indicators should be developed to represent the whole health impact.

– Reliability: As functions, the indicators are fully reliable.

– Sensitivity: As the indicators are not very valid (they are not representative of the whole health impact), they cannot be very sensitive.

**Table 27. Evaluation of the health impact indicators (per unit of increase in PM10 concentration and per population unit)**

| Indicator | Category | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Representation | | | Operation | | | Application | | | |
| | Validity | Reliability | Sensitivity | Measurability | Data availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
| Short term mortality (all causes) | x | xxxx | xx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Short term mortality (non-accidental) | xxx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Short term mortality (cardiac) | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Short term mortality (pulmonary) | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Hospital admissions for respiratory reason | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| hospital admissions for cardio-vascular reason | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Hospital admissions for acute bronchitis | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Hospital adm. for children asthma attacks | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Hospital adm. for adult acute asthma attacks | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Long term mortality | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Chronic bronchitis | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Lung cancer | xx | xxxx | xxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |
| Number of lost life years | xxx | xxxx | xxxx | xxx | xx | xxxx | xxxx | xx | xxx | xx |

x=poor; xx=limited; xxx=good; xxxx=excellent.

- Measurability: The indicators are based on pollutant concentrations, which have to be calculated first, usually using a dispersion model. The measurability is therefore quite low.

- Data availability: The data availability is low (need to calculate them by quite complex modelling).

- Ethical concerns: No problem.

- Transparency: The indicators are very transparent (their building mode is clear).

- Interpretability: The interpretation could be difficult because the indicators are not very representative.

- Target relevance: As the indicators represent only certain types of health impact, a policy target expressed in global health impact cannot be measured through them.

- Actionability: As the indicators take into account only the health impacts statistically correlated with PM10, any policy action that changes other pollutants than PM10 cannot be measured by these indicators.

Among other health-related air pollutants, PM10 is usually included in programmes for the monitoring of air pollutants in cities. An example from Athens is given in Annex 2.


# 5.2. Example chain: Natural habitat fragmentation

Habitat fragmentation is a characteristic and conspicuous effect of the presence of road and rail transport infrastructures and their traffic. Its ecological consequences are still little understood, however. The infrastructure itself takes up land and, together with the traffic, causes disturbance of various kinds in the surrounding area. Modern road and rail networks tend to encroach on landscapes, break up habitats and distort ecosystem functions. This is often in contrast to old road networks that, over a long period of time, have provided prerequisites for the rich biodiversity characterizing many rural European landscapes.

Habitat fragmentation due to transport is an area that only fairly recently has attracted the interest of landscape ecologists, one of the main scientists in this area being Richard Forman (e.g. Forman, 1995).

Habitat fragmentation is primarily attributed to roads and railways but also to canals where these exist. The presentation below is restricted to roads and railways.

A description of the chain of causalities is found in Annex 6 (chain 31).

## 5.2.1. Application situations

Typical situations where fragmentation indicators are, or could be, used are Environmental Impact Assessment of road and rail projects and their follow-up. They can also be used in landscape planning and other forms of physical planning. They may also help indicating the need, and location, of measures to compensate for habitat or landscape damage caused by infrastructure or of actions or measures to reinforce ecological structures or functions in a landscape or ecosystem fragmented by infrastructure and other human activities. They may also be an instrument in planning or following-up of activities concerning nature conservation and outdoor recreation.

## 5.2.2. Relative importance of criteria

For the selection from existing sets of indicators, a recommendation is to use the selection criteria in Table 25 on page 126. In the absence here of a specified application situation, a first option may be to devote equal importance to the ten criteria.

## 5.2.3.  A review of main candidate indicators

The relative ranking of infrastructures present in the landscape according to a certain index can be obtained by calculating the indicator with and without the presence of the infrastructure. The difference is used to measure the impact (Geneletti, 2006; Saura and Pascual-Hortal, 2007).

Following Rutledge (2003), indicators can be classified into tree types: composition indicators, shape indicators, and patch configuration indicators.

### 5.2.3.1.  Composition indicators

Composition indicators describe the basic characteristics of fragmentation. The two basic indicators used to quantify fragmentation are number of patches and patch area. These measures are affected by the resolution. To overcome this, patch density is used (McGarigal and Marks, 1995; Saura and Martínez-Millán, 2001). Others introduced an ecological basis such as core area (McGarigal and Marks, 1995; Ritters *et al*., 1995; Saura and Martínez-Millán, 2001; McGarigal *et al*., 2002; Rutledge, 2003). The formula and description of some of them are shown in Annex 8.

Most species have minimum area requirements. In other words, the individual habitat patch must be larger than the minimum area requirement for the species to occupy the patch. In infrastructure assessments, this kind of indicators can be used to measure whether the area available to the species is reduced below the minimum area needed. Thus, patch size information alone could be used to model species richness and species distribution patterns in a landscape.

These indicators have some limitations: The scale of investigation is an important factor in these indicators. Minimum patch size and landscape extent set the lower and upper limits of these area metrics, respectively. These are critical limits to recognize because they establish the lower and upper limits of resolution for the analysis of landscape composition and configuration (McGarigal *et al*., 2002).

## 5.2.3.2.   Shape indicators

Shape indicators attempt to quantify patch complexity, which can be important for different ecological processes (Forman, 1995). For example, squares and, especially, circles will have less edge and, potentially, more core area. Other shapes, e.g. long, narrow features such as tree lines, or sinuous features such as riparian areas, may have comparatively little core area despite a large total area (Rutledge, 2003). Most measures of patch shape focus on some variation of the perimeter-to-area ratio (see Krummel *et al*., 1987; McGarigal and Marks, 1995; Ritters *et al*., 1995; Schumaker, 1996; Frohn, 1998; McGarigal, *et al*., 2002; Rutledge, 2003). The formula and description of some of the measures are shown in Annex 8.

The primary significance of patch shape in determining the nature of patches in a landscape seems to be related to the 'edge effect'. In small patches, the permeability increases (Saunders *et al*., 1991). Habitat conditions, e.g. solar radiation, temperature and wind characteristics, are modified, which affects the dynamics of species interactions near the edge and consequently alter the original ecosystem. These indicators will be useful when the habitats are sensible to edge effects.

These indicators have limitations too. Although patches may possess very different shapes, they may have identical areas and perimeters. For this reason, they are considered as measures of overall shape complexity instead of measures of patch morphology (McGarigal *et al*., 2002).

## 5.2.3.3.   Patch configuration indicators

Patch configuration indicators measure the degree of connectivity or isolation between patches on a landscape. Connectivity is a vital element of landscape structure (Taylor *et al*., 1993) and is defined as the degree to which the landscape facilitates or impedes the movement of organisms between patches (Taylor *et al*., 1993; Tischendorf and Fahrig, 2000). Although connectivity is considered a "vital element of landscape structure" (Taylor *et al*., 1993), it is difficult to quantify and implement in practice.

Following Rutledge (2003) measures of patch configuration can generally be divided into two categories: indicators based on distances between patches and indicators that compare the overall spatial pattern, often called texture, of a landscape.

*Distance-based configuration indicators*

These indicators of patch configuration are based on distance between patches. The simplest measure of configuration is the nearest neighbour distance (Moilanen and Nieminen, 2002).

These indicators can be useful when habitats studied are sensitive to isolation. As habitat is lost and fragmented, residual habitat patches become more isolated from each other in space and time. One of the more immediate consequences of this is the disruption of movement patterns and the resulting isolation of individuals and of the local population. If movement among habitat patches is significantly impeded or prevented, then individuals in remnant habitat patches may become functionally isolated.

*Pattern-based configuration indicators*

Pattern-based indicators of configuration attempt to provide a measure of the overall complexity of the landscape. They do not have a patch focus and are calculated using the entire landscape. Distance between patches is not calculated straightforward as Euclidean distances. Instead, a measure of distance is based on the organism's least-cost path between the patches (Bunn *et al*., 2000), because some elements of the landscape matrix offer more resistance to movement than others. For instance, if the movement requires crossing a motorway, the energy demand is usually higher (higher cost) compared to moving the same distance in only natural habitat (lower cost). The least-cost modelling combines territorial features, ecological characteristics and Euclidean distance in determining the distance between patches.

These indicators are related with the connectivity idea, and there are a lot of formulations (Li and Reynolds, 1993; Schumaker, 1996; Bunn *et al*., 2000; Ortega, 2004; Beazley, 2005; Pascual-Hortal and Saura, 2006; Martín, 2008). Annex 8 shows the formula of some of them.

The measurement of connectivity needs to take into account both the structural and functional aspects that define connectivity. These aspects are associated with the behaviour of the species that must cross this matrix in order to move between patches (Adriaensen *et al*., 2003). Structural connectedness refers to the physical continuity of a patch type (or a habitat) across the landscape. Some elements of the landscape matrix offer more resistance to movement than others, and can condition the dispersion patterns of organisms. Many studies have used effective distance models that take into account the resistance to the movement of organisms between patches (Bunn *et al*., 2000; Adriaensen *et al*., 2003; Nikolakaki, 2004; Beazley, 2005; Martín, 2008). The formula and description of some of them are shown in Annex 8.

This type of indicators enables the measurement of effects on landscape structure regardless of the presence of an infrastructure that directly affects the habitat patches.

The most important limitation of these indicators is that they require additional territorial and ecological information. Resistance coefficients are needed, that are unique to the ecological phenomenon under consideration.

## 5.2.3.4. Conclusions

There are an important number of indicators to measure habitat fragmentation. They measure different ecological aspects, have limitations and are complementary.

The scale is an important factor. An ecological system works through a variety of scales. Certain characteristics perceived at a particular resolution are not observed on another scale.

Fragmentation indicators need to be complemented with other ecological indicators or/and key species (or habitat types) need to be selected, in order to set meaningful targets.

Fragmentation indicators need accurate and detailed interpretation that includes not only the numerical value of the indicator. In addition to territorial aspects, also environmental aspects have to be considered. For example, in general, fewer and larger patches implies less fragmentation, though the Figure 18 shows that it is not always the case.

**Figure 18. Example of ambiguous interpretation of habitat fragmentation: The disappearance of small patches (habitat loss) increases the mean patch size (Geneletti, 2002)**
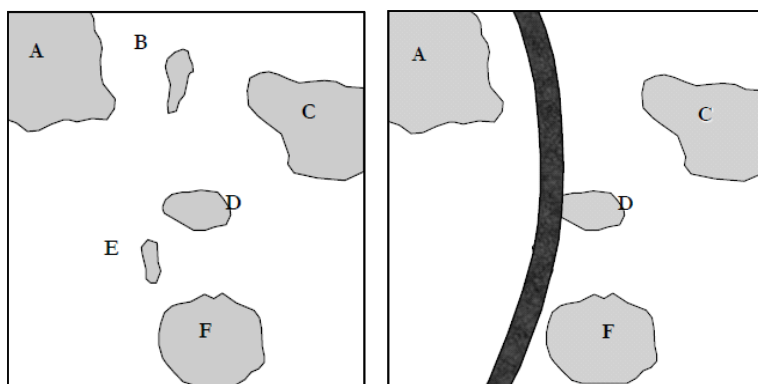


# 5.2.4. Application of criteria for the choice of indicators

A list of criteria for the selection of existing indicators is given in Table 25. Using these criteria, an evaluation of the fragmentation indicators briefly presented above and described in more detail in Annex 8 is given in Table 28. It shows that:

– Validity: All indicators are based on the conceptual meaning of habitat fragmentation. The differences between them depend on the degree of complexity with which they evaluate aspects of fragmentation.

– Reliability: As functions, the indicators are fully reliable.

**Table 28. Evaluation of the fragmentation indicators**

| Indicator | Representation | | | Operation | | | Application | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Validity | Reliability | Sensitivity | Measurability | Data Availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
| Number of patches, NP (Turner *et al*., 1989) | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | x | x |
| Mean patch size, MPS (McGarigal *et al*., 2002) | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | x | x |
| Largest patch index, LPI (With and King, 1999; Saura & Martínez-Millán, 2001) | xxx | xxxx | x | xxxx | xxxx | xxxx | xxxx | xxxx | x | x |
| Patch density, PD (McGarigal and Marks, 1995; Saura & Martínez-Millán, 2001) | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | x | x |
| Average patch carrying capacity, Kavg (Vos *et al*., 2001) | x | xxxx | x | x | x | xxxx | xx | xx | x | x |
| Core area (McGarigal and Marks, 1995; Schumaker, 1996) | xxx | xxxx | x | x | x | xxxx | xx | xxx | x | x |
| Perimeter area ratio, P/S (Krummel *et al*., 1987; McGarigal and Marks, 1995) | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xx | x | x |
| Shape index, SI (McGarigal and Marks, 1995; Schumaker, 1996) | xxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxx | x | x |
| Square pixel, SqP (Frohn, 1998) | xx | xxxx | x | xxxx | xxxx | xxxx | xxxx | xxx | x | x |
| Nearest neighbour, $d_{ij}$ (Moilanen and Nieminen, 2002) | xx | xxxx | x | xxxx | xxxx | xxxx | xxxx | xx | x | x |
| Relative size of the biggest patch in the landscape, $RS_i$ (Turner, 2001) | xxxx | xxxx | x | xxxx | xxxx | xxxx | xxx | xxx | x | x |
| Connectivity index, CI (Martín *et al*., 2007) | xxxx | xxxx | xxxx | x | xxxx | xxxx | xx | xx | x | x |
| Patch cohesion (COH) index (Schumaker, 1996) | xxxx | xxxx | xxxx | x | xxxx | xxxx | xx | xx | x | x |
| Integral index of connectivity, (IIC) (Pascual-Hortal & Saura, 2007) | xxxx | xxxx | xxxx | x | xxxx | xxxx | xx | xx | x | x |

x=poor; xx=limited; xxx=good; xxxx=excellent.

– Sensitivity: Some of the indicators are very capable of revealing important changes in the factor of interest. However, others are not sensitive to certain actions that cause habitat fragmentation.

– Measurability: It depends on the complexity of the indicator. Some of the indicators require complex software and a lot of time for calculation because large amounts of information are taken into account.

– Data availability: They require digital maps. The data availability is high when the indicator is based only on territorial structure, shape of patches, etc. It is low when the indicator is based on ecological factors.

– Ethical concerns: No problem.

– Transparency: Most of the indicators are very transparent. Some of them are less transparent because it is necessary to have some knowledge of ecological aspects.

– Interpretability: The interpretation could be difficult because some knowledge of ecological aspects is required.

– Target relevance: the indicators are low in target relevance.

– Actionability: the indicators are low in actionability.

## 5.2.5. DPSIR chain

Regarding the DPSIR approach described in section 1.4, habitat fragmentation indicators correspond to the S (State) category.

# 5.3. Example chain: Non-renewable resource use

Non-renewable resources are broadly defined as natural resources, which do not regenerate in due time with regard to their consumption rates. Typical examples of non-renewable resources are minerals and fossil fuels such as crude oil and natural gas. Another example is land, which, however, is not considered in detail here.

Instead of 'non-renewable resources', the term 'abiotic resources' is also used. Abiotic resources can be flows, funds or stocks. Depending on the definition, abiotic resources include both minerals and fossil fuels or only minerals (see e.g. Guinée *et al*., 2001; Goedkoop *et al*., 2009).

The issue of non-renewable resource depletion has been prominently raised by Meadows *et al*. in their book 'The Limits to Growth' (Meadows *et al*., 1972). Since then, the focus has shifted away from this issue. However, with the increasing discussions on peak oil and decreasing uranium resources as well as the emergence of technologies based on scarce metals such as gallium, indium, platinum or ruthenium in, e.g., automotive catalysts, consumer and office electronics or photovoltaics, the issue has recently come to the fore again.

A necessary prerequisite for measuring resource depletion is the application of a life cycle approach which considers all relevant processes from cradle to gate, from cradle to grave, or from well to wheel. The target resource indicator in transport applications, however, must be the dissipation of critical resources, which stands for the irreversible loss of these resources. This, in turn, requires a model of the system, which adequately represents resource dissipation and the associated processes, including recycling.

# 5.3.1. Indicators of non-renewable resource use

In the Life Cycle Impact Assessment (LCIA) community, possible indicators for abiotic (stock) resource depletion have been discussed for many years, e.g. in the context of the life cycle initiative of the Society of Environmental Toxicology and Chemistry (SETAC). Whereas there is a broad consensus that impact category indicators should represent significant environmental issues, there seems to be less consensus on how relevant the issue of abiotic resource depletion is and by which type of indicator it should be represented.

For Udo de Haes *et al*. (1999), possible abiotic resource depletion indicators are:
− rareness of resources
− exergy content of resources
− mineral concentrations
− degree of use of flow resources in relation to the size of the flow
− total material requirement
− indicators related to other categories, such as energy requirement or land use

According to Steen (2006), who mainly focused on mineral deposits, mainly four types of abiotic resource depletion indicators are discussed in the Life Cycle Assessment (LCA) community:
1. Indicators based on energy and mass
2. Indicators based on the relationship between use and deposits
3. Indicators based on the future consequences of resource extractions
4. Indicators based on exergy consumption or entropy production

Goedkoop *et al*. (2009) propose an alternative method based on the geological distribution of mineral and fossil resources and assess how the use of these resources causes marginal changes in the efforts to extract future resources.

## 5.3.1.1. Indicators based on energy and mass

Simply adding all abiotic resources on the basis of mass or energy suggests that they are exchangeable and equally important with respect to their mass or energy content. An indicator summing up the quantities of resources used for a product or a service has e.g. been proposed by Schmidt-Bleek (1994) in his Material Intensity per Service Unit (MIPS) concept (see section 6.2.4). In the

LCIA community, there is little support for these types for indicators (Steen, 2006).

## 5.3.1.2. Indicators based on the relationship between use and deposits

The characterisation factors typically used in LCIA are 1/R, U/R and 1/R * U/R, where R corresponds to the mass of a specific resource (e.g. mineral ore reserves) and U corresponds to the present use of the resource. The last of these formulas is applied in the CML 2000 method (Guinée *et al.*, 2001).

## 5.3.1.3. Indicators based on the future consequences of resource extractions

The basic idea of these indicators is that extracting high-concentration resources today will force future generations to extract lower-concentration resources, which will lead to an increased impact on environment and economy. For example, the increase of land use and energy requirements for future provision of the currently used quantities per type of abiotic resource could be taken as a damage indicator. An approach based on the surplus energy use for future mining of low-grade resources has e.g. been applied in the Eco-indicator 99 model (Goedkoop and Spriensma, 2001; Steen, 2006).

## 5.3.1.4. Indicators based on exergy consumption and entropy production

Exergy has been suggested as an indicator for abiotic resource depletion. This is based on two assertions. First, exergy is the ultimate limiting resource because it has an associated energy cost that will be limiting to some extent when it becomes too high. Second, matter, in contrast to exergy, will not be depleted.

## 5.3.1.5. Indicators based on the marginal increase in costs due to the extraction of a resource

Goedkoop *et al*. (2009) base their model (ReCiPe) on the geological distribution of mineral and fossil resources and assess how the use of these resources causes marginal changes in the efforts to extract future resources. Unlike the model used in Eco-indicator 99, they do not assess the increased energy requirement in a distant future but rather base their model on the marginal increase in costs due to the extraction of a resource.

To this end, Goedkoop *et al*. (2009) develop a function that reflects the marginal increase of the extraction cost due to the effects that result from continuing extraction. In terms of minerals, the effect of extraction is that the average grade of the ore declines, while for fossil resources, the effect is that not only conventional fossil fuels but also less conventional fuels need to be

exploited, as the conventional fossil fuels cannot cope with the increasing demand.

The marginal cost increase (MCI) is the factor that represents the increase of the cost of a commodity *r* (US $/kg) due to an extraction or yield (kg) of the resource *r*. The unit of the marginal cost increase is dollars per kilogramme squared (US $/kg$^2$).

$$MCI_r = \frac{\Delta Cost_r}{\Delta Yield_r}$$

## 5.3.2. Evaluation of non-renewable resource use indicators

The following advantages and disadvantages of the indicators presented have been reported (Steen, 2006):

- Non-renewable resource *indicators based on summing up energy or mass* are easy to calculate and apply; on the other hand they are oversimplifying as they suggest that abiotic resources are exchangeable and equally important.

- Problems associated *with indicators based on the relation between use and deposits* are:

  (i) There is no common idea of what a resource is and what substances to include: R could be ores that are identified reserves of concentrates, which can be economically extracted, or anticipated amounts of such concentrates, or even the total amount of a substance in the earth's crust.

  (ii) If indicator results for different elements or substances are added up (as in an LCA), the total value will depend on how many substances are included and on how the resources are grouped. For example, if all fossil fuels are added together, an extraction of a certain amount of oil will have a lower result than if only oil reserves are considered.

  (iii)Typically there is an underlying assumption about exchangeability of resources; depletion of specific resources is considered to be a second order problem. Compared to indicators based on only energy and mass there seems to be a little more support for type of indicators related to use and deposits. However, these indicators are sometimes considered to be indicators of economic rather than environmental sustainability (Steen, 2006).

- For *indicators based on the possible future consequences of resource extraction*, there seems to be some consensus in the LCIA community on further developing the future consequences option with consideration of the resource functionality (Steen, 2006). Here, different methods have been proposed, each with its own specific limitations, e.g. with regard to the time perspective (decades, centuries, no temporal limitations). In particular, however, these indicators are rather uncertain because their

building methods need to assume future scenarios (Goedkoop *et al*., 2009).

- *Indicators based on exergy consumption and entropy production* typically do not truly express ore depletion, because exergy reflects the effort to produce the resource irrespective of its scarcity. Therefore, even if a resource becomes depleted rapidly, the exergy value will not change (Goedkoop *et al*., 2009). Furthermore, as Steen (2009) points out, exergy only will be limiting at galactic scales, as long as the sun will shine on earth.

**Table 29. Evaluation of non-renewable resource indicators**

| Indicator | Category | | | | | | | | | |
| | Representation | | | Operation | | | Application | | | |
| | Validity | Reliability | Sensitivity | Measurability | Data Availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
|---|---|---|---|---|---|---|---|---|---|---|
| Indicators based on energy and mass | x | xx | x | xxx | xxx | xxxx | n.a. | xx | x | x |
| Indicators based on the relationship between use and deposits | xx | xx | xx | xx | xxx | xxxx | n.a. | xx | x | x |
| Indicators based on the future consequences of resource extractions | xxx | xx | xxx | xx | xxx | xxxx | n.a. | xx | x | x |
| Indicators based on exergy consumption and entropy production | xx | xx | xx | xx | xxx | xxxx | n.a. | x | x | x |
| Indicators based on the marginal increase in costs due to the extraction of a resource | xx | xx | xx | xx | xxx | xxxx | n.a. | xx | x | x |

x=poor; xx=limited; xxx=good; xxxx=excellent

n.a.: not applicable; evaluation depends on specific application context

- *Indicators based on the marginal increase in costs due to the extraction of a resource* indirectly determine the damage of abiotic resource extraction via their exploitation costs (Goedkoop *et al*., 2009).

In Table 25 criteria to be considered when building or selecting an indicator have been defined. In Table 29, the non-renewable resource indicator groups presented above are evaluated with regard to these criteria.

For reliability and transparency, the critical issue appears to be the modelling of the life cycle. Because transparency depends on how this is done in the specific application context, an evaluation is not possible for this criterion.

### 5.3.3. Location in the DPSIR chain

As regards the DPSIR chain, all indicators addressed here belong to the I (impact) category.

## 5.4. Example chain: Loss of cultural heritage due to land take

Up till now, the concept of environmental indicators has hardly been applied to the interaction of transport with the cultural heritage (see in Annex 6 the description of this chain of causality – chain 34). Possibly, this is because archaeologists use other means of describing cultural values and have found little incentive to develop indicators. Contributing reasons may include the absence of a universally accepted terminology defining ancient monuments and dwellings, cultural legacy and other fundamental concepts. Subjective factors, political and religious aspects, inflation factors, ethical considerations, etc. also contribute to the difficulty of developing rational and clear-cut indicators in the field of cultural legacy. For a holistic perspective of the environmental impact of transport infrastructure, however, it is obvious that also the cultural heritage should be covered by environmental indicators. The following text aims at reporting one of the first attempts to develop an indicator in this field.

### 5.4.1. Application situations

Situations where indicators of loss of cultural heritage can be useful include many stages in the planning of transport infrastructure. The applicability is probably highest in early planning stages, e.g. when strategic environmental assessment is to be performed. Indicators are also useful in spatial planning, e.g. regional development planning, preferably co-ordinated with infrastructure planning. Other applications include long-time monitoring of land use where conflicts between, for instance, the demand for infrastructure improvement and the preservation of cultural legacy may arise.

### 5.4.2. Relative importance of criteria

In the absence of experience of developing indicators in the field of interaction between cultural legacy and transport infrastructure, it is difficult to judge the relative importance of the criteria set up in Table 25. As a preliminary point of departure, it is reasonable to attach equal importance to the ten criteria in that table. The criterion concerning ethical concerns may seem to be uncomplicated but a closer examination may well indicate a need of further consideration (see research needs in Chapter 7). In (the many) situations where explicit targets for the cultural legacy are lacking, the criterion of target relevance seems to be of limited relevance.

# 5.4.3. The construction of a possible indicator

In our trial to develop an indicator of the loss of cultural heritage due to land uptake, we have based our work in the legal and planning framework pertaining to the current situation in Greece.

We have taken our point of departure in the definition provided by the UNESCO convention (see Annex 6, chain 34). In addition, we have found it necessary to also include the following concepts: i) integral entity (natural integral entity and socio-economic integral entity), ii) the inflation factor. Further, we have taken into account ethical, educational and decision-making aspects as well as specific criteria. These concepts are elaborated in Annex 6.

*The description of the indicator*

As a first step, we make a distinction between two levels of protected areas, reflecting a qualitative and a quantitative measure, respectively:
− level 1: "absolute" protected areas (qualitative measure)
− level 2: non-protected areas, or areas whose protection can be temporarily annulled for reasons of high national importance (quantitative measure)

In areas that fall into the 1$^{st}$ level as defined by Greek law (Karakostas, 2006) and satisfy the definition of the International Convention of UNESCO (see Annex 6), any manipulation is prohibited. Only qualitative criteria can be used.

For areas belonging to level 2 (areas without strict protection), the situation is less rigid but still subject to strong limitations: only in the case of relevant public works of national defence or foremost economic importance defined by law, it is possible to permit some protection adjustments where these are absolutely necessary for these reasons. In these cases, an assessment of the value of the cultural heritage as an integral entity can be computed. To this end, we propose a very simple quantitative indicator:

> Loss of Cultural Heritage Unit (LCHU) defined as the loss or alteration of the volume of the integral entity of the cultural heritage due to land uptake. A simple formula of LCHU is:
> $$LCHU = C_{ch} V$$

where:

– V is the volume (in m$^3$) of dwelling / monument / area, as it is defined structurally as an integral entity, above or below the ground.

– $C_{ch}$ is the Cultural Heritage Coefficient, which can take values $\{1, x_1, x_2,$ or $x_3\}$. $C_{ch} = 1$ if none of the below situations (A, B, C) can be verified up to the present state of technological and archaeological know-how. The values of $x_1$, $x_2$, or $x_3$ need to be further assessed and they depend on the occurrence of the conditions A, B, C below:
  A. Verified existence of a Degree of Preservation. Integrity of the assemblage (example: isolated or integrated archaeological remains). Preservation level (foundation, superstructure, etc.). Presence of carvings, mosaics, wall paintings, etc.

B. Verified existence of an evaluation in terms of monumental and natural surroundings. Historical associations. Interrelation with the human and natural milieu. Correlation with historically known events or personages. Religious, calendar or astronomical functions, etc.

C. Verified existence of a Degree of Originality / Rarity in the archaeological record. Frequency of occurrence in the local, regional, national and international archaeological record.

If any one of the three conditions A, B, C can be certified, we have $C_{ch} = x_1$. If two can be verified, we have $C_{ch} = x_2$. If all three can be verified, we have $C_{ch} = x_3$, and if none can be verified, we have $C_{ch} = 1$.

Since this is an initial attempt to construct an indicator in this field, the concept has to be further elaborated and also tested in different practical application situations. Also, the necessity of testing this approach on other national frameworks than the Greek one must be acknowledged.

The LCHU indicator is to be categorized as an Impact (I) indicator in the DPSIR system.

## 5.4.4. Evaluation of the suggested indicators of loss of cultural heritage

The above approach is but a first attempt to evaluate the possibility of building an indicator pertaining to the loss of cultural heritage due to land uptake by transport infrastructure. The concept and method of mathematical calculation of the LCHU have been kept as straightforward as possible in order to permit the maximum transparency and simplicity for evaluation purposes. A preliminary evaluation of the 1st and 2nd level indicators of loss of cultural heritage is given in Table 30 using the criteria defined in Table 25 on page 126.

**Table 30. Evaluation of indicators of loss of cultural heritage**

| Indicator | Category | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Representation | | | Operation | | | Application | | | |
| | Validity | Reliability | Sensitivity | Measurability | Data availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
| 1st level | xxx | xx | xx | x | xx | xx | x | xx | xx | xx |
| 2nd level | x | xx | xxx | xxx | x | xxx | xxx | xxx | xx | xx |

x=poor; xx=limited; xxx=good; xxxx=excellent.

More in detail, the evaluation can be commented as follows:

- Validity: the indicator at 1st level being a qualitative indicator is superior in validity; however it suffers from the limited breadth of its definition. The 2nd level indicator is an integral indicator with a superior breadth, but being quantitative, it has limited validity

- Reliability: the indicators are reliable

- Sensitivity: the 2nd level indicator presents a higher sensitivity

- Measurability: the 1st level indicator is almost impossible to measure. The 2nd level indicator could be adjusted in order to present a high level of measurability, depending on the values of the Cultural Heritage Coefficient ($C_{ch}$)

- Data availability: the data is scarce for the 1st level indicator and even more scarce for the 2nd level indicator

- Ethical concerns: from an ethical point of view, the 2nd level indicator is superior to the 1st level indicator

- Transparency: the indicators are transparent; the mathematical formula in the 2nd level indicator is quite straightforward

- Interpretability: the indicators are clearly related to the field of assessment. The 2nd level indicator presents a more global nature than the 1st level indicator

- Target relevance: both indicators are high in target relevance

- Actionability: Both indicators have a good actionability with the 2nd level indicator being slightly superior

# 5.5. Example chain: Noise – annoyance to humans

The noise pollution produced by transport is an aspect, which is critical for the evaluation of the sustainability of the transport system. In urban areas the transport infrastructures represent the most important source of noise and some studies have been conducted to define mitigation techniques to reduce the noise emitted in residential areas. A lot of surveys, in the field of environmental acoustics, show that in the EU countries about 40 % of the population is exposed to road traffic noise with an equivalent sound pressure level (Leq) exceeding 55 dB(A) daytime while 20 % are exposed to levels exceeding 65 dB(A). More than 30 % of the people is exposed at night to Leq exceeding 55 dB(A), creating disturbance to sleep (WHO, 1999b).

## 5.5.1. Description of the chain of causality

The chain of causality is short and simple: noise is emitted from a source such as traffic (this is a Pressure in the DPSIR system). The noise energy is

spread by diffusion in air and absorbed or reflected by natural or artificial obstacles (this is also a Pressure). This exposure of humans to the noise causes various types of annoyance (which is an Impact). The target is thus human well-being.

The spatial scale of these processes is from metres to kilometres, and the temporal scale ranges from short to long time periods. Human annoyance and the relationship between noise exposure and annoyance are briefly commented in Annex 6 (chain 2).

## 5.5.2. Application situations

Indicators concerning noise find a broad usage in various kinds of planning situations. Sectors and interests concerned include transport (transport planning, infrastructure design, traffic engineering, etc), spatial planning and housing, public health, outdoor recreation, nature conservation, cultural heritage, etc. Noise issues are of relevance in planning, design, construction and maintenance situations. Depending on planning situation, the spatial scales may vary from the individual vehicle to the infrastructure and to the whole city.

## 5.5.3. Relative importance of criteria

Depending on the situation in which the indicator(s) are to be used, the planner, considering the most relevant criteria (Table 25) to well fit the scope, selects the most appropriate indicator(s). Often, however, certain indicators are well established due to their use in previous studies (or studies in progress). Also in such cases, careful analysis should be conducted to check the indicators against the criteria.

In the text below, real applications of indicator selection according to the criteria will not be described. Therefore, the relative importance of the ten criteria has not been evaluated.

## 5.5.4. A review of the main noise indicators

The first important aspect in the analysis of the noise–annoyance relationship is the choice of proper noise indicators to describe disturbance to people.

In general, different energetic noise indicators have been used to describe the noise emission depending on the source analysed. Those indicators are focused on the ability to describe the acoustic emission of the sound events or the noise sources and, in general, do not take into account the relationship with the annoyance to the humans exposed to noise.

In this section an overview of the most common noise indicators used for acoustical environmental monitoring is reported. Moreover, some typical

applications of the indicators in the noise–annoyance relationship are given to understand the aspects on which recent and past research has focused.

## 5.5.4.1. General acoustical noise indicators

First of all there are some basic indicators that are used in acoustics to generally describe the noise and which are used as a basis to build other indicators.

In particular we have:

- the "equivalent level *Leq*". As defined in ISO 1996/1-1982, it is a basic energetic indicator used to describe a noise varying over time. It represents the average noise level changing its pressure level during a period *T* of observation of the emission. For the formula and details, see Annex 9. To describe the meaning of the indicator, a typical representation of noise measure called "time history", representing the time evolution of the emission, is illustrated in Figure 19. Precisely, Figure 19 shows a time history of a noise emission in a street. The blue line depicts the instantaneous pressure level while the red line shows the "*running Leq*" that represents the equivalent level integrated from the beginning of the measurement to the selected point on the curve. A characteristic of *Leq* is its influence on the higher values of noise; in fact, even if during the night period the instantaneous level decreases sensibly, the corresponding *Leq*, calculated on all night period, has a minimum decrease.

**Figure 19. Example of time history of road traffic noise**
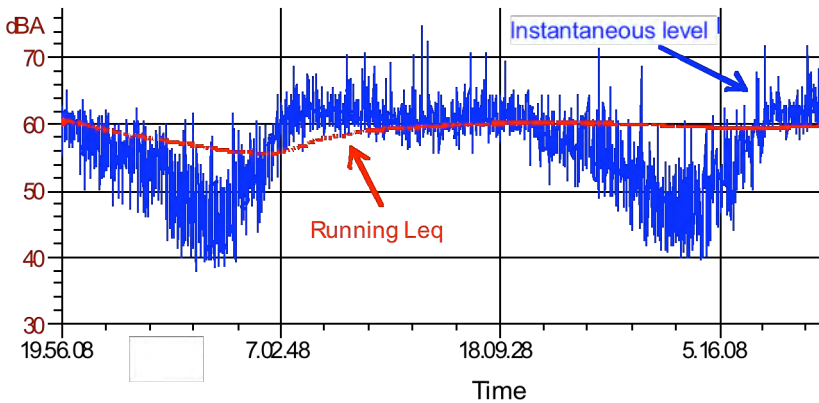


The *Leq* is useful to have a synthetic evaluation of the noise but it is easy to understand that different types of noise, emitted by different sources in different ways (constant or impulsive), are differently perceived but they could record the same *Leq*. It is sometimes useful to have the value of *Leq* on a specific time, for example every hour. In that case the indicator is written *Leq,h.* In general, the noise emitted by traffic is not impulsive. However, there are some circumstances, for example during night or in a street with low traffic, where it is possible to define the emission of a

single transit instead of a global traffic noise. Using *Leq* to describe such situations is not enough to shed light on the real impact. Furthermore, in urban areas there are some places where the traffic is discontinuous, e.g. near intersections and at traffic lights. At those points the *Leq* is not effective in describing the noise variation (Can *et al.*, 2008)

- the "maximum level *Lmax*": It is the maximum value of the noise level recorded during the measurement time

- the "minimum level *Lmin*": It is the minimum value of the noise level recorded during the measurement time

- the "statistical level *Lxx*": As defined in ISO 1996/1-1982, it represents the pressure level that is exceeded or the "xx" % of the measurement time. It is measured in dB(A). The statistical levels usually considered are $L_5$, $L_{10}$, $L_{50}$, $L_{90}$, $L_{95}$. The last two indicators, $L_{90}$, $L_{95}$, are typically used to describe the "background noise". In fact they represent, respectively, the level exceeded for 90 and 95 % of the measurement time

- the "sound exposure level *SEL*" or "*LAE*" or "*LAX*": It is defined in ISO 1996/1-1982. It is used to describe the energetic emission of a single noise event in a particular context, e.g. a passage of a single vehicle in an empty street or a passage of a train. For the formula and details, see Annex 9.

## 5.5.4.2. Road traffic noise indicators

The most common indicators used specifically to evaluate road traffic noise emission include:

- The "traffic noise index *TNI*": It was proposed by Griffiths and Langdon (1968) as cited by Schultz (1972). For the formula and details, see Annex 9. The indicator was developed in the UK but is little used because it becomes representative only when the traffic is fluent. Some examples of the use of *TNI* are presented in Langdon (1976, part I and II).

- The "noise pollution level *NPL*": This indicator was developed by Robinson (1969, cited by Schultz, 1972). For the formula and details, see Annex 9. The indicator is composed of two terms: the first one, the "$L_{eq}$", is the "average" level of the noise, the "energetic mean"; the second, the "$\sigma$", represents the fluctuation of the level during the emission time. Moreover, the parameter $\sigma$ is influenced by the background noise: in fact if we have a lower background noise, the fluctuation and the variability of the events are higher. The above indicator has not had a good success because of the difficulty to correctly define the parameter $\sigma$. Some examples of its application are presented in Rice (1975), Langdon (1976, part I and II) and Hall and Taylor (1977).

- The "CRTN Indicators $L_{10,18h}$": The most common noise indicator of traffic noise used at present in the UK and in Ireland is the $L_{A10,18h}$. This indicator comes from the use of the Calculation of Road Traffic Noise (CRTN) prediction method. This indicator is the arithmetic average of eighteen $L_{A10,1h}$ values (i.e. the noise level exceeded for 10 % of the hourly period)

from 06:00 to midnight. It is used in the UK for the purpose of national Insulation Regulations; in that case the value of noise contains a correction factor of +2.5 dB for the reflection from a façade (O'Malley *et al.*, 2009).

- The "statistical level $L_{50}$": This indicator, calculated on a specific period of the day (e.g. day or night or 24h), was used to evaluate the road traffic noise (Hall and Taylor, 1977) but now it is in disuse. In some cases the $L_{10}$ over 24, 18 and 12 hours has been used to predict annoyance in residences (Langdon, 1976, part I and II) but the result shows a low correlation between the variables.

## 5.5.4.3. Railway noise indicators

For railway traffic, there are few specific noise indicators. The most common indicators are:

- The "transit exposure level *TEL*": it is an index used to describe the noise emitted by rail. Its formulation is given by the EN ISO 3095:2005 (EN ISO, 2005). For the formula and details, see Annex 9.

- The "sound exposure level *SEL*" or "*LAE*" or "*LAX*": see above for its definition.

## 5.5.4.4. Aircraft noise indicators

For aircraft traffic noise, the most common specific indicators are (for formulas and details, see Annex 9):

- The "perceived noise level *PNL*": Developed by Kryter (1959), this indicator is used to describe the noise emitted by a single aircraft flying over.

- The "effective perceived noise level *EPNL*": It is an evolution of the *PNL* (Bishop and Horonjeff, 1967 as cited by Schultz,1972). This indicator takes into account the evolution of the *PNL* during the time with an increase of the level depending on the duration of the high level.

- The "noise number index *NNI*": Its basic measure is the perceived noise level (HMSO, 1963, cited by Schultz, 1972 and DORA, 1981). The index was developed during a social survey in 1961 in the vicinity of the London (Heathrow) Airport.

- The "noise exposure forecast *NEF*": This indicator is proposed by the US Federal Aviation Administration for the noise emitted by aircrafts (Bolt Beranek and Newman, 1964-1965, cited by Schultz, 1972).

- The "weighted noise exposure forecast *WECPNL*": This indicator is an evolution of the indicator *EPNL* proposed by International Civil Aviation Organisation, as mentioned by Changwoo *et al.* (2007). There are different computations of the index. In general the *WECPNL* represents a unique index to describe the noise emitted in a time period by different numbers of flights.

- The "indicator *LVA*": This indicator, used in Italy, is described in the Italian norm D.M. 31/10/1997.

### 5.5.4.5. General environmental noise indicators

There are some noise indicators used to describe noise emitted by different noise sources (e.g. road, railway and aircraft traffic) that take into account the period of the emission during the day. These common indicators are (for the formula and details, see Annex 9):

- The "Day-Night equivalent level $L_{DN}$ or *DNL*": It is an indicator used for different noise sources: road, railway and aircraft. This indicator was proposed by the U.S. Environmental Protection Agency (EPA, 1974, cited in Langdon, 1976, Part II). The $L_{DN}$ is an A-weighted average noise level that takes into account the different impact of the noise according to the period of the day when noise is emitted.

- The "Day-Evening-Night equivalent level *Lden* or *DENL*": It is an A-weighted average level of the noise emitted in the three periods of the day, with a penalty of 5 dB(A) for the evening period and a penalty of 10 dB(A) for the night period. It is an indicator proposed in the European Directive 49/2002/EC.

- The "Night level *Lnight*": It is an annoyance indicator proposed in the European Directive 49/2002/EC. It represents the equivalent level during the "night period".

## 5.5.5. Use of noise indicators for annoyance description

The introduction of the European Directive (2002) gives some strong restrictions on the noise indicators used to describe the acoustical impact of the transport infrastructure.

The use of a common indicator for all the transport sources and for all the European countries gives the possibility to compare noise emitted by different transport systems in different contexts. However, there is a need to evaluate the relationship between the noise level, represented by *Lden* and *Lnight*, and the annoyance to people. Due to the subjective nature of people's perception and attitude, however, it is difficult to find a relationship with the average energetic noise levels. The European Directive (2002) suggests every country to "draw" the dose-response relationship to evaluate the impact.

Some studies have been done to evaluate the dose–response relationship (Schultz, 1978; Kryter, 1982; Miedema and Oudshoorn, 2001). In general, the above dose–response relationship allows evaluating how many people are annoyed at different levels of $L_{DN}$, *Lden* or *Lnight*. In the surveys whose data have been used to feed their model, the authors had considered the annoyance degree evaluated on a 0 to 100 scale where the value of 100 is maximum annoyance. On that scale, three cut-off points are taken: 72, 50 and 28, and the

percentages of responses exceeding the cut-off are evaluated. In this way, three levels of annoyance are defined:

− %HA is the percentage of highly annoyed people. They are the respondents whose resulting annoyance score exceeds the value of 72;
− %A is the percentage of annoyed people. They are the respondents whose resulting annoyance score exceeds the value of 50;
− %LA is the percentage of little annoyed people. They are the respondents whose resulting annoyance score exceeds the value of 28.

An analytical expression of the above relationship is presented in Annex 10. An illustration of the relationship, computed by Miedema and Oudshoorn (2001), is given in Figure 20. For each transport system, three curves are evaluated: %HA, %A and %LA.

**Figure 20. Dose–response relationship as a function of two noise indicators, DNL and DENL: percentage of annoyed people as a function of noise level (upper curve: %LA, middle curve: %A, lower curve: %HA) (Miedema and Oudshoorn, 2001)**
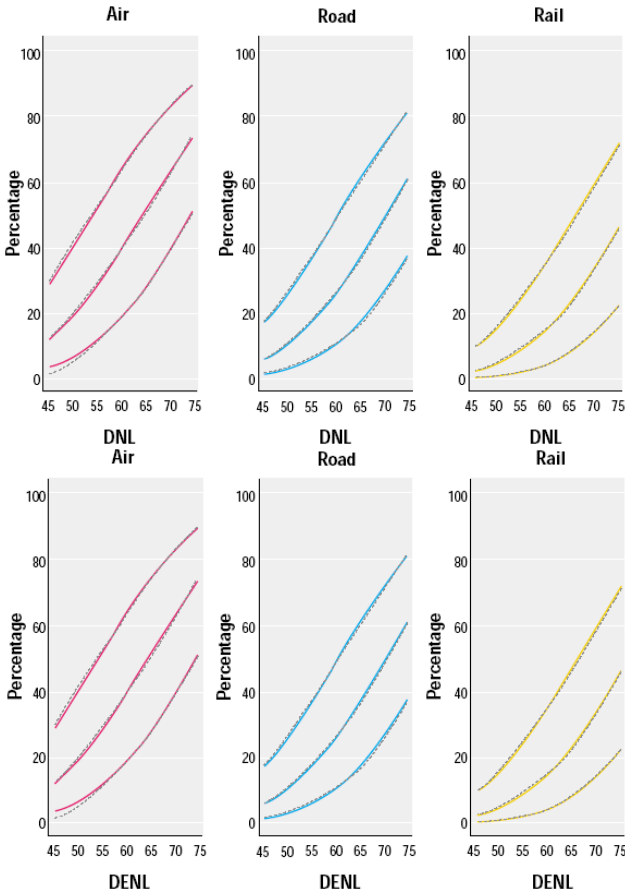
It is obvious that a certain noise level gives rise to more annoyance if the source is air traffic compared to road and especially rail traffic. Different noise limits must therefore often be used for different transport modes.

The use of the equivalent level or its "evolution" $L_{DN}$ and *Lden* is very common in environmental acoustics and often used to produce noise maps (See Figure 21). The noise maps, often using different colours to represent different noise level, are produced by models and/or softwares validated through in situ measurements.

**Figure 21. Road traffic noise emission: example of acoustic map**
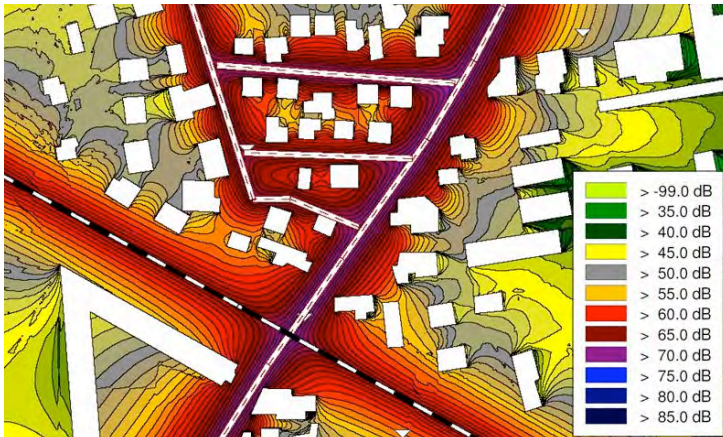


## 5.5.6. Indicators for combined sources

In many areas, residents are exposed to different noise sources because of the presence of different transport modes. For the evaluation of the total annoyance produced by different transport systems, some examples are reported in the literature. One method is the "Energy summation model" (Taylor, 1982 cited in WHO, 2002) where the total noise exposure "*L*" is calculated as the energetic sum of the single noise level "$L_i$" for "*n*" noise sources:

$$L = 10 Log\left( \sum_{i=1}^{n} 10^{0,1 \cdot L_i} \right) \text{ [eq. 1]}$$

The total annoyance "*A*" could be calculated as:

$$A = h(L) \text{ [eq. 2]}$$

where:

      *h(L)* = the exposure–annoyance relationship.

That model is not accurate enough because it does not consider that at the same value of noise level, different transport infrastructures generate different level of annoyance.

Another method is the "Dominance model" (Rice, 1986, as cited by WHO, 2002). The total annoyance "*A*" resulting from simultaneous noise sources, is equal to the maximum of the single source annoyances:

$$A = \max\left[h_i\left(L_i\right)\right] \text{ [eq. 3]}$$

where:

$h_i$ = exposure–annoyance function for source i

$L_i$ = noise level for the i source

The source causing the highest annoyance is called the dominant source.

The dominance model implies that the total annoyance doesn't change if the noise level of a non-dominance source changes. However, Miedema (1987, as cited by WHO, 2002), showed that the above hypothesis doesn't work at any time.

Another procedure is the "*Annoyance equivalent model*" (Vos, 1992; Miedema, 1996, cited in WHO, 2002). This method is an evolution of the energy summation model. In that case all the noise levels "*L*" from the individual i-source are translated into the equally annoying sound energy levels of a reference source and then the levels are summed in the total level "*L*". The corresponding annoyance from the total combined sources is found by using the exposure–annoyance relationship of the reference source, with exposure *L*.

In general the total noise "*L*" is given by:

$$L = 10 Log\left( \sum_{i=1}^{n} 10^{0,1 \cdot h_{ref}^{-1} \circ h_i\left(L_i\right)} \right) \text{ [eq. 4]}$$

where:

$h_i$ = exposure–annoyance function for the source *i*;

$h_{ref}^{-1}$ = inverse of the exposure–annoyance function for the reference source.

The composite function $h_{ref}^{-1} \circ h_i$ transforms the noise level of source *i* into the equally annoying level of the reference source. The total annoyance is given by:

$$A = h_{ref}\left(L\right) \text{ [eq. 5]}$$

**Figure 22. Example of use of the annoyance equivalent model in the case of two sources A and B (elaborated from WHO, 2002)**
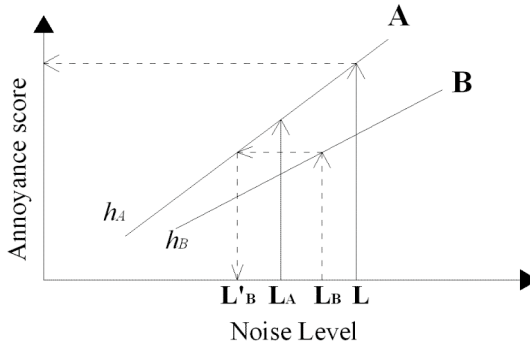
Figure 22 gives a graphical example of the evaluation of the total annoyance with the "annoyance equivalent model" in the case of two sources A and B where A is used as a reference source.

**Table 31. Classification of noise indicators**

| Indicators | Noise level indicator | Noise exposure indicator | Noise annoyance indicator | DPSIR |
|---|---|---|---|---|
| Leq,h | x | | | P/S* |
| Lmax | x | | | P/S* |
| Lmin | x | | | P/S* |
| Lxx | x | | | P/S* |
| SEL | x | | | P/S* |
| TNI | x | | | P/S* |
| NPL | x | | | P/S* |
| CRTN | x | | | P/S* |
| TEL | x | | | P/S* |
| PNL | x | | x | P/S* |
| EPNL | x | | x | P/S* |
| NNI | x | | x | P/S* |
| NEF | x | | x | P/S* |
| WECPNEL | x | | x | P/S* |
| LVA | x | | | P/S* |
| DNL | x | | x | P/S* |
| DENL | x | | x | P/S* |
| Lnight | x | | x | P/S* |
| km$^2$ of the territory with *Lden>Lden,limit* | | x | | S |
| km of the infrastructure with *Lden>Lden,limit* | | x | | S |
| km$^2$ of the territory with *Ln>Ln,limit* | | x | | S |
| km of the infrastructure with *Ln>Ln,limit* | | x | | S |
| % of people exposed to 55<*Lden*<65 dB(A) | | x | | S |
| % of people exposed to 65<*Lden*<75 dB(A) | | x | | S |
| % of people exposed to *Lden*>75 dB(A) | | x | | S |
| Population having access to quiet areas (within 500 m of residence) | | x | | S |

*the indicator represents a Pressure (P) if measured as "emission" value near the source; a State (S) if measured as "immission" value close to the receptor.

## 5.5.7. Classification of noise indicators

A first analysis of the above noise indicators allows classifying them in three classes (Table 31):

1. noise level indicators: they describe noise in terms of energetic and physical characteristics
2. noise exposure indicators: they are used to describe the noise effect on the exposed people in terms of magnitude and territorial extension
3. noise annoyance indicators: they try to explain annoyance to humans through corrections of measured noise levels

Each noise indicator could be in more than one class. Taking into account the aforementioned definitions, Table 31 shows the classification of the above indicators also considering the DPSIR approach.

It is possible to consider noise exposure indicators as "sustainability" indicators, as they can help in understanding the change in noise exposure after the construction of a new infrastructure.

Typologies of indicators are suggested by, e.g., Gilbert *et al*. (2002), WHO (2003), Marsden (2005), Litman (2007) and Calderón *et al*. (2009).

The last indicator in Table 31 is proposed by WHO (2003) to take into account the importance of the access to quiet areas by residents (see Annex 9 and Table 51 for details).

Table 31 highlights the importance of taking human noise annoyance into account in the planning of infrastructure projects and in the development of a sustainable transport policy. For this reason, it is important to define the "dose–response" relationship to understand how much people are annoyed at different noise levels.

## 5.5.8. Evaluation of noise indicators

An evaluation of noise indicators, according to the criteria defined in Table 25, is given in Table 32.

The evaluation of noise indicators shows that:

- Validity: all the noise indicators are effective from the energetic point of view but they are not suited to fully evaluate the impact.

- Reliability: the indicators are fully reliable.

- Sensitivity: all the noise indicators are little depending on noise source fluctuations. Large variations in traffic and cinematic conditions thus in general give rise to only small variations of the noise indicator. Only the statistical levels Lxx are more sensible to the source characteristics (e.g. the $L_{90}$, used to measure the background noise).

**Table 32. Evaluation of noise indicators**

| Indicator | Representation | | | Operation | | | Application | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Validity | Reliability | Sensitivity | Measurability | Data availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
| Leq,h | xx | xxxx | xx | xx | xx | xxxx | xxx | xx | xx | xx |
| Lmax | xx | xxxx | xx | xx | xx | xxxx | xxx | xx | x | xx |
| Lmin | xx | xxxx | xx | xx | xx | xxxx | xxx | xx | x | xx |
| Lxx | xx | xxxx | xxx | xx | xx | xxxx | xx | xx | xx | xxx |
| SEL | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| TNI | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| NPL | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| CRTN | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| TEL | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| PNL | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| EPNL | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| NNI | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| NEF | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| WECPNEL | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| LVA | xx | xxxx | xx | xx | xx | xxxx | xx | xx | xx | xx |
| DNL | xx | xxxx | x | xx | xx | xxxx | xxx | xx | xx | xxx |
| DENL | xx | xxxx | x | xx | xx | xxxx | xxx | xx | xx | xxx |
| Lnight | xx | xxxx | xx | xx | xx | xxxx | xxx | xx | xx | xxx |
| km$^2$ of the territory with *Lden>Lden,limit* | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxxx | xxx | xxxx |
| km of the infrastructure with *Lden>Lden,limit* | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxxx | xxx | xxxx |
| km$^2$ of the territory with *Ln>Ln,limit* | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxxx | xxx | xxxx |
| km of the infrastructure with *Ln>Ln,limit* | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxxx | xxx | xxxx |
| % of people exposed on the interval 55<*Lden*<65 dB(A) | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxxx | xxx | xxxx |
| % of people exposed on the interval 65<*Lden*<75 dB(A) | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxxx | xxx | xxxx |
| % of people exposed on the interval *Lden*>75 dB(A) | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxxx | xxx | xxxx |
| Population having access to quiet areas (<500 m resid.) | xxx | xxxx | xx | xx | x | xxxx | xxxx | xxx | xx | xxxx |

x=poor; xx=limited; xxx=good; xxxx=excellent.

- Measurability: the indicators are generally not easy to measure. Several indicators represent energetic means continuously measured on a 7-day period with stable weather conditions; this implies that they are demanding in terms of time and money.

- Data availability: data are scarce as the measurements are quite demanding. A limited number of public data bases are available. Some indicators (e.g. LDEN and the percentage of people exposed) are quite young; they have just recently been introduced in the European Directive and the countries have just started to measure and use them.

- Ethical concerns: there are not any obvious ethical concerns.

- Transparency: the indicators are transparent as their calculation is clearly described. Energetic indicators do not give a useful interpretation in terms of disturbance or annoyance, however.

- Interpretability: the indicators are well related to the emissions but some of the indicators are not strongly related to the annoyance since noise perception is highly subjective. Indicators which take into account the number of events could be better for interpretability and for the actionability, especially when the events are easy to identify (for example in the night period).

- Target relevance: some indicators simply represent the noise emissions, being not so relevant to political targets. The indicator describing the territorial impact is instead more useful.

- Actionability: to the decision maker, indicators representing the territorial impact or the number of exposed people are more useful than indicators describing only the emission.

## 5.5.9. Recommended indicators

The energetic indicators in Table 31 are mainly useful for the noise-emission monitoring by infrastructure owners as they must respect the noise limits.

The last eight indicators in Table 31 are suitable for monitoring of existing infrastructures, for strategic environmental assessment (SEA), and environmental impact assessment (EIA), as well as for strategic political choices. The reason is that they are easy to manage and understandable to a non-technical audience.

Among the indicators listed in Table 31, Lmax, Lmin, SEL and TEL cannot be recommended for general use, but for specific acoustical reasons.

# 5.6. Example chain: Greenhouse effect

For the greenhouse effect, a brief description of the chain of causalities is given in Annex 6 (chain 42).

# 5.6.1. Existing indicator sets

The greenhouse effect is not caused by carbon dioxide alone but other compounds also contribute. Multi-compound approaches to climate change policies require a metric establishing "equivalences" among emissions of various species. Climate scientists and economists have proposed four classes of such metrics: Global Warming Potentials, Global Damage Potentials, Global Cost Potentials, and Global Temperature change Potentials (O'Neill, 2000). The Global Warming Potential (GWP) is recommended to use within the Kyoto Protocol to the United Nations Framework Convention on Climate Change as a metric for weighting the climatic impact of emissions of different greenhouse gases (GHG). As an alternative to GWP, the Global Temperature Change Potential (GTP) is proposed. GTP represents the temperature change at a given time due to either a pulse emission of a gas or a sustained emission change relative to a similar emission change of carbon dioxide. Another alternative to GWP, the CEWN (Carbon Dioxide Equivalent Warming Number), is developed by Sekiya and Okamoto (2007) based on the atmospheric lifetime of each greenhouse gas.

## 5.6.1.1. Global Warming Potential (GWP)

The building of the indicator "Global Warming Potential", called also "Global Warming", is the output of the work of a college of international specialists of the greenhouse effect, mainly atmosphere physicists and chemists (Goger, 2006a, p. 9; Goger, 2006b, p. 41). In the cause–effect chain from the net emission of greenhouse gases to the damage caused by climate change, the range of variables that can be used in a common metric is limited to the range from global mean radiative force to the increase in global mean surface temperature. The increase in atmospheric concentrations of greenhouse gases and preceding variables is not suitable because they cannot be added for different greenhouse gases.

The formulation of the indicator expresses the contribution of greenhouse gases to the global warming through a weighted sum of the emissions: See the formula (Houghton *et al*., 2001):

$$GWP = \sum_{g} m_g \text{ x } GWP_g(T) \qquad \text{[eq. 6]}$$

where:

$m_g$ : mass of greenhouse gas *g* emitted

$GWP_g(T)$ : relative Global Warming Potential rated by $CO_2$ (set to 1), for the gas *g* and integrated over a time period *T*. It is defined by:

$$GWP_g(T) = \frac{\int_0^T RF_g(t)\,dt}{\int_0^T RF_{CO_2}(t)\,dt} \qquad \text{[eq. 7]}$$

where:

*T* is the time horizon

$RF_g$ is the global mean radiative forcing of component *g*

The numerator and denominator are called the Absolute Global Warming Potential (AGWP) of the gas *g* and of the reference gas, respectively. All GWPs use $CO_2$ as the reference gas. Many simplifications (Forster *et al*., 2007) have been made to derive the standard GWP index which has been criticised (O'Neill, 2000; Smith and Wigley, 2000; Bradford, 2001; Godal, 2003).

The indicator GWP is based on the IMAGE model (Integrated Model to Assess the Greenhouse Effect) developed by IPCC (Intergovernmental Panel on Climate Change) (Houghton *et al*., 1996, 2001; Hauschild and Wenzel, 1998). It calculates the compound concentration in the atmosphere from the initial concentrations, the chemical reactions and the diffusion-dispersion phenomena. The concentration is then multiplied by the infrared absorption coefficient, which depends on the molecular absorption spectrum of each species (and which is a function of the pollutant concentration) and on the presence of other pollutants with an absorption spectrum, which is superposed. The results are integrated on the time *T*. The GWP represents the ratio between the warming induced by a given mass of compound *g* and the warming induced by the same mass of $CO_2$. When the impacts on the continent temperature are looked for, IPCC recommends an integration over 100 years because the equilibrium with the atmospheric temperature is quick (Houghton *et al*., 2001). A 500 year integration is preferable when looking at the impacts on the ocean temperature, because of the higher thermal inertia. An integration on 20 years allows to model gases with very short life time. The indirect contribution of a greenhouse gas is furthermore calculated from the effects of its degradation: $CO_2$ emissions, tropospheric ozone formation or ozone depletion.

The GWP is therefore obtained from the global mean radiative force by a simple time integral, thus representing the total amount of energy given to the climate system over a period of time. The warming is in this way built as a linear mechanism, although the concentration model is a non-linear model. In the cause-effect chain, there is no such variable from which the temperature increase could be derived (Shine *et al*., 2005).

The present Global Warming Potential is given for an integration period of 100 years and only six gases: carbon dioxide $CO_2$, methane $CH_4$, nitrous oxide $N_2O$, hydrofluorocarbons HFCs, perfluorocarbons PFCs and sulphur hexafluoride $SF_6$. The GWP is usually expressed in amount of $CO_2$ equivalent (metric tonne $CO_2$ eq.), but it could also be expressed in tonne of carbon of $CO_2$ equivalent. Both units are proportional, according to the molar weights: 48 tonnes of $CO_2$ eq. correspond to 12 tonnes of C of $CO_2$ eq. Therefore the figures in C are 4 times lower than the figures in $CO_2$ eq. Although the name of the indicator makes reference to an expression of the result in terms of radiative forcing or temperature variation, it is only proportional to this, which can be easily calculated by multiplying the GWP by the $CO_2$ radiative power.

## 5.6.1.2.  Simplified versions of the Global Warming Potential

As $CO_2$ is the main compound responsible of the greenhouse effect – it accounted for 77 % of the total GHG emissions in 2004 (Pachauri and Reisinger, 2007, p. 36), and as it is the compound easiest to calculate because its emission factors are well known and quite accurate, a simplified version of the GWP considers only the mass of $CO_2$ emitted.

GWP' = pure $CO_2$ mass, expressed in tonnes of $CO_2$ or in tonnes of C

$CO_2$ is a greenhouse gas only when it does not participate in the carbon cycle, i.e. when it is emitted from fossil fuels or captured permanently. Then GWP' is sometime calculated as primary fossil fuel consumption, expressed in toe for instance (tonne oil equivalent). Nevertheless, it expresses the same indicator GWP'.

## 5.6.1.3.  Global Temperature Change Potential

The GWP has been subject to much criticism because of its formulation, but nevertheless it has retained some favour because of the simplicity of its design and application, and its transparency compared to other proposed alternatives.

It has been recognised that in general the relevance of the impacts becomes greater as we move down the chain of causalities (see the description of chain 42 in Annex 6), and hence a metric designed to compare more relevant impacts would be desirable. However, it has also been recognised that the uncertainty generally becomes greater as we move down this chain.

One of the main criticisms of the application of GWPs is that the impacts of two equal GWP-weighted emissions are equal only in terms of integrated radiative forcing over the chosen time horizon and not in terms of actual temperature change along the path or at the end of the time horizon (O'Neill, 2000; Smith *et al*.; 2000; Fuglestvedt *et al*., 2000, 2003). Furthermore, the application of integrated radiative forcing may overestimate the effect of short-lived species if the goal of climate policies is to limit long-term temperature increase (Manne *et al*., 2001).

Alternative approaches include choosing the change in global mean temperature for a selected year as an indicator (Shine *et al*., 2005, 2007). This would reduce the contribution from short-lived components compared with using the integrated radiative forcing concept, when the thermal inertia of the system is taken into account.

The alternative to the GWP moves one step further down the chain from radiative forcing to represent the global-mean surface temperature change.

*The general concept of GTP*

Shine *et al*. (2005b) proposed the GTP as a new relative emission metric. The GTP is defined as the ratio between the global mean surface temperature change at a given future time horizon ($T^H$) following an emission (pulse or sustained) of a gas *g* relative to a reference gas *r* ($CO_2$):

$$GTP_g^{TH}(t) = \frac{\Delta T_g^H}{\Delta T_r^H} \qquad\qquad \text{[eq. 8]}$$

where $\Delta T_g^H$ denotes the global mean surface temperature change after *H* years following an emission of gas *g*. The GTPs do not require simulations with models, but are given as transparent and simple formulas that employ a small number of input parameters required for calculation. While the GWP is an integral quantity over the time horizon (i.e. the contribution of the radiative forcing at the beginning and end of the time horizon is exactly equal), the GTP uses the temperature change at time H (i.e. radiative forcing closer to time H contributes relatively more).

The GTP metric requires knowledge of the same parameters as the GWP metric (radiative efficiency and lifetimes) but in addition, the response times for the climate system must be known, in particular if the lifetime of gas *g* is very different from the lifetime of the reference gas. Differences in climate efficacies can be incorporated into the GTP metric. Due to the inclusion of the response times for the climate system, the GTP values for pulse emissions of gases with shorter lifetimes than the reference gas will be lower than the corresponding GWP values. Shine *et al*. (2005b) noted the near equivalence between the GTP for sustained emission changes and the pulse GWP. The GTP metric has the potential advantage over GWP that it is more directly related to surface temperature change (Forster *et al*., 2007).

*The GTP$_p$ and GTP$_s$*

There are two alternatives to the GWP which represent the impacts of emissions on global-mean surface temperature change. The GTP$_p$ compares the temperature effect of pulse emissions, while the GTP$_s$ compares the effect of sustained emission changes.

Although the GTP$_p$ follows the general philosophy of the GWP, a major distinction is that the final result is the ratio of the temperature changes at a particular time, t, rather than, as it is the case for the GWP, the ratio of the integrated changes over the period leading up to t. Hence a pulse emission of 1 tonne of gas *g* will give an identical temperature change in year t as $GTP_p^g$ tonnes of carbon dioxide.

The concept can be extended to consider the impact of sustained changes in emissions of a gas, a quantity that may arguably have greater policy relevance if a country were to make changes in a given industrial or agricultural process that had a long-term impact on emissions; at the very least the difference between the pulse and sustained forms is instructive. This is denoted as AGTP$_s$ where the subscript S indicates a sustained emission change. The units of AGTP$_s$ are taken to be K (kg year$^{-1}$)$^{-1}$.

It is used in the similar manner as GWP but there is an example in Table 33 for comparison. It is always reported to $CO_2$ as a reference. But the absolute value is calculated first as indicated above.

Both new metrics retain some of the advantages of the GWP, such as a transparent formulation, the reliance on relatively few parameters and the possibility of use by policymakers with little further input from scientists. They have a clear advantage over the GWP in that they represent an actual climate impact, rather than the more abstract concept of integrated radiative forcing due to a pulse emission.

*Comparison of components*

Two examples of differences between GWP and GTP based approaches are given below:

- The GWP values of $CH_4$ for 20, 100 and 500 years are 62, 22 and 7, respectively. The GTP values for the same time horizons are 46, 5 and 0.8 (Shine *et al*., 2005a).

- For black carbon (BC) the GWP values are 2900 and 830 for 20 and 100 years and 290 and 60 for GTP for the same horizons (Rypdal *et al*., 2009).

Thus, the choice between the two metrics as well as the choice of time horizon (H) will strongly affect the calculated contributions to total man-made emissions of $CO_2$ equivalents and which components to be given high priority.

*Short- and long-lived species*

Emissions of short-lived species (such as ozone precursors, primary aerosols or aerosol precursors) have a direct radiative effect on climate through the radiative forcing of the ozone (including methane changes) or aerosols (including cloud effects). The radiative forcing of a pulse emission only lasts as long as the species persist in the atmosphere (weeks for ozone and aerosols, 13 year lifetime for methane). The thermal inertia of the climate system extends the timescales for the induced temperature perturbations, but even so, after about 20 years the surface temperature change as characterised by the GTP (Shine *et al*., 2007; Boucher and Reddy, 2008) for short-lived species (such as ozone or black carbon) becomes very small. Some short-lived species can affect vegetation growth and hence affect the amount of $CO_2$ taken up by the vegetation or released to the atmosphere. Sitch *et al*. (2007) showed that the damage caused to vegetation by anthropogenic ozone precursors over the 20th century caused extra atmospheric $CO_2$ that had a radiative forcing comparable to the ozone itself. Mercado *et al*. (2009) have shown that aerosols increase photosynthesis rates and hence draw down $CO_2$ by increasing the diffuse fraction of the radiation. These indirect effects of the short-lived species on $CO_2$ become increasingly important at longer timescales.

Table 33 shows the absolute AGWP for carbon dioxide and the values of the GWP, $GTP_p$ and $GTP_s$ for 5 other gases with a wide range of properties: $HFC_{152a}$ is chosen as a very short-lived gas in quite widespread use; methane is the most important greenhouse gas (in terms of total radiative forcing since pre-industrial times) after carbon dioxide; $HFC_{134a}$ is the dominant hydrofluorocarbon in terms of its total contribution to radiative forcing; $N_2O$ is a relatively long-lived gas, $CF_4$ is a representative of the very long-lived greenhouse gases. For all these gases, lifetimes and the radiative forcing per ppbv (part per billion by volume) are taken from IPCC (2001) (Shine *et al*., 2005a).

**Table 33. Absolute GWP [$10^{-14}$ Wm$^{-2}$kg$^{-1}$year], GTP$_p$ [$10^{-16}$ K kg$^{-1}$] and GTP$_s$ [$10^{-14}$ K kg$^{-1}$ year] for $CO_2$ and relative values of these parameters for 5 other greenhouse gases at time horizons of 20, 100 and 500 years**

| Gas | Indicators for different time horizon in years | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 20 | | | 100 | | | 500 | | |
| | GWP | GTP$_P$ | GTP$_S$ | GWP | GTP$_P$ | GTP$_S$ | GWP | GTP$_P$ | GTP$_S$ |
| Absolute $CO_2$ | 2.66 | 8.34 | 1.24 | 9.05 | 5.46 | 6.67 | 29.1 | 3.47 | 23.0 |
| $CH_4$ | 62 | 52 | 69 | 22 | 0.35 | 24 | 7 | 0 | 7 |
| $N_2O$ | 270 | 290 | 260 | 290 | 270 | 290 | 150 | 13 | 160 |
| $CF_4$ | 3850 | 4150 | 3610 | 5650 | 7490 | 5480 | 8730 | 11700 | 8690 |
| HFC152a | 400 | 170 | 570 | 120 | 0.15 | 130 | 37 | 0 | 40 |
| HFC134a | 3290 | 2840 | 3590 | 1260 | 34 | 1370 | 390 | 0 | 400 |

The values for methane include the indirect forcing. The GTP values are calculated with a climate sensitivity of 0.8 K(Wm$^{-2}$)$^{-1}$ and a mixed layer with a depth of 100 m.

*An example in the transport system*

The GTP$_s$ can be used to help decision making in a particular trade-off situation. The possibility of fitting a particulate filter on new (or old) diesel vehicles offers a case study which is particularly relevant to policy-makers. Some off-road and heavy-duty vehicles can indeed show very large black carbon (BC) emission factors. While it is possible to retrofit diesel particulate filters, it is usually considered that there is an associated fuel penalty in doing so. It is shown that retrofitting a diesel particulate filter on these heavy-duty vehicles would lead to less climate warming up to a period of 25 to 68 years even though a fuel penalty of about 2-3 % has been assumed (Boucher and Reddy, 2008).

However, over longer time horizons, the $CO_2$ warming effect would dominate. Further calculations have been made to estimate the change in surface temperature in response to a large programme for retrofitting diesel particulate filter on heavy-duty trucks in the United States (Figure 23).

Shine *et al*. (2005b) explore the difficulties when designing metrics to compare the climate impact of emissions of oxides of nitrogen (NOx) with other emissions. NOx emissions increase tropospheric ozone, and decrease methane concentrations, causing a global-mean radiative forcing similar in size but opposite in sign to the ozone forcing.

If it becomes a political imperative to include NOx emissions in future climate agreements, policy makers will be faced with difficult choices in selecting an appropriate metric.

Berntsen and Fuglestvedt (2008) compared emissions from the main transport sectors (road transport, aviation, shipping, and rail) by using the change in global mean temperature as a function of time as the climate impact indicator.

Figure 24 shows a comparison of the transport modes in terms of net warming for four chosen time horizons after 1 year's (i.e. year 2000) emissions. These results show that road transport is the largest contributor, followed by aviation. For time horizons of 20 to 100 years, the net warming from road transport is 7 and 6 times as high as the net warming from aviation, respectively.

**Figure 23. Surface temperature change ($10^{-4}$ K) for a 20-year programme for retrofitting diesel particulate filter on heavy-duty trucks in the United States (Hill, 2009, p. 28)**
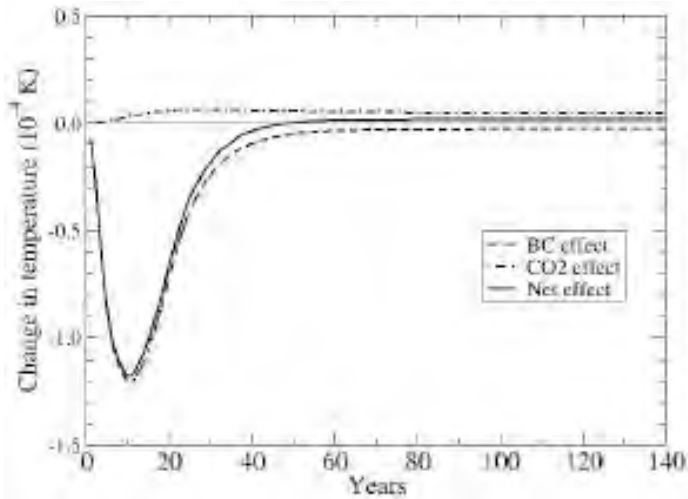


**Figure 24. Contribution from a 1-year pulse of current emissions to net future temperature change (millikelvin) for each transport mode for four future times (20, 40, 60, and 100 years), including uncertainties at the 1-sigma level (Berntsen and Fuglestvedt, 2008)**
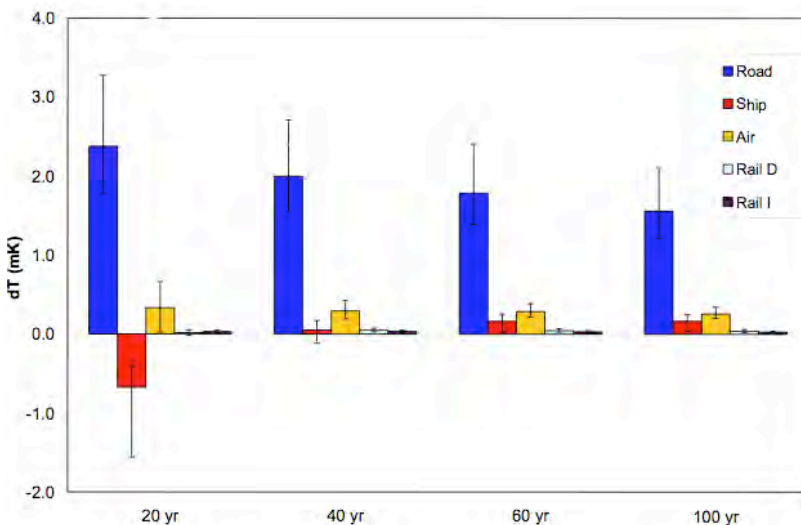
*Conclusions*

The choice of metric depends on which aspects of climate change one is concerned about and how it will be applied in a policy context. Thus the choice of time horizon goes beyond natural sciences and requires value judgments. The perceived relative importance of different emissions and sectors / activities depends greatly on the choice of indicator. The widely accepted GWP concept does not account for the response of the climate system to emissions, while the GTP accounts for the response in global mean surface temperature.

However, as a rule, they are calculated with different detailed climatic models and, therefore, results are strongly influenced by specific model assumptions and uncertainties of model parameters. This makes it problematic to correctly compare results of different modellers and obtain common conclusions.

The further development of GTP as a common metric must take into account the non-linearities in the functional relationships involved and it should allow for the policy makers to choose the starting times of consideration of emissions (Meira Filho, 2009).

The science community may present various metrics and tools that can be used in assessments of emissions and measures. The choice of metric for climate agreements should not be made by scientists from the natural sciences and economics alone but in dialogue with policymakers.

## 5.6.1.4. Carbon Equivalent Warming Number (CEWN)

Sekiya (2007; 2008) and Sekiya and Okamoto (2009a and b) suggested a new GWP-alternative indicator called CEWN (Carbon dioxide Equivalent Warming Number), which is proposed for the global warming values of individual gases. The CEWN is a metric that allows the comparison of warming effects of gases by assigning a single warming value incorporating a time-dependent evaluation based on the atmospheric lifetime of gas to each greenhouse gas.

The CEWN (x) of gas *g* is derived by dividing the cumulative global mean radiative forcing of gas *g* from when 1 kg of gas *g* is emitted into the atmosphere to when x % of the emission is removed from the atmosphere, ACEWN(X)$_g$, by that of the reference gas, carbon dioxide, ACEWN(x)$_{CO2}$.

$$CEWN(x) = \frac{ACEWN(x)_g}{ACEWN(x)_{CO2}} \qquad \text{[eq. 9]}$$

$$CEWN(x) = \frac{\int_0^{t_{xg}} A_g RF(t)\,dt'}{\int_0^{t_{xCO2}} A_{CO2} RF(t)_{CO2}\,dt'} \qquad \text{[eq. 10]}$$

**Table 34. Carbon dioxide Equivalent Warming Numbers (CEWN) for some GHGs in the case where the coefficients for concentration response function of $CO_2$ are the same as those of Pachauri and Reisinger (2007)**

| Common name | Lifetime [years] | CEWN (70) | CEWN (75) | CEWN (78) | GWP$_{100}$[a] |
|---|---|---|---|---|---|
| Years until $CO_2$ deceases by the given removal rate | | 196 | 356 | 770 | – |
| Years until gas *g* deceases by the given removal rate / Lifetime of gas *g* | | 1.20 | 1.39 | 1.51 | – |
| Carbon dioxide | – | 1 | 1 | 1 | 1 |
| Methane[b] | 12 | 10.6 | 7.37 | 4.32 | 25 |
| CFC-11 | 45 | 2 249 | 1 558 | 913 | 4 750 |
| HFC-134a | 14 | 603 | 418 | 245 | 1 430 |
| HFC-43-10mee | 15.9 | 693 | 480 | 281 | 1 640 |
| Nitrogen trifluoride | 740 | 60 117 | 41 635 | 24 410 | 17 200 |
| PFC-14 | 50 000 | 1 560 558 | 1 080 802 | 633 658 | 7 390 |

The radiative efficiency of $CO_2$ used for the calculation is $1.805 \times 10^{-15}$ [W m$^{-2}$ kg$^{-1}$].

a) Quoted from Pachauri and Reisinger (2007)

b) The CEWN values for methane have been multiplied by 1.4 to account for the indirect forcing following GWP for methane in Pachauri and Reisinger (2007)

The CEWN(x) value relative to carbon dioxide is derived by dividing the time-integrated global mean radiative forcing *RF* of gas *g*, which was yielded by integrating the values obtained by multiplying its quantity remaining in the atmosphere by its radiative efficiency over the period between the emission of gas *g* and the time when *x* % of the emission is removed from the atmosphere, by the time-integrated forcing of carbon dioxide calculated in a similar way. *A* is the radiative efficiency due to 1 kg increase in atmospheric abundance of the considered gas.

The GTP corresponds to a value after a given period of time has elapsed, whereas the CEWN corresponds to an integrated value until a given removal rate has been reached.

Table 34 shows the comparison between GWP and CEWN calculated for some GHGs, based on a response function of Pachauri and Reisinger (2007).

## 5.6.1.5. Indicator of health impact due to greenhouse effect

The figures of "(marginal) health damages due to climate variations" [eq. 11] are calculated from the death number variation due to the average temperature variations, or due to malaria, the dengue fever and the cardio-vascular attacks, and from the number of people transferred because of the sea level increase in nine world regions, by using the Fund model (Mayerhover *et al*., 1997). The results are extrapolated for all other greenhouse gases according to three

reference gases, as a function of the pollutant life time (CH$_4$: 20 years; CO$_2$: 20 to 110 years; N$_2$O: > 110 years).

$$D_g = \frac{GWP_g \times D_{ref}}{GWP_{ref}} \qquad \text{[eq. 11]}$$

where:

D$_g$: damage due to the unit emission of the pollutant *g* [Daly, for Disability Adjusted Life Years] (number of human life years when the health is affected)

GWP$_g$: warming potential of the pollutant *g* [without dimension]

D$_{ref}$ and GWP$_{ref}$: equivalents for the reference pollutant.

# 5.6.2. Greenhouse effect indicator assessment

The evaluation of the greenhouse effect indicators presented in section 5.6.1 according to the criteria defined in Table 25, summarized in Table 35, shows:

- Validity: The representativity is excellent for GTP and CEWN. It is high for the GWP, but it measures an intermediate impact (average temperature increase) and not the final impacts. It is lower for GWP' (CO$_2$ emission) because other gases can play an important role in global warming. D$_p$ measures a final impact, but other final impacts are not taken into account.

**Table 35. Evaluation of the greenhouse effect indicators**

| Indicator | Category | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Representation | | | Operation | | | Application | | | |
| | Validity | Reliability | Sensitivity | Measurability | Data availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
| GWP | xxx | xxxx | xxx | xxx | xxx | xxxx | xxxx | xxxx | xxx | xxx |
| GWP' | xx | xxxx | xxx | xxxx | xxxx | xxxx | xxxx | xxxx | xxx | xxx |
| GTP$_P$ | xxx | xxxx | xxx | xxx | xxx | xxxx | xxxx | xxxx | xxxx | xxx |
| GTP$_s$ | xxx | xxxx | xxx | xxx | xxx | xxxx | xxxx | xxxx | xxxx | xxx |
| CEWN | xxx | xxxx | xxx | xxx | xx | xxxx | xxxx | xxxx | xxx | xx |
| D$_p$ | xx | xxxx | xxx | xxx | xxx | xxxx | xxx | xx | xxxx | xxxx |

x=poor; xx=limited; xxx=good; xxxx=excellent.

- Reliability: As functions, the six indicators are very reliable.

- Sensitivity: Similar to validity, but a bit lower for GWP, GWP' and $D_p$.

- Measurability: All indicators are rather easy to calculate. The only difficulty is the availability of emissions of other pollutants than $CO_2$.

- Data availability: See measurability. The exception is CEWN where the data availability is low.

- Ethical concerns: No problem.

- Transparency: The methods used are all very transparent.

- Interpretability: All the indicators are easy to understand, but the interpretability is lower for $D_p$ because it represents only a part of what it should measure (the impact of the greenhouse effect).

- Target relevance: The indicators, especially GTP, are well adapted to thresholds or policy targets.

- Actionability: GWP and $D_p$ are quite well adapted to measure the impact of a policy action, but only when these actions impact the greenhouse gas emissions, i.e. most of the actions. $D_p$ is based on the outputs of a model (Fund), whose input parameters are not variables of the indicator – they are fixed. Therefore the policy actions influencing these parameters (e.g. move an island population) cannot influence this indicator. GWP' is less adapted because it is not influenced by the actions on other pollutants than $CO_2$. $GTP_p$ can be used for a pulse emission change to estimate impact on temperature for short-lived species. CEWN is less adapted to measure the action of a policy.

# 5.7. Example chain: Waste

The five basic activities for all transport modes affecting the environment with waste generation (see in Annex 6 the description of the chain of causalities 40) are as follows (EPA, 1996):

1. Infrastructure construction, maintenance, and abandonment
2. Vehicle and parts manufacture
3 Vehicle travel
4. Vehicle maintenance and support
5. Disposal of used vehicles and parts

For each of these five activities, indicators related to activities generating wastes are described with their environmental impacts whenever available.

# 5.7.1. Application situations

There are many environmental issues related to solid waste management which, among other things, include:
− health and environmental impacts of accumulated uncollected waste and illicit disposal sites
− health and environmental impacts of solid waste facilities, including transfer, composting and landfill facilities
− special handling and disposal of hazardous wastes, and industrial hazardous waste.

Solid waste accumulations and dumping facilities raise environmental concerns because of potential smoke from open burning, odours, insects, rodents, gaseous emissions and water pollution that might result.

# 5.7.2. A review of main candidate indicators

In the literature, waste-related indicators are often presented by transport mode (road, railway, aviation and maritime) and categorized according to waste generation: manufacture, use, maintenance, disposal, recycling.

Many indicators have been developed for all transport modes to estimate waste generation from each activity but there is limited published knowledge on the transport's share of the environmental impact.

The quantities of waste originating in various sources of the transport system are usually expressed as tonnes per day, month or year. These indicators can be used to estimate the quantity of waste in different settings, e.g. according to population size, industrialization levels or economic development.

In addition to the quantities of waste generated, its physical and chemical composition and density provide essential information for the environmental impact assessment and for decision-making about collection, processing and disposal methods (WHO, 2005).

## 5.7.2.1. General waste indicators

According to NZME (2000) and WHO (2005):
− Waste from road vehicles (number and treatment of used tires)
− Physical composition (%)
  • Paper
  • Plastics
  • Glass
  • Metals
  • Rubber and leather
  • Leachate quality parameters (heavy metal species, BOD, COD, solids, specific conductivity, pH, PCB, etc.).

## 5.7.2.2. Road transport indicators

*Biofuel production (BRDI, 2008)*
− Tons of waste products used for biofuel or biodiesel production
− Tons of waste (residues) generated per ha cultivated (pertaining to the biofuel production)
− Waste generated in the process (ton/ton)
− Wastewater generated by the biofuel process ($m^3$/ton)
− BOD loadings to land or water (ton/year)

*Road construction and maintenance (EPA, 1996; EEA, 2002; 2003; HEC, 2009)*
− Volume of pavement waste to landfill

As an example of indicator of the handling of waste from infrastructure maintenance, the simple indicator "percentage of waste circulated" can be used, with the unit "weight of recycled waste as a percentage of total waste produced per year". This has been suggested for the maintenance of railway infrastructure in Sweden (Lundberg *et al*., 2009). To go one step further, waste separation can be described by using indicators for the weight percentage of waste separated in classes such as "reused", "recycled", "extracted for energy retrieval" and "deposited on land-fill". This categorization has been used as one of many environmental requirements stated in the procurement of road maintenance contracts by the Swedish Road Administration (Faith-Ell, 2000; Faith-Ell *et al*., 2006).

*Disposal of vehicles and parts*
− Number of vehicles scrapped, quantity of various materials in vehicle
− Quantity of used motor oil improperly disposed
− Quantity of used tires landfilled or stockpiled
− Quantity of lead-acid batteries discarded into municipal waste stream
− Amount of waste produced by scrap cars
− Number of vehicles scrapped, quantity of various materials in vehicle, percentage of mass landfilled
− Number of motor vehicles disused annually (number of end-of-life vehicles).

## 5.7.2.3. Railway and air transport indicators

According to EPA (1996) and Greene (1997):

*Rail car and parts manufacture indicators*
− Quantity of reported releases of toxic chemicals
− Quantity of new cars installed to replace those disposed.

*Disposal of aircraft and parts*
− Recycling of aircraft scrappage
− Quantity of waste generated per workload unit in an airport
− Quantity of in-flight waste generated per RTK/RPK (revenue per ton or passenger kilometre).

### 5.7.2.4. Maritime transport indicators

According to Ryan *et al*. (1988), Sheavl (1995), EPA (1996), MCS (1998), Sloan *et al*. (1998), Mato *et al*. (2001), HELCOM (2006) and DEWHA (2009):

*Construction and maintenance of navigation fairways*
− Direct deterioration of habitats by dredging
− Habitat disruption and contamination by disposal of dredged material
− Water quality degradation from dredging

*Manufacture and disposal of maritime vessels and parts*
− Quantity of releases of toxic chemicals
− Dilapidated or scrapped vessels

*Maritime travel*
− Quantity of garbage generated by the maritime sector
− Percentage of shell fish waters reported contaminated due to sewage dumping
− Number of oily birds
− Length of beaches contaminated by oil (in km)
− Abundance of marine litter
− Amounts of wastes delivered to ports compared to general shipping activities
− Mortality of marine animal due to ingestion, entanglement, toxicity in marine debris
− Number of polluters found
− Accidental oil spills from marine shipping
− Number of vessels implementing ballast water management according to IMO BW Convention.

### 5.7.2.5. Waste disposal indicators

Indicators that relate to waste disposal which is the last step of the integrated waste management cycle are:
− Quantity of waste disposed (tonne or m$^3$ per day or year)
− Volume of waste illegally dumped per year
− Volume of waste entering unpermitted landfills per year.

## 5.7.3. Application of criteria for the choice of waste indicators

The evaluation, according to the criteria defined in Table 25, of the waste indicators presented in section 5.7.2 is summarized in Table 36. An attempt to categorize the presented indicators according to the DPSIR system is reported in Table 37.

The basic indicators are usually used for ascertaining the status of waste management and are also used in policy targets as measures are introduced for controlling waste generation, recycling promotion, and environmental impacts. When setting numerical targets for policies, it is possible to set target values using selected indicators which are compared to other places in similar conditions. But

such indicators are more response indicators (R in the DPSIR system), measuring environmental policies, rather than environmental impact indicators (I in the DPSIR system). Among all the selection criteria, waste indicators are mainly selected based on the source generating waste and the pressure (P in the DPSIR) system) on the environment. In few cases, the state (S) of the environment can be estimated as for soil contamination or water pollution.

**Table 36. Evaluation of waste indicators**

| Indicator | Represent. | | | Operation | | | Application | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Validity | Reliability | Sensitivity | Measurability | Data availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
| SOURCE CATEGORY: ROAD TRANSPORT | | | | | | | | | | |
| Tons of waste generated / acre | xxx | xxx | xxx | xxxx | xx | xxxx | xxxx | xxxx | xxx | xx |
| Solid waste generated biofuel process... | xxx | xxx | xxx | xxxx | xx | xxxx | xxxx | xxxx | xxx | xx |
| Wastewater generated by the biofuel... | xxx | xxx | xxx | xxxx | xx | xxxx | xxxx | xxxx | xxx | xx |
| Volume of pavement waste to landfill | xxx | xxx | xxx | xxxx | x | xxxx | xxxx | xxxx | xx | x |
| Number of vehicles scrapped | xxx | xx | xx | xxx | xxx | xxxx | xxxx | xxxx | xx | x |
| Quantity of used motor oil ... disposed | xx | xx | xxx | xxx | xx | xxxx | xxxx | xxxx | xxx | xx |
| Quantity of used tires landfilled... | xxx | xxx | xxxx | xxx | xx | xxxx | xxxx | xxxx | xxx | xx |
| Quantity of lead-acid batteries... | xx | xxx | xxx | xxx | xxx | xxxx | xxxx | xxxx | xxx | xx |
| Amount of waste produced by cars... | xx | xx | xxx | xx | xx | xxxx | xxxx | xxxx | xx | x |
| Number of motor vehicles stopped... | xx | xx | xx | xxx | xxx | xxxx | xxxx | xxx | x | xx |
| SOURCE CATEGORY: RAIL TRANSPORT | | | | | | | | | | |
| Quantity of reported releases of toxic... | xx | xx | xx | xx | x | xxxx | xxx | xxx | xx | xx |
| SOURCE CATEGORY: AIR TRANSPORT | | | | | | | | | | |
| Recycling of aircraft scrappage | xx | xx | xx | xxx | xx | xxxx | xxx | xxxx | xx | x |
| Quantity of waste generated per WLU... | xxx | xxx | xxx | xxx | x | xxxx | xxx | xxx | x | x |
| Av. quantity in-flight waste / RTK/RPK | xxx | xxx | xxx | xxx | x | xxxx | xxx | xxx | x | x |
| SOURCE CATEGORY: MARITIME TRANSPORT | | | | | | | | | | |
| Quantity releases toxic chemicals | xxx | xx | xxxx | x | x | xxxx | xx | xxx | xx | xx |
| Dilapidated or scrapped vessels | xxx | xxx | xx | xxx | xx | xxxx | xxx | xxx | x | x |
| Quantity of garbage generated... | xx | xxx | xxx | x | xx | xxxx | xxx | xxxx | xxx | x |
| Number of oily birds | xx | xx | xxxx | x | x | xxxx | xxxx | xxx | xxxx | xxx |
| km of beaches contaminated by oil | xxx | xxx | xxxx | xx | xxx | xxxx | xxxx | xxxx | xxxx | xxx |
| Abundance of marine litter | xx | xxx | xx | x | x | xxxx | xxxx | xxx | xx | x |
| Amounts of wastes delivered to ports... | xx | xxx | xx | x | xx | xxxx | xxxx | xxxx | x | x |
| Number of polluters found in sea... | x | x | xx | x | x | xxxx | xxx | xxxx | xx | x |
| Accidental oil spills from shipping | xx | xx | xxx | xx | xxx | xxxx | xxx | xxxx | xxx | xxx |
| Number of vessels w ballast water... | xx | xx | xxx | xxx | xx | xxxx | xxx | xxxx | xx | xx |

x=poor; xx=limited; xxx=good; xxxx=excellent.

**Table 37. A tentative categorization of some waste indicators according to the DPSIR system**

| | D | P | S | I | R |
|---|---|---|---|---|---|
| SOURCE CATEGORY: ROAD TRANSPORT | | | | | |
| Tons of waste generated / acre | | x | | | |
| Solid waste generated biofuel process... | | x | | | |
| Wastewater generated by the biofuel... | | x | | | |
| Volume of pavement waste to landfill | | x | | | |
| Number of vehicles scrapped | x | | | | |
| Quantity of used motor oil ... disposed | | x | | | |
| Quantity of used tires landfilled... | | x | | | |
| Quantity of lead-acid batteries... | | x | | | |
| Amount of waste produced by cars... | x | | | | |
| Number of motor vehicles stopped... | x | | | | |
| SOURCE CATEGORY: RAIL TRANSPORT | | | | | |
| Quantity of reported releases of toxic... | | x | | | |
| SOURCE CATEGORY: AIR TRANSPORT | | | | | |
| Recycling of aircraft scrappage | | | | | x |
| Quantity of waste generated per WLU... | | x | | | |
| Av. quantity in-flight waste / RTK/RPK | | x | | | |
| SOURCE CATEGORY: MARITIME TRANSPORT | | | | | |
| Quantity releases toxic chemicals | | x | | | |
| Dilapidated or scrapped vessels | | x | | | |
| Quantity of garbage generated... | | x | | | |
| Number of oily birds | | | x | x | |
| km of beaches contaminated by oil | | | x | x | |
| Abundance of marine litter | | x | x | | |
| Amounts of wastes delivered to ports... | x | | | | |
| Number of polluters found in sea... | x | | | | |
| Accidental oil spills from shipping | x | | | | |
| Number of vessels w ballast water... | x | | | | |

# 5.7.4. Recommended indicators

Possible fields or activities where use could be made of some of the indicators listed above are suggested in Table 38.

**Table 38. Recommended waste indicators**

| Selected Indicator | Use |
|---|---|
| Total number of contaminated sites | Hazardous waste management policy |
| Quantity of waste generated per workload unit in an airport during a given period of time | Waste management policy |
| Average quantity of in-flight waste per revenue per ton or passenger kilometre | Waste management policy |
| Volume of waste collected by the municipality for disposal per annum | Evaluation and efficiency of waste collection |
| Volume of waste illegally dumped per year | Evaluation and efficiency of waste collection, control and regulation |
| Volume of waste entering unpermitted landfills per year | Evaluation and efficiency of waste collection, control and regulation |
| Direct deterioration of habitats from dredging | Environ. impact control and policy |
| Habitat disruption and contamination from disposal of dredged material | Environ. impact control and policy |
| Wetland losses due to dredging | Environ. impact control and policy |
| Quantity of releases of toxic chemicals by vessels | Hazardous waste management policy |
| Number of certain species killed by entanglement in plastic marine debris | Environ. impact control and policy |
| Quantity of garbage generated by the maritime sector | Environ. impact control and policy |
| Number of oily birds | Environ. impact control and policy |
| Number of beaches contaminated by oil (in km) | Environ. impact control and policy |
| Number of polluters found in sea, ocean, rivers, etc. | Environ. impact control and policy |
| Mortality of marine animal due to ingestion, entanglement, toxicity in marine debris | Environ. impact control and policy |
| Degraded wetlands integrity due to salinity | Environ. impact control and policy |
| Number of roadsides trees killed per year due to salting typical road | Environ. impact control and policy |
| Quantity of used tires landfilled or stockpiled | Recycling policy efficiency |
| Number of motor vehicles stopped annually (number of end-of-life vehicles), | Evaluation and management of waste from transport |
| Recovery / recycled rate for used tires and their share of the solid waste stream | Recycling policy efficiency |

# 5.8. Discussion

Defining and describing the chain of causality is the natural starting point for the search for indicators for a certain chain. Without a clear definition and description of the chain, there will be no solid ground for the choice of chain stage(s) for which indicators are sought.

The criteria for the choice of the causality chains used to exemplify indicator selection in this chapter were met to varying degrees. For each of the seven example chains, the criteria on relevance to planners and policy makers are hopefully met for at least one of the three decision levels specified (European, national and regional). All seven chains can also be judged to be of interest to researchers and other academics. Indicators for some chains are of immediate interest to the general public (e.g. "Noise") whereas indicators for some chains are more directed towards policy makers (e.g. "Greenhouse effect" and "Non-renewable resource use") or scientists (e.g. "Habitat fragmentation" and "Loss of cultural heritage").

The pedagogic value of choosing these chains is difficult to judge but some comments could be given: The chain "Loss of cultural heritage due to land take" demonstrates one of the first trials to construct an indicator in a sector where experts are usually not acquainted with the indicator concept. This example clearly points to the need for further indicator development but, perhaps more importantly, will possibly give rise to discussions on the practicability of indicators in that field.

The chosen chains are qualitatively different - some are short and easily grasped such as "Noise" or "Waste disposal" whereas some are long, complicated and characterized by multiple interacting inter-relationships, such as "Greenhouse effect". The chosen chains also show the great variation in the means in which indicator data can or have to be gathered: field studies of varying duration, inquiries, archive studies, simple desk-top calculation work, computer-heavy simulations, etc. The chain "Greenhouse effect" is well described since substantial scientific effort has been put into clarifying its multiple and complicated chain steps, and far-reaching consensus has been reached on the scientific underpinning of the widely used indicator GWP. In contrast, the chain "Waste disposal" has only relatively recently become subject to deeper scientific study, and existing indicators appear to cover only some of the chain steps. This chain, together with "Noise" and "Non-renewable resource use", is also an example of chains where there is a wide range of indicators for different types of usage. This in contrast to "Loss of cultural heritage" where no indicator seems to have existed hitherto.

In the lack of specified application situations, the seven examples treated in this chapter cannot do justice to the importance of adapting the process of candidate indicator selection to the actual application situation. On the other hand, most of the treated indicators can possibly be re-designed to fit a range of application situations.

The interpretation of the criteria defined in the Chapter 4 (Table 25) for the selection of indicators runs the risk of being highly subjective. What value to put

on each of the criteria should be discussed among experts. Such discussions have not taken place in the work presented here - the application of the criteria to the indictor selection has been made by single working-group members who are not necessarily experts in the respective fields. Likewise, the grounds for recommending specific indicators to be used should ideally have been discussed among scientists, and this has not taken place here. Instead, the recommendations given here for some indicators are rather based on some knowledge on which indicators are much used.

As evident, the procedure for the selection / construction of indicators recommended in section 4.4.2 has been followed only in some of the example chains in Chapter 5. Where followed, the examples intend to demonstrate the practicability of the procedure. Lack of sufficient information, experience or time are common reasons where compliance with the recommended procedure has been out of reach of the authors.

The reported efforts to assess indicators with the use of the ten specified criteria also provide the opportunity of assessing the criteria themselves. Interestingly, in all cases where indicators have been assessed against the criteria, the criterion "Ethical concerns" has been judged to be "excellent", i.e. without problems. Further elaboration, and discussion among true experts, may lead to other judgments on ethical concerns. Also, the seeming lack of concern in the cases reported here does not indicate any lack of relevance of this criterion in other cases.

# 6. Methods for joint consideration of indicators

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Chapter 6 deals with methods for a comprehensive joint consideration of environmentally sustainable transport (EST) indicators. The term 'joint consideration' has been chosen to include methods allowing to build aggregated and composite indicators as well as methods which are considering different indicators without integrating them to a single indicator or index, e.g. multi-criteria methods.

Structure and content of Chapter 6 are organized along the following questions defined to guide the research process:

i   Which are the boundary conditions that affect the selection of a method for joint consideration of indicators and the outcomes of its application?

ii  Which are possible methods for an aggregation of EST indicators and what are their characteristics?

iii What are possible, non-aggregating methods for a joint consideration of indicators?

iv  What is the performance of these methods in view of supporting environmentally sustainable transport?

v   Which were the strengths and weaknesses of methods for joint consideration of indicators in specific application contexts?

vi  Which conclusions can be derived for a comprehensive joint consideration of EST indicators?

In section 6.1 some general reflections on a comprehensive, joint consideration of indicators are presented, including the different steps involved

In section 6.2, methods for building aggregated or composite indicators are presented, in particular life cycle assessment methods, the ecological footprint approach, the MIPS-approach and economic approaches (guiding question ii).

In section 6.3, some discrete and continuous multi-criteria methods for a joint consideration of indicators are introduced (guiding question iii).

With section 6.4, the methods presented in sections 6.2 and 6.3 are evaluated from a general perspective, under abstraction of the specific applications contexts (guiding question iv).

Section 6.5 describes selected cases of application of methods to jointly consider indicators introduced by the participants of the research and identifies strengths and weaknesses of these applications, mainly based on own considerations (guiding question v).

Finally, based on the general reflections, the evaluation of the methods for joint consideration of indicators and the discussion of selected application cases, conclusions are drawn with regard to the suitability of joint consideration methods for the assessment of environmental sustainability of transport.

Chapter 6 builds upon the outputs of the previous chapters, in particular Chapters 4 and 5, literature review and case studies. Being based on the particular knowledge and experience of researchers involved in the COST 356 action, chapter 6 does not intend to cover all the approaches and issues related to joint consideration, but rather to highlight some particular aspects of a joint consideration of indicators.

# 6.1.  General considerations

The need for a joint consideration of indicators derives from the need for a comprehensive view, either in a system analysis or a policy development context. In principle, there are three ways to jointly consider indicators:

1) Select one or more environmental indicators which represent a more global issue (e.g. $CO_2$-emissions representing the environmental impacts of a project);

2) Aggregate indicators or impacts to one indicator, either within an environmental issue or across different environmental issues. For example, for the noise issue, aggregate indicator of disappearance of quiet areas (chain 1), indicator of annoyance to people due to noise (chain 2), indicator of effects on human health (restricted meaning) of noise (chain 3), and indicator of effects on animal health of noise (chain 4), or aggregate different environmental issues into one indicator (e.g. biodiversity, global warming, and health).

3) Other ways of joint consideration of environmental indicators, e.g. by applying multi-criteria decision analysis (MCDA) methods such as AHP (with aggregation) or ELECTRE III (without aggregation).

## 6.1.1. Tasks involved in joint consideration of indicators

When jointly considering indicators, a number of tasks are typically involved in the process:

- First, it is necessary to decide which impacts are relevant and should be assessed, often termed scoping.

- Second, for the chosen impacts, it is necessary to select which aspects or which effects within impact chains that should be represented by the indicator or included in the aggregated indicator. For a noise indicator, for instance, one needs to decide whether indoor noise, outdoor noise, loss of silent areas or other effects should be represented by indicators for noise or be included in the aggregated noise indicator.

- Third, when the impacts and effects are selected, the magnitude of these needs to be measured, calculated or predicted. Selected representative indicators can now be presented for decision-makers.

- Fourth, when jointly considering indicators within impact chains, their significance needs to be decided in order to weight the different effects and, in the case of aggregated indicators, to sum up weighted indicators. The resulting indicator(s) can now be presented to decision-makers as one aggregated indicator within an impact chain or as number of jointly considered representative indicators within the impact chain.

- When aggregating indicators across impact chains, it is necessary to do a fifth operation, namely to decide on the relative significance of the different kinds of impacts (local health, global warming, traffic deaths, biodiversity, landscape quality etc.) in order to use this weighting in aggregation.

In the next two sections, the issues of scoping and significance analyses are further discussed. The issue of selection of indicators has already been addressed in the previous chapters.

## 6.1.1.1. Scoping

In the scoping stage, several approaches can be found for taking the decision about which impacts are relevant and should be assessed, or, in general, for identifying the content and extent of the environmental information. Following, the framework within which this must take place and the differences in context and procedures that exist in different countries, are briefly addressed.

According to the European Commission (EC, 2001), the scoping procedure must be made
- having enough information about the project and the area which will be affected
- understanding the relevant legislation and its implications for the project and the environment;
- having a good understanding about the decision-making process.

In some countries scoping procedures involve some measure of consultation. In more developed systems, consultation is extended widely to all interested parties, including the general public with public hearings. In others, consultation is less extensive and focuses on seeking the views of relevant environmental authorities.

Effective scoping will involve the competent authority and the developer (of the plan, programme, project, alternatives, …) in a dialogue about the project and the issues it raises. It is also important to remember that the activity of scoping should continue throughout the evaluation process, so that the scope of work can be changed, at any time, in the light of new information. The scope of an evaluation process must be flexible enough to allow new issues which emerge during the course of the environmental studies, or as a result of design changes or through consultations, to be incorporated.

Advantages of this task are, amongst others, that (i) it helps ensure that the environmental information used for decision making provides a comprehensive picture of the important effects of the project, including issues of particular concern to affected groups and individuals and (ii) it stimulates early consultation between the developer and the competent authority, the environmental authorities, other interested parties and the public, about the project and its environmental impacts.

## 6.1.1.2.   Impact significance appraisal

As shown for environmental impact assessment in particular (Beanlands and Duinker, 1983; Sadler, 1996), the allocation of significance values to impacts is one of the most crucial steps in joint consideration or, rather, aggregation of indicators. Significance values reflect the relative importance the society will grant to each of the consequences stemming from implemented action in the horizon year.

To appraise the significance of impacts usually implies allocating weights reflecting their relative importance within the context of the policy under consideration. There is considerable amount of guidance on techniques for allocation of significance factors (see i.e. James and Tomlinson, 2004; Arce-Ruiz, 2002). However, Calderon *et al*. (2009b, in particular section 5.1) set out some remarks highlighting the subjectivity of score allocation.

The allocation to significance scores to the different impacts geared to their possible aggregation can be, as it has been argued, highly subjective and dependent on local circumstances. However, not only the European Commission (in the SEA Directive, for instance), but likewise different administrations in Europe, Australia and other countries (Lawrence, 2007) have already released guidance about the allocation of significance scores in an attempt to facilitate the joint consideration of all effects affecting a transport policy decision.

Arce-Ruiz (2002) argues that the allocation of significance scores can be split in two different parts:

- The first is centred upon the "intrinsic" characteristics of the effects and the affected area and it provides a measure of the severity of impacts (see also section 2.4). These are related mostly to objective features such as:
  a. Impact nature: simple, synergistic or cumulative.
  b. Probability of occurrence.

c. The delay in appearance: short, medium or long term. Effects showing in the long term are likely to be consequence of long chain of cause and effect, or due to a cumulative character, surely more difficult to offset. An impact expected to appear in the long run will usually be considered more severe than those appearing in the medium or short term, as these impacts can be readily detected, and even, minimized or eliminated.

d. The duration, permanent or temporary impacts. Temporary impacts, which disappeared shortly after their onset, are considered less severe than permanent ones.

e. The reversibility or recoverability. One impact will be considered less severe if it is reversible and much more severe if it is irreversible. The severity is often related recovery time and cost (see also section 2.2.5).

f. The special value and vulnerability of the area likely to be affected due to special natural or cultural characteristics, exceeded environmental quality limit values, or intensive land-use.

g. The risks to human health or the environment.

h. The spatial extent of the impact, which can be broad (air pollution) or localized (noise). This does not normally affect magnitude, but impacts are usually considered more severe when large territorial areas can be affected.

- Second, the characteristics called "extrinsic" are related to political aspects, which are external to the characteristics of the impacts: For example, the question if the impact is relevant for a specific policy of interest for promoting sustainable development (e.g. climate change issues are more relevant at present).

Three main areas to be taken into account when allocating significance scores then are:

1. The characteristics of the policy option under consideration (this corresponds to the source characteristic, see sections 2.1 and 2.4.1);
2. The quality of the receiving environment, related with the target characteristic (see section 2.4.1);
3. The intrinsic characteristics of the impact under consideration (see sections 2.4.1 and 2.4.2).

Significance in the context of impact aggregation includes the relative importance assigned to impacts within the framework of the joint consideration of all the consequences of a transportation policy option or the examination of the current state of a transportation system ("do-nothing" option). These relative values are allocated in the form of normalised scores for each individual impact respective of all others.

Normalization is the process whereby impact indicators scores are transformed into a uniform scale of measurement, thus directly allowing the aggregation of consequences as forecast in the horizon year. There are a few techniques for normalization which have been described in the literature (see Nardo *et al*., 2005; Pomerol and Barba-Romero, 2000; see also section 6.2.1) and can be resumed as: ranking, standardisation, re-scaling, distance to a

target, categorical scale, indicators above or below the mean, methods for cyclical indicators, percentage of differences.

The selection of a suitable method for normalization is not trivial. Because different methods will yield different results, then, some previous tests might be needed to assess their impact on the outcomes (Nardo *et al*., 2005).

The practical application of all the above considerations may suggest that techniques for determining significance in accordance with guidance from existing EU documents may involve:
− Expert judgement
− Dialogue with stakeholders
− Reference to legislation and regulations, as well as existing environmental thresholds
− Risk assessment
− Ranking and weighting procedures
− Some notion of environmental capacity
− Trends analysis, literature reviews and consulting with professionals

# 6.1.2. Aspects related to the joint consideration of indicators

## 6.1.2.1. Factors affecting the decision making process

The following factors are known or expected to influence the decision making process and constitute determining elements for the joint consideration of impacts (see also Chapter 3):

- **The level of decision**, plan, program or project. Arguably, for each of these levels, objectives are different and, hence the available information on which the decision is based, the typology of indicators and the possibilities of aggregation. But also, in regard to the consideration of environmental impacts, the processes of environmental assessment (e.g. in Europe through the so-called SEA Directive 2001/42/EU and EIA Directive 85/337/EEC as amended by Directive 97/11/EC) allow the integration of the environment into decisions.

- The **socio-economic context**, in terms of information availability, level of development of the country or region in which the decision is made, the prevailing technical expertise, etc.

- The **type of decision making process**, more or less akin to rational models and with more or less public participation. The balance between "technocratic" processes and those based on expert opinion, or more "participatory", with integration of public opinion, may indeed, become a limiting factor in what concerns the selection of approaches for joint consideration of impacts. However, the participation of the public in development planning processes is statutorily regulated and involves quite diverse situations in what concerns the time and types of participation, the

appointed stakeholders, the legal consequences of the participatory process, etc.

- The **quest for sustainability**. This overriding issue (see section 2.2) presides over all parts of the selection processes and, likewise, makes up a limiting condition when selecting methods for the joint consideration of impact indicators. Nevertheless, there stand some issues which mainly affect the usability of certain methods for jointly consideration of impacts. Among those, the following have been highlighted:

− Methods to be used for impact aggregation must allow the consideration of sustainable development goals and comply with statutory regulations.

− Sustainable development as a framework where the trade-offs between indicators describing the three main pillars of sustainability may be analysed. The debate between "strong" and "weak" sustainability finds its place here (see section 2.2.3)

− Lawrence (2007) argues impact significance determinations can change dramatically when sustainability is a primary goal of environmental assessment requirements, processes and documents (Vanclay, 1999). Alternatives, for example, are scoped for sustainability and compared in regard to their relative contribution to sustainability (IAIA, 2003). The focus shifts from minimizing damage (i.e., reducing the negative) to maximizing long-term gains and opportunities for multiple parties (Gibson, 2005). The significance of both positive and negative impacts is addressed. Time horizons are extended to consider significance for future generations. More attention is devoted to interdependencies within and among social, economic, physical and ecological systems (Goodland, 1998; Sadler, 1996), as well as to cumulative impacts (e.g., lasting, net environmental and human benefits), and to systems-level, collective impact significance (e.g., net contribution of social, economic, physical, and ecological changes to sustainability) (Barrow, 2000). Proposed actions are viewed as potential sustainability catalysts or as impediments to sustainability. Some of these arguments (significance appraisal, uncertainty, etc.) are discussed further in sections 6.1.1.2 and 6.1.2.2.2.

− The different tiers of impact evaluation, as we presented at the beginning of the section. Joint consideration necessarily involves the previous allocation of weights reflecting the relative significance of each and every one of the impacts under consideration.

## 6.1.2.2. Subjectivity, uncertainty, transparency and interpretability

In this section, four different, but intertwined, aspects related to joint consideration of indicators are discussed. The first aspect addresses the number of subjective considerations necessary in indicator production, and the distribution of the subjective considerations among experts and decision-makers for different aggregation levels. A second aspect concerns the differences in kinds and sizes of uncertainty, and a third the degree of transparency connected to the different kinds of indicators. The fourth aspect is related to the kind of information submitted to the decision-makers, the form this

information is submitted in, and the way how variations of this affect decision-makers' abilities to make enlightened decisions. This is termed interpretability.

In the following discussion, we do not distinguish between an aggregation of indicators and the use of multi-criteria decision analysis. Instead, the focus is on the necessary tasks involved in constructing indicators based on selection of representative indicators, construction of indicators within impact chains including any kind of weighting and aggregation and construction of indicators across impact chains including any kind of weighting and aggregation. For all three, it is assumed that the outcome could be one indicator or a suite of indicators.

### 6.1.2.2.1. *Subjective considerations and value judgements*

From the description of the process of producing indicators, it is clear that subjective considerations are necessary in all steps of indicator production. The knowledge and ideas of people involved in the process of making indicators, including their personal and professional values, world view, background and experience, as well as the culture, views and understandings at their workplace or in the system they are working within, will inevitably influence the way the problem is approached and thus the results (see i.e. Emmelin, 1998; Emmelin and Kleven, 1999; Richardson, 2005; Tennøy, 2008). Schön (1983) discussed this as different framings of a problem (see also Tennøy, 2010). This also opens for more or less conscious bias (Flyvbjerg *et al*., 2002; Tennøy at al., 2006). Even if there are a number of methodologies for bringing the value judgements and subjective considerations of decision-makers and others into the production of indicators (all steps), these processes will almost always be designed and facilitated by experts. This influences which judgements and considerations are done, how they are considered and the methodology for doing it (see e.g. Richardson, 2005) and leave the agenda-setting power in the hands of the experts (Lukes, 2005).

The possible ways of jointly considering indicators differ in several ways when it comes to the necessary subjective considerations. The number of subjective considerations involved in producing indicators increases when going from selection of representative indicators (scoping, selection, prediction), via aggregation within impact chains (including one weighting) to aggregation across impact chains (including two weightings). This also affects the distribution of subjective considerations and value judgements. One can argue that the higher the aggregation level, the more value judgements are integrated in the indicator making. As a consequence, a higher share of the value judgements and subjective considerations are put in the hands of the experts.

For all ways of doing joint considerations of indicators, more or less subjective decisions need to be made in the scoping process in order to decide which impacts to include in the assessment. This could be impacts on local health, global warming, biodiversity, landscape quality or others (see e.g. de Jongh, 1988; Glasson *et al*., 1999; Teigland, 2000). The same goes for selection of which effects to choose to be represented by an indicator or to include in the aggregation of effects within impact chains (whether indoor noise, outdoor noise, loss of silent areas should be chosen as representative of noise

impact or be included in the aggregated indicator for noise). These decisions may be made on the basis of more or less clearly stated politically defined objectives or thresholds, on the basis of monitoring of various environmental (and other) factors, on the basis of public concern for certain aspects of the environment, or on the basis of professional knowledge and judgement about the situation or combinations of these, as discussed in previous sections. When predicting, measuring or calculating the magnitudes of the effects and impacts, it is necessary to decide which assumptions and theories to build on, which methodology, baseline data, time horizons, geographical horizons to use, how to interpret the results, etc. (see e.g. Wachs, 1990; De Jongh, 1988; Flyvbjerg *et al.*, 2002; Tennøy *et al.*, 2006).

When aggregating indicators within and across impact chains, it is necessary appraise the significance or to weight the importance of different effects and impacts, respectively. This significance appraisal or weighting represents and entails value judgements and subjective considerations. When aggregating within impact chains, experts are in different ways and to different degrees doing or forming the weighting or significance appraisal between e.g. indoor or outdoor noise in a noise indicator. When aggregating across impact chains, this also includes weighting among e.g. noise and air pollution in a health indicator or impacts on local health and climate change in a sustainability indicator. There are a number of methodologies for doing such weighting and significance appraisal, as will be describe in sections 6.2 and 6.3. Since this is about values - about deciding what is more and less important - there is however no purely objective way of doing this. The higher the aggregation level, the more subjective considerations and value judgements are made by the experts constructing the indicators and included in the indicators.

### 6.1.2.2.2.   Uncertainty

Uncertainty can be understood as the deviation between reality and measurements in monitoring, and the deviation between predicted impacts of a project and measurements of the real impacts after implementation for ex ante indicators (Wood *et al.*, 2000).

In the scoping and selection processes, there will be uncertainties or disagreements concerning what the most relevant and important impacts to assess are, and how to best represent these impacts. There may among others be unknown cumulative effects and discussion of whether and how to include long-term effects such as consideration for future generations. The predictions needed when making ex ante indicators cause more multiple and complex reasons for uncertainty (de Jongh, 1988; Teigland, 2000; Glasson *et al.*, 2005; Tennøy *et al.*, 2006; Tennøy, 2008).

Uncertainties are unavoidable for all ways of jointly considering indicators. Still, the uncertainty increases as the aggregation level increases, because more entities are included in the indicator. The uncertainties also get more problematic, since the variation in what kinds of entities are aggregated, as well as the variation in the types and sizes of the uncertainties attached to these, increase.

When selecting representative indicators, there are uncertainties attached to which impacts are most relevant in the situation and should be included in the indicator set, and attached to the magnitude of the impacts chosen. Decision-makers are thus submitted to a number of indicators, which are uncertain in the sense that they may represent the contemporary or future state of the environment activity wrongly.

This uncertainty is enhanced when impacts are aggregated across impact chains, since the number of impacts needed to be measured or predicted increase. Also, the weighting among impacts requires that the different kinds of impacts (for instance the changes of number of people affected by indoor noise and loss of silent areas) need to be translated into comparable entities (e.g. number of people affected, money values) in order to constitute an aggregated indicator (discussed as normalization in section 6.2.1). This poses several problems, which among others include the aggregation of impact predictions of different kinds (e.g. whether it will happen or not and which impact it will have), of different magnitudes and possibly very different sizes of uncertainties. If we follow the many steps involved in for instance doing cost-benefit analysis of transport infrastructure investment projects, as Næss (2006) has done, the number of sources for, and types of, uncertainties become overwhelming. Thus, as the aggregation levels increase, the number of entities and the differences of the types of entities calculated increase. This means that the number of sources of uncertainties increases, as do the differences in types and kinds of uncertainties.

### 6.1.2.2.3. *Transparency*

A main difference between the various ways of jointly considering indicators lies in the transparency of the resulting indicators. It can be argued that transparency is reduced as the aggregation level increases, and that this reduces the decision-makers chances of understanding the indicators and thus the consequences of decisions made on the basis of these.

In the case of selected representative indicators, the decision-makers are submitted to a number of indicators directly representing different kinds of impacts (health problems, global warming). These indicators are non-transparent in the sense that decision-makers need to study the background materials in order to decide whether they agree on for instance the assumptions made in the scoping, selection and prediction of the indicators.

If decision-makers (and others) have to decide which actions to take on the basis of aggregated and integrated indicators such as cost-benefit factors or ecological footprints, it will be hard (if possible) for them to understand what the indicator represents. The sheer number of subjective considerations, ontological, epistemological and methodological assumptions and uncertain calculations included in the construction of such indicators turn them into impenetrable entities, sometimes termed black boxes or Russian dolls in the literature (Sager and Ravlum, 2005; Duncan, 2008). This means that decision-makers cannot understand or ask critical questions about which impacts are included and assessed, the assumptions underpinning the calculations, the weighting done, or the types and sizes of uncertainties involved.

It can be argued that when presented for highly aggregated indicators, decision-makers can't know what they are making decisions about. Sager and Ravlum (2005) found that this reduces the use of indicators in decision-making in their studies on use of expert analyses in decision-making regarding the National transport plan in Norway.

As a consequence, it can be said that the transparency, with respect to what the indicator represents, how it is constructed, the types and sizes of uncertainties embedded in the indicator and the subjective considerations and value judgements, are reduced as aggregation levels increase. This is also understood by decision-makers, and affects their use of such indicators.

### 6.1.2.2.4. *Interpretability*

The main advantage of aggregating indicators to higher levels is probably that different kinds of effects can be calculated and translated into the same entity (e.g. money), and compared. It can be argued that if the same way of thinking, the same goal rating and weighting and the same methodology etc. are used for all alternatives, effects, impacts etc., we can come up with value neutral indicators which may not represent reality, but which still are comparable. The indicator is thus the result of an optimisation of goal achievements. The decision-makers are by this given good information about the situation, and can make their decisions on a few or one indicator(s). As previously argued, this may be opposed by arguments saying that the uncertainties, value judgements and subjective considerations hidden in such indicator obscure the view rather than to present good information about the situation or phenomenon investigated (Wachs, 1990; Ravetz, 1998).

A main advantage of representative indicators is from this point of view that they bring 'purer' information to decision-makers, which is not obscured by the experts' interpretation, simplification and translation of the knowledge. An important question would then be if decision-makers are able to cope with a large number of representative indicators, representing very different kinds of impact with very different seriousness, time horizons etc. They may lose the overview, get lost in details, or lose sight of the superior objectives. In order to provide decision-makers with a better understanding of the consequences of their decisions, one could argue, experts need to organize and summarise the information.

It is thus hard to determine which aggregation level is most interpretable for decision-makers. With basis in the discussions in Chapter 3, one could argue that this will be context dependent and situation driven. What is decision relevant will vary; Sometimes a highly aggregated indicator will be better, while representative indicators would be better in other situations.

### 6.1.2.2.5. *Synopsis*

The above findings may be summarised as follows (see Table 39).

Selected representative indicators and highly aggregated indicators, respectively, may be viewed as representing two different worldviews with respect to decision-makers' and experts' tasks and roles in decision-making. On

the one hand, there is the idea that the decision-makers should define the main objectives, and the experts should do analyses resulting in a ranking of alternatives with regard to these objectives. The more precise and aggregated indicators the experts can produce, the easier it is for decision-makers to make 'right' decisions with respect to their own objectives. On the other hand, there is the idea that decision-makers are supposed to and need to know what they are making a decision about. Implicit in this there are requirements for transparency, both with respect to the probable consequences of the decisions with respect to different kinds of factors and about the uncertainties embedded in the indicators.

**Table 39. Comparison of three types of joint considerations of indicators**

| | Selected representative indicators | Indicators aggregated | |
| --- | --- | --- | --- |
| | | within impact chains | across impact chains |
| Who is doing the subjective considerations | Decision-makers | ⟹ | Experts |
| Number of subjective considerations included | Fewer | ⟹ | More |
| Uncertainty levels | Lower | ⟹ | Higher |
| Types of uncertainties | Fewer | ⟹ | More |
| Transparency | Higher | ⟹ | Lower |
| Number of indicators | Many | ⟹ | Few |
| Interpretability | ? [1] | ? [1] | ? [1] |

[1] The question marks in the last row signalises that it is not determined which indicators are most interpretable for decision-makers; This will vary with the decision-making situation.

Within planning-theory, this is a central and long-standing discussion, which also includes the comprehension of what kinds of predictions social science can deliver (see Chapter 3 and e.g. Friedmann, 1987; Sager, 1990; 2002; Healey, 1997; Danermark *et al.*, 2002). The first understanding (which would argue for highly aggregated indicators) can be related to the strong definition of the rational or synoptic planning ideal (see e.g. Hudson, 1979; Friedmann, 1987). Here it is assumed that decision-making as well as decision-makers are rational, and that scientists can deliver relatively objective, certain and accurate predictions about the future. The other understanding (which would argue towards selected representative indicators) recognises the shortcomings of synoptic or rational decision-making (see e.g. Friedmann, 1987). This includes among others that decision-making and decision-makers are not that rational or reflect other rationalities than assumed in rational or synoptic planning, that unambiguous and fully agreed objective-rating is not feasible and that certain and objective calculations or predictions are not possible in social science or in decision-making regarding social systems.

If the purpose of bringing indicators into decision-making is to enable decision-makers to make 'right' decisions, for instance to make transport environmentally more sustainable, it is often claimed that this must be because it contributes to inform decision-makers about the possible or likely impacts of their decisions (see for instance Wathern, 1990). In Chapter 3, it was found that decision relevance is a main criterion for choosing indicators, and that this varies with situation and context.

Constructing EST indicators is a challenging task since the indicators need to relate to very different types of activities (for instance construction of transport infrastructure, changing transport services, land use development, implementation of taxes, tolls or use of legislative instruments), to very different types of impacts on different scales and with different time frames (for instance noise, climate change, loss of human lives, equity in time and space) and to very different decision-making situations. It could be argued that the idea of constructing highly aggregated and integrated indicators, representing multiple future realities (if different actions are carried out) 'rightly', which are also understood as useful and usable by decision-makers, is futile.

In Chapter 3, decision relevance was found to be a main criterion for choosing indicators from a decision-making point of view. Decision relevance varies depending on context and situation. In strategic decision-making, where one aims at comparing different strategies with respect to main objectives, decision relevance is about making indicators that represent these (few) main objectives, and which reveal the differences between alternative options with respect to consequences for main objectives or main thresholds. Decision-relevance at the tactical level is more related to the specific context. On the operational level, detailed and specific knowledge is needed, and indicators are mainly needed for monitoring effects in order to know whether to implement mitigating measures.

Finally, another important issue to consider is the differences of knowledge available. On the strategic level, few details are known, and there is a need for robust and generic indicators. On the tactical level, the type of project (what to do or build) is known, but not necessarily how or where. The indicators need to be more specific, more detailed and more numerous. On the operational level, the action as well as the context is known. The task is not to choose between alternatives, but to find ways of optimising the chosen solution.

# 6.2. Methods for building aggregated or composite indicators

In this section, some general methodological issues associated with the aggregation of indicators or impacts are discussed and some common methods applied in environmental impact assessment introduced with regard to how they aggregate environmental impacts or impact indicators. The methods and approaches considered are:
– Life Cycle Assessment (LCA)

– The ecological footprint
– The MIPS-method
– Economic approaches.

These methods are later evaluated with regard to their performance in assessing environmental sustainability in section 6.4.1.

# 6.2.1. General considerations

When aggregating indicators, normalizing the score of indicators and weighting the normalized indicators are important steps to be performed, as demonstrated with the Battelle methodology used in EIA (Canter, 1995; Arce-Ruiz, 2002). Normalization is also required for building composite indicators as referred to by Nardo *et al*. (2005) to convey information on countries' performance in fields such as environment, economy, society, or technological development. It is, however, not necessary in the context of a joint consideration of indicators with multi-criteria methods e.g. of the ELECTRE type (see section 6.3).

As mentioned in Nardo *et al*. (2005), a composite or aggregated indicator is the mathematical combination of individual indicators that represent different dimensions of a concept whose description is the objective of the analysis (see Saisana and Tarantola, 2002). A composite indicator is formed when individual indicators are compiled into a single index on the basis of an underlying model.

Composite indicators often seem easier to interpret by the general public than finding a common trend in many separate indicators. For example, a composite indicator such as the "ecological footprint" is highly effective in the communication to the public to transmit the impact of a city or a region in natural resources consumption.

The debate between pros and cons of composite indicators use is very well reflected in Saisana and Tarantola, 2002, as mentioned in Nardo *et al*. 2005. Based on that, the pros and cons for its use in evaluation of environmental impacts of transport are listed in Table 40.

Weights typically have a great impact on the results of an aggregation. This is why weighting models need to be made explicit and transparent. Moreover, one should have in mind that, no matter which method is used, the subjective components of the weights are essentially value judgments and have the property to make explicit the objectives underlying the aggregation.

Whenever indicators in a dataset are incommensurable with each other and/or have different measurement units, for an aggregation it is necessary to bring these indicators to the same scale. Normalization, which converts all values in values between 0 and 1, serves primarily for this purpose.

**Table 40. Pros and cons of use of composite indicators in transport**

| Pros | Cons |
|---|---|
| • Can summarise complex or multi-dimensional issues in view of supporting decision-makers. | • May send misleading policy messages if they are poorly constructed or misinterpreted. |
| • Easier to interpret than trying to find a trend in many separate indicator | • May invite simplistic policy conclusions. |
| • Facilitate the task of reflect complex issues in a comparative exercise. | • May be misused, e.g., to support a desired policy, if the construction process is not transparent and lacks sound statistical or conceptual principles. |
| • Can assess evolution in environmental impacts on complex issues. | |
| • Reduce the size of a set of indicators or include more information within the existing size limit. | • The selection of indicators and weights could be the target of political challenge. |
| • Facilitate to place issues of environmental performance and progress at the centre of the policy arena. | • May disguise serious failings in some dimensions and increase the difficulty of identifying proper remedial action. |
| • Facilitate communication with general public (i.e. citizens, media, etc.) and promote accountability. | • May lead to inappropriate policies if dimensions of performance that are difficult to measure are ignored. |

Source: Adapted from Saisana and Tarantola, 2002.

There are a number of normalization methods available, such as ranking, standardization, re-scaling, distance to reference measure, categorical scales, cyclical indicators, balance of opinions (Nardo *et al*., 2005). The selection of a suitable normalization method to apply to the problem at hand is not trivial and deserves special care. The normalization method should take into account the data properties and the objectives of the aggregation or the composite indicator. For example, Nardo *et al*. recommend that, in the presence of extreme values, normalization methods that are based on standard deviation or distance from the mean are preferred.

Different normalization methods will supply different results for the aggregation, therefore, it is necessary to consider the measurement units in which the indicators are expressed when choosing the normalization procedure (Ebert and Welsch, 2004). Scale transformation can be necessary prior to normalization. Certain normalization procedures provide normalized values that conserves proportionality of the indicator measurement unit. Applying a normalization procedure, which is not invariant to changes in the measurement unit, however, could result in different outcomes.

In Table 41, Nardo *et al.* (2005) summarize the normalization methods that can be used for elaborate composite indicators and where $x_c^t$ are values of indicators for a country c at time t. In the context of environmental evaluation, in a similar way, these normalization methods can be applied to impact values to aggregate them.

## Table 41. Normalization methods
## according to Nardo *et al*. (2005)

| Method | Equation |
|---|---|
| Ranking | $I_{qc}^t = Rank(x_{qc}^t)$ |
| Standardisation (or z-scores) | $I_{qc}^t = \dfrac{x_{qc}^t - x_{qc=\bar{c}}}{\sigma_{qc=\bar{c}}^t}$ |
| Re-scaling | $I_{qc}^t = \dfrac{x_{qc}^t - \min_c(x_q^{t_0})}{\max_c(x_q^{t_0}) - \min_c(x_q^{t_0})}$ |
| Distance to a reference | $I_{qc}^t = \dfrac{x_{qc}^t}{x_{qc=\bar{c}}^{t_0}} \ or I_{qc}^t = \dfrac{x_{qc}^t - x_{qc=\bar{c}}^{t_0}}{x_{qc=\bar{c}}^{t_0}}$ |
| Categorical scales | $I_{qc}^t = \begin{cases} 25 \ \text{if} \ x_{qc}^t \in \{p^{25th}\}\text{percentile} \\ 50 \ \text{if} \ x_{qc}^t \in \{p^{50th} - p^{25th}\}\text{percentile} \\ 75 \ \text{if} \ x_{qc}^t \in \{p^{75th} - p^{50th}\}\text{percentile} \\ 100 \ \text{if} \ x_{qc}^t \in \{p^{100th} - p^{75th}\}\text{percentile} \end{cases}$ |
| Indicators above or below the mean | $I_{qc}^t = \begin{cases} 1 \ \text{if} \ w > (1+p) \\ 0 \ \text{if} \ (1-p) \le w \le (1+p) \\ -1 \ \text{if} \ w < (1+p) \end{cases}$ <br><br> Where $w = x_{qc}^t / x_{qc=\bar{c}}^{t_0}$ |
| Cyclical indicators (OECD) | $I_{qc}^t = \dfrac{x_{qc}^t - E_t(x_{qc}^t)}{E_t(\lvert x_{qc}^t - E(x_{qc}^t)\rvert)}$ |
| Balance of opinions (EC) | $I_{qc}^t = \dfrac{100}{N_e} \sum_e^{N_e} \text{sgn}_e(x_{qc}^t - x_{qc}^{t-1})$ |
| Percentage of annual differences over consecutive years | $I_{qc}^t = \dfrac{x_{qc}^t - x_{qc}^{t-1}}{x_{qc}^t}$ |

Note: $x_{ic}^t$ is the value of indicator for country *c* at time t. *c* is the reference country. The operator *sgn* gives the sign of the argument (i.e. +1 if the argument is positive, -1 if the argument is negative). $N_e$ is the total number of experts surveyed.

Based on Pomerol and Barba-Romero (2000), Table 42 shows the principal procedures for value normalization.

**Table 42. Some normalization methods and interpretation according to Pomerol and Barba-Romero (2000)**

| | Procedure 1 | Procedure 2 | Procedure 3 | Procedure 4 |
|---|---|---|---|---|
| Definition | $v_i = \dfrac{I_i}{\max I_i}$ | $v_i = \dfrac{I_i - \min I_i}{\max I_i - \min I_i}$ | $v_i = \dfrac{I_i}{\sum_i I_i}$ | $v_i = \dfrac{I_i}{(\sum_i I_i^2)^{1/2}}$ |
| Normalized value | $0 < v_i \le 1$ | $0 \le v_i \le 1$ | $0 < v_i < 1$ | $0 < v_i < 1$ |
| Maintain proportionality | Yes | No | Yes | Yes |
| Interpretation | % of the maximum | % of the range (max $I_i$ – min $I_i$) | % of the total $\Sigma I_i$ | $i^{th}$ component of unit vector |

# 6.2.2. Life Cycle Assessment methods

Life cycle assessment (LCA) typically consists of the following four phases (ISO 14040, 2006, p. V):

a) the goal and scope definition phase,

b) the inventory analysis phase,

c) the impact assessment phase, and

d) the interpretation phase.

The *scope* of an LCA, including the system boundary and level of detail, depends on the subject and the intended use of the study. Depending on the *goal*, the depth and the breadth of an LCA can differ considerably. The *life cycle inventory analysis* phase (LCI phase) consists of establishing an inventory of input and output data with regard to the system being studied. The purpose of the *life cycle impact assessment* phase (LCIA) is to assess a system's LCI results with regard to their environmental significance (ISO 14040, 2006, p. V).

Within life cycle impact assessment, different methods have been developed, which allow to aggregate environmental impacts or environmental impact indicators to a single score. Following, two different ways of aggregating are presented and discussed: The aggregation according to the ecological scarcity method or Eco-factors 2006 method (Frischknecht *et al*., 2009), and the aggregation according to the ReCipE method (Goedkoop *et al*., 2009), respectively.

As stated in ISO 14040 (2006, p. 9), there is no scientific basis for reducing LCA results to a single overall score or number, since weighting requires value choices. For guidelines on weighting within LCA see, in particular, the technical report ISO/TR 14047 (2006).

## 6.2.2.1. The ecological scarcity method

According to the ecological scarcity method, every load of a pollutant or quantity of a resource determined in a life cycle inventory analysis is multiplied with its corresponding eco-factor, allowing for a comparative weighting and aggregation of different environmental impacts. The eco-factor for a pollutant or resource, expressed in eco-points (EP), is derived according to the following general formula (Frischknecht *et al*., 2009):

$$Eco-Factor = \underbrace{K}_{\substack{\text{Characterisation} \\ \text{(optional)}}} \cdot \underbrace{\frac{1[EP]}{F_n}}_{\text{Normalization}} \cdot \underbrace{\left(\frac{F}{F_k}\right)^2}_{\text{Weighting}} \cdot \underbrace{c}_{\text{Constant}} \quad \text{[eq. 12]}$$

With:

K = Characterization factor of a pollutant or of a resource

$F_n$ = Normalization flow: current annual flow, presently with Switzerland as system boundary

F = Current flow: current annual flow in the reference area

$F_k$ = Critical flow: critical annual flow in the reference area

c = Constant ($10^{12}$/year): serves to obtain readily presentable numerical quantities

EP = Eco-point: the unit of environmental impact assessed "Flow" refers to the load of a pollutant, the quantity of a resource consumed, or the level of an environmental impact characterized.

The formula for the determination of an eco-factor includes an optional characterisation, a normalization as well as a weighting step.

*Characterization* captures the relative harmfulness of a pollutant emission or resource extraction with regard to a reference substance within a given impact category (global warming potential, acidification potential, radioactivity etc.). For instance, the global warming potential of methane ($CH_4$) is for a time horizon of 100 years 23 times higher than that of carbon dioxide ($CO_2$). Sulphur hexafluoride ($SF_6$), which is used to insulate electric components, even has a global warming potential 22 000 times that of $CO_2$ (see section 5.6.1).

*Normalization* quantifies the contribution of a unit of pollutant or resource use to the total current load / pressure in a region (in this case the whole of Switzerland) per year. If, for instance, 100 000 tonnes of a substance are released annually ($F_n = 10^8$ kg/a), then the contribution of 10 grams is small. If, in contrast, only 70 grams per year are released in total ($F_n = 0.07$ kg/a), then the same contribution of 10 grams is very large. The smaller the normalization flow, the larger the eco-factor will tend to be.

*Weighting* expresses the relationship between the current pollutant emission or resource consumption (current flow) and the politically determined emission or consumption targets (critical flow). The weighting factor corresponds to the square of the ratio between the current and the critical flow. As a consequence, a major exceeding of the target value (critical flow) is weighted above-proportionately. If, however, the current flow is substantially lower than the critical flow, weighting is performed under-proportionately.

The ecological scarcity method is a so-called 'distance-to-target' method as defined by the Society of Environmental Toxicology and Chemistry / SETAC (Udo de Haes, 1996). Weighting of pollutants and resources with eco-factors is based primarily on environmental protection targets set at national level and, in some cases, international level. According to Frischknecht *et al*. (2009), such targets are ideally adopted in legally binding form or at least defined as targets by competent authorities, formulated by a democratically selected or legitimated body, and oriented to sustainability as far as possible. New statutory and political settings, new findings and experience, and the changing emission situation make it essential to adapt the eco-factors regularly.

In order to be applicable onto other countries, several variants of a former version of the ecological scarcity method have been developed, e.g. in Austria, the Netherlands, Norway and Sweden (see Doka, 2002). An adaptation of the method to specific regional or national boundary conditions are also possible for the new version.

The ecological scarcity method is evaluated with regard to its performance in section 6.4.1.1 on page 239.

## 6.2.2.2. The ReCiPe method

ReCiPe has been conceived as an LCIA method that is harmonised in terms of modelling principles and choices. The ReCiPe method can be considered as a synthesis of two previously developed LCIA methods: the characterisation method described in the *Handbook on LCA* (Guinée *et al*., 2001), also referred to as 'the midpoint approach', and the method advanced in *The Eco-indicator 99* (Goedkoop and Spriensma, 2001), also referred to as 'the endpoint approach' (Goedkoop *et al*., 2009; p. 1). Whereas midpoint approaches focus on indicators which appear in an earlier stage of a chain of causality (e.g., global warming, acidification) – see section 2.4, endpoint approaches focus on indicators appearing late in the chain of causality (e.g. incidence of cancer).

With ReCiPe, the aggregation of midpoint indicators such as e.g. global warming potential (in kg $CO_2$ eq. to air), ozone depletion potential (in kg CFC-11[5] eq. to air) or terrestrial acidification potential (in kg $SO_2$ eq. to air) into the endpoint indicators 'damage to human health', 'damage to ecosystem diversity' and 'damage to resource availability' is done by transforming them into damages with common units through so-called 'environmental mechanisms' (ISO 14040, 2006) closely related to the chains of causality defined in section 2.4.1: Disability-adjusted loss of life years (DALY) for the damage category 'damage to human health', loss of species during a year (in species x years) for the damage category 'damage to ecosystem diversity' and increased cost (in a monetary unit, here US$) for the damage category 'damage to resource availability'.

According to the authors, an advantage of the method is that it provides a common framework which gives the choice either to select more robust, but not easily interpretable midpoint indicators, or easy to understand but more uncertain endpoints (www.lcia-recipe.net/). A major drawback of the method is that some links (i.e. environmental mechanisms) between mid- and endpoint

indicators are not (e.g. marine eutrophication) or not fully (e.g. the links between ozone depletion, photochemical oxidant formation or ionizing radiation and ecosystem diversity or water depletion) established for some of the environmental issues (Goedkoop *et al*., 2009, p. 17).

In order to better deal with uncertainties and different possible attitudes towards environmental issues when transforming life cycle inventory data into mid-point indicators and midpoint-indicators into endpoint indicators, ReCiPe refers to the 'Cultural Theory' of Thompson and discerns the following three perspectives (Goedkoop and Spriensma, 2001, p. 16 ff.; Hofstetter, 1998):

- The individualist perspective (I), which is based on the short-term interest, impact types that are undisputed, and technological optimism as regards human adaptation,

- The hierarchic perspective (H), which is based on the most common policy principles with regards to time-frame and other issues,

- The egalitarian perspective (E), which is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available, etc.

With ReCiPe, the three perspectives are specified for every midpoint-category (e.g. for climate change, the time frames are 20 years for the individualist, 100 years for the hierarchist and 500 years for the egalitarian perspective). The perspectives are also applied to aggregate the damage categories (human health, ecosystem diversity, resource availability) into a single score, the weighting factors for each of the damage categories having been determined in a panel procedure, which is described by Goedkoop and Spriensma (2001). However, according to Goedkoop and Spriensma (2001, p. 16), the results of the panel procedure cannot be considered to be representative for European conditions, because the panel consisted of 365 persons from a Swiss LCA interest group.

As an alternative to the application of the default weighting factors from the panel procedure, in particular for comparative assessments disclosed to the public, Goedkoop and Spriensma (2001) propose to apply the triangle concept (Hofstetter, 1998). This concept can be used to graphically depict the outcome of product comparisons for all possible weighting sets. Each point within the triangle represents a combination of weights that add up to a 100 % (see Figure 25). According to Hofstetter (1998), such a representation is a very useful tool to enhance the transparency of the weighting process, as it shows under which conditions (i.e. which weighting factors) a product A is better than a product B. The stakeholders do not have to set discrete weights, but they have to agree whether it is plausible that the weights would fulfil the conditions under which A is better than B or not (Goedkoop and Spriensma, 2001).

The ReCiPe method is evaluated with regard to its performance in section 6.4.1.2 on page 240.

**Figure 25. Triangle concept according to Hofstetter (1998)**



www.pre.nl/eco-indicator99/triangle.htm
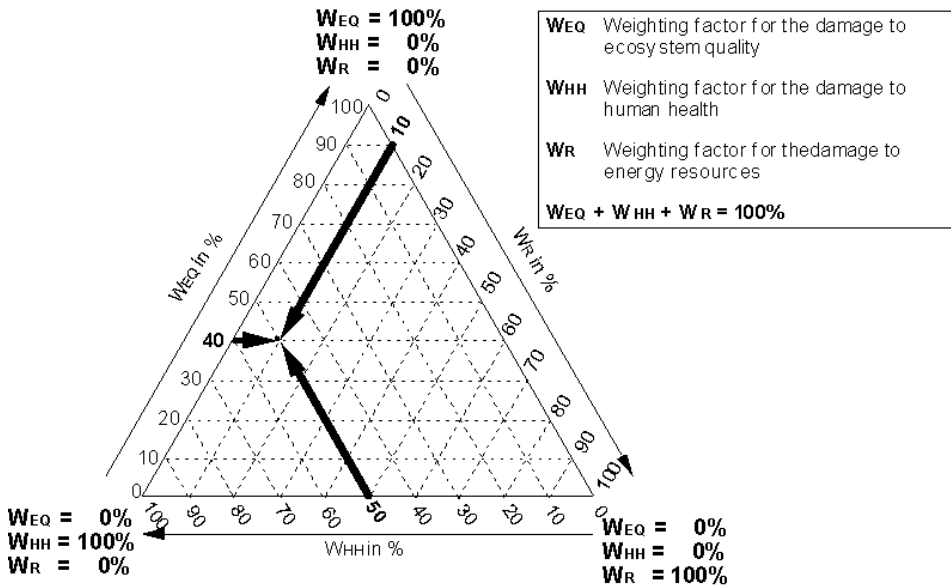
# 6.2.3. The ecological footprint approach

The ecological footprint, notion proposed by William Rees and Mathis Wackernagel (Rees and Wackernagel, 1994; Wackernagel and Rees, 1996) is now considered as one of the main environmental indicators. The presentation of a WWF-World Wide Fund For Nature report on this topic for the 2002 Johannesburg Summit made a great fuss (WWF international and WCMC, 2002).

## 6.2.3.1. Definition

The creators of the method tried to find a synthesis indicator able to measure the impacts in terms of resource use and in terms of emissions to the ecosystem. According to Franz and Papyrakis (2009), its purpose is ultimately to inform individuals and societies of 'unsustainable' behaviour, and influence consumers towards consumption patterns and lifestyle choices with a reduced environmental impact.

According to its initiators (Wackernagel and Rees, 1996; Rees, 1996), the ecological footprint of a given individual or group can be defined as the area of Earth's productive land and water required to supply the resources that this individual or group demands, as well as to absorb the wastes that the individual or group produces, wherever is this area, given the prevailing technology and resource management practices. The chosen unit is the world average biologically productive land called global hectare.

The ecological footprint represents the quantity of regenerative capacity of the biosphere to be used in order to provide to the econosphere the resources needed during a given year, and to biologically assimilate the waste produced. It means that it considers only the regenerative and biological part of the ecosystem and that the elements of the natural capital which cannot be regenerated more or less directly through photosynthesis are per definition out of the field of ecological footprint, e.g. nuclear waste, resource from the lithosphere (Boutaud and Gondran, 2009, p. 44 et 50).

## 6.2.3.2. Method

The ecological footprint takes into account different resource uses and waste disposals. According to Ewing *et al*. (2008b, p. 2), ecological footprint accounting is based on fundamental assumptions (Wackernagel *et al*., 2002), among which:

– Resource and waste flows that cannot be measured are excluded from the assessment, leading to a systematic underestimate of humanity's true ecological footprint.

– By weighting each area in proportion to its bioproductivity, different types of areas can be converted into the common unit of global hectares, hectares with world average bioproductivity.

– Human demand, expressed as the ecological footprint, can be directly compared to nature's supply, biocapacity, when both are expressed in global hectares.

The ecological footprint represents appropriated biocapacity, and biocapacity represents the availability of bioproductive land. It considers six land use types: Cropland, forest land, grazing land, fishing grounds (marine, inland water), and built-up land. In addition, carbon uptake land is calculated.

– Cropland: Cropland is the most bioproductive of all the land use types and consists of the area required to grow all crop products, including livestock feeds, oil crops and rubber.

– Forest land: The forest land footprint is calculated based on the annual harvests of fuelwood and timber to supply forest products consumed by an individual or a group and includes all forested area.

– Grazing land: The grazing land footprint measures the area of grassland necessary in addition to crop feeds to support livestock.

– Fishing grounds: The fishing grounds footprint is calculated based on the amount of annual primary production required to sustain a harvested aquatic species. Marine yields are calculated as the primary production equivalent of the estimated global sustainable catch for a representative set of fish species, distributed according to local rates of primary production.

– Built-up land: The built-up land footprint is calculated based on the area of land covered by human infrastructure - transport, housing, industrial structures and reservoirs for hydroelectric power generation.

– Carbon uptake land: To measure the ecological footprint due to the consumption of fossil energy, two methods are available: the waste

assimilation method (sequestration), and the substitution method via biomass.

The first method estimates the bioproductive land needed to uptake atmospheric $CO_2$ really emitted during the fossil fuel combustion. The bioproductive surfaces considered are forest lands, according to an average carbon sequestration ratio estimated from the guidelines published by IPCC (IPCC, 2006) (Boutaud and Gondran, 2009, p. 76). It makes the hypothesis that oceans absorb approximately 35 % of the carbon, forest being sink for the remaining 65 %. Therefore carbon uptake land is a subcategory of forest land. Carbon uptake land is the only component of the ecological footprint which is exclusively dedicated to tracking a waste product: carbon dioxide. The formula for the carbon footprint $EF_C$ is

$$EF_C = \frac{P_C \cdot \left(1 - S_{Ocean}\right)}{Y_C} \cdot EQF \qquad \text{[eq. 13]}$$

where $P_C$ is annual emissions (production) of carbon, $S_{Ocean}$ is the percentage of anthropogenic emissions sequestered by oceans in a given year and $Y_C$ is the annual rate of carbon uptake per hectare of world average forest land.

The second method estimates the bioproductive land required to produce an equivalent substitution energy amount via photosynthesis – especially via the production of vegetal biomass. Till now, nevertheless, this method estimates only the amount of forest land needed to produce the equivalent wood-energy. The substitution method is rather a future method to be improved (Boutaud and Gondran, 2009, p. 75).

For any land use type, the ecological footprint $EF$ of a country, in global hectares, is given by

$$EF = \frac{P}{Y_N} \cdot YF \cdot EQF \qquad \text{[eq. 14]}$$

where $P$ is the amount of a product harvested or waste emitted, $Y_N$ is the national average yield for $P$, and $YF$ and $EQF$ are the yield factor and equivalence factor, respectively, for the land use type in question. Yield and equivalence factors are applied to both footprint and biocapacity calculations to provide results in consistent, comparable units (Ewing *et al.*, 2008b, p. 3 and 5).

The yield factor is justified by the fact that average bioproductivity differs between various land use types, as well as between countries for any given land use type: see Table 43. The yield factor provides comparability between various countries' ecological footprint or biocapacity calculations. Through the consideration of the different products of a given land use type in the calculation of the yield factor, the possible uses of an ecosystem are not exclusive.

In order to combine the ecological footprints or biocapacities of different land use types, a second scaling factor is necessary. Equivalence factors convert the actual areas in hectares of different land use types into their global hectare equivalents (see Table 43). The equivalence factor for built-up land is set equal

to that for cropland and carbon uptake land is set equal to that for forest land. This reflects the assumptions that infrastructure tends to be on or near productive agricultural land, and that carbon uptake occurs on forest land. Equivalence factors are currently calculated using suitability indexes from FAO (FAO and IIASA Global Agro-Ecological Zones, 2000; FAO Statistical Databases, 2007). All land is assigned a quantitative suitability index. The calculation of the equivalence factors assumes the most productive land is put to its most productive use. The equivalence factors are calculated as the ratio of the average suitability index for a given land use type divided by the average suitability index for all land use types.

The ecological footprint approach is evaluated with regard to its performance in section 6.4.1.3 on page 240.

**Table 43. Equivalence factors and yield factors for some countries, 2005 (Ewing *et al*., 2008b, p. 4 and 6)**

| Area Type | Yield factor | | Equivalence factor (gha/ha) |
|---|---|---|---|
| | Algeria | Hungary | |
| Primary Cropland | 0.6 | 1.5 | 2.64 |
| Forest | 0.9 | 2.1 | 1.33 |
| Grazing Land | 0.7 | 1.9 | 0.50 |
| Marine | 0.9 | 0.0 | 0.40 |
| Inland Water | | | 0.40 |
| Built-up Land | | | 2.64 |

# 6.2.4. The MIPS-approach

The Material Input per Service-unit (MIPS) concept was developed by Schmidt-Bleek (1994) to estimate the resource use caused by a product or service unit. It is based on the assumption that the *potential* environmental impacts of a product can be assessed on the basis of the life-cycle-wide material input: The fewer raw materials used, the less environmental impacts ensue. As stated by Ritthoff *et al*. (2002, p. 10 ff.), if every input becomes an output anyway, then, by measuring the input, one can arrive at an estimation of the environmental impact potential.

MIPS calculates the material input along the life cycle ('from cradle to grave'), i.e. it adds up all material consumption along the chain of extraction, production, use and recycling or disposal. The reciprocal value of MIPS is considered to correspond to resource productivity or eco-efficiency (Ritthoff *et al*., 2002).

The MIPS concept considers five resource input categories: abiotic resources (including i.a. mineral raw materials and fossil energy carriers), biotic resources (including i.a. plant biomass from cultivation), earth movements in agriculture and silviculture (including mechanical earth movements and

erosion), water (including surface, ground and deep ground water) and air (including i.a. combustion) (Ritthoff *et al*, 2002).

The MIPS-approach is evaluated with regard to its performance in section 6.4.1.4 on page 243.

# 6.2.5. Economic approaches

In our society, economic arguments play a decisive role in establishing facts and justifying collective action, with the result that monetary valuations often weigh heavily in assessments of environmental impacts. But the high degree of variability among such evaluations (cf., for example, Chanel and Vergnaud, 2001) raises questions about their interpretation and reliability.

The Welfare economics approach sees individuals as having preferences and their utility, or welfare, arises from consumption. In this perspective anything is a benefit that increases human well-being and anything is a cost that reduces human well-being. Economic theories and ideologies are founded on the principle that consumers have well-defined preferences, and consistently behave to advance their self-interest. Jeremy Bentham (1789) states "My notion of man is that ... he aims at happiness ... in everything he does". Herb Simon (1959) states "The rational man of economics is a maximizer, who will settle for nothing less than the best". Some economists have even taken self-interest to tautologically explain choice. Consumers who know their own tastes, and are relentlessly self-interested and self-reliant, relish choice, and welcome market opportunities that expand their options. Most economists accept this concept of the consumer, and the attendant economic theory that demonstrates the efficiency and Pareto optimality of decentralized, competitive markets (see McFadden, 2005).

For that standard economic approach environmental goods are in most cases not subject to property rights, and are not exchanged in markets. Silence, air quality, life style, biodiversity, etc., do not have prices that can be set by supply and demand. Interactions between economic agents mediated by this kind of "special" good take place outside of markets, and are therefore known as "externalities".

How, in such a context, are prices to be set? There are five or six groups of methods that are commonly used to calculate the economic value of environmental goods, and the economic costs of environmental damage.

The following points are then particularly important and need to be focused on:

- To begin with, the extreme diversity of environmental impacts means that evaluations are carried out in very different domains, and with regard to different kinds of good. The methodologies of evaluation do not always start out from the same standpoint, or end up with comparable results. It is thus important to be clear about what is being measured, and the degrees of relevance of the different methods, along with their areas of complimentarily and opposition.

- The economic valuation lays on the principle of the aggregation of individual preferences, which is not so obvious (how can Smith's preferences can be compared to Jones'?) and is often discussed by economists themselves.

- In environmental terms, the temporal dimension is important. Sources of problems change over time, and they can have effects both immediately and in the long term. The way in which time is dealt with in economic evaluation is crucial; And the systematic use of the discounting method can conceal important questions about its real validity.

- The long-term effects of any private or public policy necessary deal with risk and uncertainty. How does the economic approach take this stake into account?

- Last, radical criticism insists on the fact that the economic approach is too closed on its problems of individual preferences and exchanges to be able to take environmental and ecological problems into consideration. It would be difficult to ignore such a criticism in this report…

## 6.2.5.1. Which evaluation methods, to evaluate what?

Environmental economists have identified several different types of value. For example, Barde (1991) posits four major families (see Pearce and Turner, 1990, for a similar approach). To begin with there is *use value*, which is linked to the utility of a good, and which is what one automatically thinks of as "economic" value. Then there is *optional value*, which represents potential utility, even when this is not yet known, and when it can change according to the situation and the state of knowledge. The equatorial rain forests, for example, can be considered as a reserve of substances that are potentially useful to the pharmaceuticals industry. This gives them an optional value. A good can also have a value which, outside of the use one makes of it oneself, or expects of it, is transferable to one's descendants, or to future generations. This is its *legacy value*. And finally, one may ascribe a value *as such* to a person, an animal, a rare species, an ecosystem, etc., irrespective of utility, whether immediate or future. This is the concept of *existence value*, which constitutes a bridge between ethics and economics. It is related to *non-use value*, which is often contrasted with the previously-mentioned *use value*.

The *total economic value* of a good is the sum of these values, each of which may have a different weighting, depending on the nature of the good.

The economic approach, to begin with, tends to be based on collective utility curves, the problem being that of assessing the value of goods which, though they can be exchanged, are not subject to market pricing mechanisms, and whose quantity or quality is affected by pollution. Such curves can be produced in one of two ways: either by reference to existing markets for which, in one way or another, preferences are reflected, or by creating a fictive market in which agents are asked to position themselves as though it actually existed.

In the first family of evaluation methods, involving substitute markets, the leading method makes use of **hedonistic prices**. The idea is that, other things being equal, the value of a good varies not only in terms of its own characteristics but also those of its location, and thus, among other things, the quality of its environment. A multiple regression procedure, taking in the principal factors that enter into the determination of a price, can then be used to measure the possible impact of a damaged environment on the economic value of a given good. This method is widely used to measure the cost of traffic noise through its impact on the property market. Other methods include the measurement of the **cost of protection** of individuals suffering from this kind of nuisance, or the **travel costs** they are prepared to accept in order to take advantage of unspoilt surroundings.

The second family of methods, that of **contingent evaluations**, is based on rigorous protocols that model the existence of a market. Their purpose is to record and attribute a monetary value to the reactions of individuals questioned about variations in the quality or quantity of non-market goods, such as noise level, atmospheric conditions or travel time. These methods have come to the fore over the last few years, and they can be applied to a wide range of problems in the fields of public health, damage to buildings, visibility, etc. Compared to other methods, they seem more able to reach the existence value, which is not linked to any real market. But, on the other hand, their results are often discussed because their values can have a wide dispersion, depending on how people are questioned, on their willingness to pay (to avoid a damage for example) or their willingness to accept (a financial compensation for the same previous damage) whatever the consistence of the survey process.

But there are also other methods which, rather than giving individuals' preferences direct monetary expression in related or fictive markets, look at the damage suffered by an environmental good as a whole. The emphasis, at least in the first instance, is placed on a logic of scientific expertise that does not appear in individuals' answers to formal questions, due to gaps in their knowledge. The cost of impacts can then be calculated in various ways, as follows:

- There may be a return to the preceding approach, using utility curves for individuals in a market, whether real or simulated, as a way of giving a monetary value to all or part of an observed impact. One might, for example, use dose-response curves showing an indicator of atmospheric pollution and an incidence of asthma to make an economic evaluation based on what asthma sufferers are willing to pay in order to avoid an attack.

- One might also calculate losses of wealth resulting from damage, for example a loss in agricultural production resulting from atmospheric ozone, or a loss of output due to the absence of workers suffering from respiratory illness caused by pollution. Discussions about **production losses** in agriculture and industry have led to the so-called **human capital** method of evaluating, then discounting, losses of production caused by illness or death, which, while eschewing any attempt at estimating the worth of a human life, allows the authorities to decide on the kind of costs they should be prepared to bear in order to avoid loss of life.

- One might also talk about **compensation costs**. It is possible, for example, to calculate the cost of medical care and hospitalisation resulting from atmospheric pollution and the resulting cardiac and respiratory conditions. This would seem to be complementary to the preceding method, in that hospitalisation, besides its medical costs, implies a loss of both working time and output. Such complementarities occur in most evaluations of impacts on health.

- Finally, and as a last resort, the cost of potential damage may be assimilated to the cost of such measures as will allow it to be avoided. This method, known as that of **avoidance cost**, is indispensable to the evaluation of such measures, but cannot logically be used to evaluate the cost of damage as such.

In estimating the applicability of a method, by reference to a given objective, there are three crucial distinctions that must be made (Manière, 1999; Nicolas *et al.*, 2005):

- The **type of damage** that is to be evaluated (involving public health, buildings and materials, flora and fauna, etc.), and its localisation in the chain of causality (direct effects, such as illness, or indirect effects, such as loss of working time). This makes it possible to distinguish what needs to be taken into account, and to apply methods of investigation, measurement and analysis other than those of economics, notably in the framework of an approach based on a "damage function".

- The **individual or collective assumption of costs**. This needs to be integrated into methods that might otherwise neglect it. For example, those that are based exclusively on individual preferences (in matters of protection, hedonistic prices, contingent evaluations, etc.) express only costs that fall on individuals. Those that are taken up collectively, such as medical charges paid for by a social security system, must be dealt with by other methods, and notably by estimating the cost of repairing damage.

- The **value type**, whether of use or of existence, that is to be measured with regard to the good that has been damaged. This distinction is important for the contingent evaluation of non-use values attached to environmental goods, which are often difficult to define in cases involving public health, with factors such as discomfort, pain, social isolation and death caused by illness.

From this point of view, the various methods are much more complementary than contradictory. The choice of a particular one will depend on the objectives of the evaluation process; or they may be used in combination (Manière, 1999; Rozan, 2001).

## 6.2.5.2. Aggregation over individuals

A frequent debate concerns the operation that is implicit in our presentation, namely that of aggregating individual preferences into a collective preference,

and thus arriving at an overall cost. This operation involves a double approximation. On the one hand, it presupposes that the unit of measurement of utility is neutral, and that the value of money, and in particular the incomes of the individuals under consideration, remains identical in all circumstances. On the other hand, it blurs the specificities of individual preferences. It can account for modifications in general collective utility related to variations in the quantity of a non-market good; but it does not identify conflicting individual interests.

There are corrective coefficients that can reduce these inconveniences by treating the value of money for different categories of the population as a function of their income (Arnsperger and Van Parijs, 2003). And it is possible to work at a semi-aggregate level, where "winners" and "losers" are distinguished for a given situation. Even it cannot be perfect until each individual is distinguished, this can provide solutions that have a less negative impact on the latter or more equitable compensations (Faivre d'Arcier, 2004).

## 6.2.5.3. Aggregation over time: Discount rates and intergenerational equity

The second key variable in socio-economic monetary evaluation is the way in which different time frames are taken into account.

A discount rate is often considered as a way of expressing a preference for current time: 100 € available immediately are preferred to 100 € available a year from now. At a discount rate of *a*, it would take 100(1+*a*) € in a year's time to persuade us to give up an immediate 100 €. The discounted value $S_0$ of a sum $S_n$ expected for the year *n* will therefore be $S_n/(1+a)^n$. The higher the discount rate, the more the value of year *n* is lowered, and the less the future is taken into account. This preference for the present varies across individuals and their situations, but it can be aggregated on the collective level through the operation of financial markets or the evaluation of projects by the authorities. As applied to transport projects, for example, it tends to lower the long-term environmental impact of infrastructure and traffic overall.

Reflections on the subject of discount rates began in the early 1930s, and recent years have seen a renewal of the subject, with the emerging problematic of sustainable development (see section 2.2). In particular, the notion of discount rates has been refined by comparison with the one presented above. There are three main reasons for its use (Arrow *et al.*, 1996).

- Pure time preference, *p*, represents economic agents' preference for the present with an estimated rate of 1-2 % per year, depending on the author, though it may actually be 0 % for intergenerational effects.

- There is a wealth effect, $\theta*g$, which is linked on the one hand to an average growth in income of $\theta$ over time, and on the other hand to a decrease, *g*, in the marginal use of that income. In western countries the rate is some 2-3 % per year.

- There is a money opportunity cost, *r*, for private economic agents such as companies that factor their cash flow needs into their purchasing and

investment decisions. The value of *r* is what orientates their preference in one direction or another. The real rate of long-term debentures, currently around 4 %, may be taken as a benchmark, though in fact the rate depends on the loan period, the degree of client risk and politico-economic factors.

These three factors, *p*, *θ*g* and *r*, apply to particular situations, and the discount rate can vary considerably between individuals or social groups. For public projects it therefore comes down to a question of aggregation, bearing in mind the need to avoid double accounting. This involves an arbitrage between different degrees of preference for the present.

Thus, for example, in the opinion of Cline (1999), a social discount rate (or a "pure" discount rate) should be used for individuals, taking into account *p* and *θ*g*, in other words a pure preference for the present and a wealth effect. This rate does not incorporate a money opportunity cost, which enters into a different logic, namely that of companies.

For companies, it is the money opportunity cost that prevails in the determination of the discount rate. A pure preference for the present and a wealth effect are in a sense implicit in a money opportunity cost. And companies' investment decisions are based on this rate. But there is also the question of the risks, sometimes high, to which innovative sectors are prone, along with that of the additional revenue needed to keep shareholders on board.

The choice of social rate of discount is not a detached and objective decision, the question of involves a discussion of intra- and intergenerational distributional issues (Stiglitz, 1994). Many economists since Pigou (1920) and Ramsey (1928) have engaged in this subject. Portney and Weyant (1999), in their introduction to a collection of articles by a number of prominent economists on discounting and intergenerational equity, suggest that "There is a sense of unease about this subject, due to the technical complexity of the issues and the ethical considerations." A low discount rate makes the evaluation of the various abatement strategies incompatible and incomparable with other environmental and social policy issues that require immediate attention. Some argue for different discount rates for different time horizons, more specifically, a smaller discount rate for a farther future: Among these are Weizman (1999) and Kopp and Portney (1999). Studies by Hausman (1979) and Horowitz (1991), among many others, support this view. Yet Solow (1999) points out that a non-constant discount rate will subject the policy path to time inconsistency. Heal (1999) suggests that there is no reason to require time consistency in decision-making involving many generations, a view embodied in the work by Chichilnisky (1996). Newell and Pizer (2001) assume a constant discount rate and allow for uncertainty to enter discounting. This approach accounts for future costs and benefits much more effectively than discounting without consideration to uncertainty. In this manner the policy path is not subject to time inconsistency. Schelling (1999), among others, even questions the validity of the standard welfare-theoretic approach for decision making with intergenerational consequences and suggests Precautionary Principles, as a way of giving shape to the intergenerational social contract. The trade-off decision has to be taken within a context of uncertainty and possible irreversibility. When harm is

irreversible, and there is uncertainty associated with its magnitude and likelihood, the purchase an "option" prevents the harm at a later date (see Sunstein, 2005, for an excellent discussion on the subject).

It may be considered that the real long-term interest rate in the financial markets, namely 4 %, indicates the collective discount rate, and thus the rate that the authorities should adopt for investment purposes and future external costs. But – and this is the dilemma with which many nations are currently confronted – a 4 % rate would involve the approval of too many projects for the authorities to finance. Countries differ in their approaches to the problem. Some have chosen to set a high discount rate in order to eliminate less profitable projects, and thereby limit budgetary strains. Up to the start of the present century, France favoured a standard rate of 8 %. And the UK also used this rate for projects in competitive sectors and nationalised companies. In the USA, the Office of Management and Budget opted for a rate of 7 %, though the debate was intense, and the General Accounting Office advocated a rate of 3.5 or 4 %. The main drawback with a high discount rate, as we have noted, is that it tends to conceal the long-term advantages and disadvantages of projects.

## 6.2.5.4. Aggregation over risk

To complete this discussion on discount rate, it is necessary to add that there is a great deal of risk and uncertainty associated with the long-term effects of an action or policy. Hence the analytical framework for decision making should be able to handle risk and uncertainty explicitly.

Most actions such as provisions of infrastructure and changes in land use have uncertainty associated with their social benefits and costs, and are irreversible. Their impacts on environment are also associated with uncertainty that can be irreversible, even catastrophic. Technology adoption is another example where investment decisions are made under uncertainty and irreversibility.

Other researchers have applied option theory for environmental risk regulation and evaluations (Sunstein, 2005). The simple concept is that when dealing with an irreversible loss, and when uncertain about the timing and likelihood of that loss, one should be willing to pay for an option in order to maintain flexibility for the future. Fisher (2001) has generalized this argument by suggesting "where a decision problem is characterized by (1) uncertainty about future costs and benefits of the alternatives, (2) prospects for resolving or reducing uncertainty with the passage of time, and (3) irreversibility of one or more of the alternatives" an extra value, an option value, should be attached to the reversible alternative(s). The implication is that irreversible decisions must pass a higher obstacle in a cost benefit test.

Arrow and Fisher (1974) give the example of the alternative actions of development or keeping a wilderness and use a linear net benefit function and an all-or-nothing choice situation and show that it will be optimal to delay or reduce investment. They suggest that: "The expected benefits of an irreversible decision should be adjusted to reflect the loss of options it entails." Other economists have since had important contribution to this subject by extending

the theory for nonlinear benefit function and continuous choice (Dixit and Pindyck, 1994) and temporal resolution of uncertainty (Hanemann, 1989; Kolstad, 1996; Ulph and Ulph, 1997; Gollier *et al*., 2000) and there have been contributions to the subject with techniques such as stochastic optimization.

## 6.2.5.5. The radical criticisms: A too static and closed approach of the environment

Finally, more radical criticisms call into question the hypotheses on which classical micro-economic theory is founded. Pearce (1976), for example, draws attention to the excessively static nature of the model. Using a dynamic approach, he shows that if economic agents do not have perfect knowledge of ecological processes, their rationality will lead them into economic inconsistencies, even if their behaviour is guided by taxes that reflect the negative externalities they generate via environmental impacts. It is especially the case when an impact is almost unknown, as it is the case with the climate change, where the final impact could be only some more degrees in temperatures, or the disappearance of a large part of our ecosystem, including humankind. Only according to assumptions made, the external cost of the climate change could be increased by a factor of 10 or 1000. And what is the meaning of a cost which can be of 10 or of 1000?

Those who favour ecological economics also point out that there is no real equivalence between environmental and manufactured goods. The benefits and services rendered by the former cannot be replaced by the latter (Costanza *et al*., 1997). And those who have carried forward the ground-breaking work of Boulding (1966) and Georgescu-Roegen (1971) insist on the need for economic activity to be controlled in such a way that natural goods are not consumed more quickly than they can be replaced, and that more waste is not produced than can be assimilated. The ability of the market to bring about an optimal situation is often placed in doubt, with a contrast between the classical economists' weak-sustainability approach, which seeks to take environmental problems into account through the evaluation of external costs, and the ecological economists' strong-sustainability approach (see section 2.2.3), in which human activity must first of all be seen in the context of an environment with a limited carrying capacity (O'Connor, 1998).

The radical criticisms also point on the current use of discount rates. In addition to the debate introduced in section 6.2.5.3, Næss (2006), as several others, questions some of the basic assumptions underpinning this practice, such as everlasting economic growth, especially when seen in relation to limited natural resources. The argument is exemplified (Næss, 2006, p. 42): "Given an annual discount rate of 7 %… a climate disaster occurring in 150 years causing damage of ten trillion dollars [i.e. $10^{13}$ \$] has a discounted cost today of only 391 million dollars [i.e. around $4 \cdot 10^8$ \$], i.e. an amount 26 000 times smaller than the non-discounted amount". Næss refers the neoclassical economist answer to this, which is 'decoupling' of economic growth from natural resource consumption. But, as he points out, even if we were able to consume four times less of natural resources per unit of economic growth, which was a target

discussed in the early 1990s, this is nothing compared to what a discount rate of 7 % requires. If we agree that natural resources are limited, and that we are over using them already, then we need to consume 26 000 times less of natural resources per unit of economic growth in the 150 year perspective. This, Næss concludes, is absurd.

## 6.2.5.6. Conclusion

In economics, there is a standard way of taking into account the negative impact of human activity on the environment. It has a coherent theoretical basis, whereby monetary indicators can be used to evaluate environmental impacts. But a survey of the methods involved shows that they are far from having reached a stable state, being subject to local contingencies such as geography, demography, culture and sensibility. They give differing results, though it cannot be said that any particular one is systematically more valid than another. In other words, monetary methods for evaluating environmental damage cannot be expected to produce definitive, indisputable values. Likewise, the ways in which discounting is used to take long-term effects into consideration are highly diverse (Nicolas *et al*., 2005).

In sum, there are internal criticisms of this approach that propose ways in which it might be improved, and more radical criticisms that question the role of economic approaches in the management of environmental problems.

Ackerman and Heinzerling (2004) summarize a most compelling criticism of cost benefit analysis (CBA) for policy analysis based technical and moral issues. Their technical objection is directed towards the methodology and assumptions connected to the calculation of willingness to pay, risk perception and discounting future non-monetary benefits. Their moral objection stems from their view that health and safety regulation should be addressed as a part of a larger social contract. In particular, they suggest that the cost benefit analysis devalues non-monetary interests in health, safety and environment.

The economic approaches are evaluated with regard to their performance in assessing environmental sustainability in section 6.4.1.5 on page 244.

# 6.3. Joint consideration with multi-criteria methods

For the evaluation of alternatives in transport policies, plans, programmes and projects a series of different formalized methods and tools could be applied. Kunicina (2008) evaluated methods and tools for different transport development projects and system control. As a result, discrete multi-criteria decision analysis (MCDA), cost benefit analysis (CBA), problem solving and genetic algorithms have been identified as options for an evaluation of alternatives, and multi-objective-programming (MOP) and expert evaluation as tools for an evaluation of impacts of different transport development planning stages (see Annex 12, where other non-MCDA approaches are also presented).

Following, the focus will be laid on multi-criteria decision analysis methods. After some introductory considerations on possible classifications of multi-criteria decision methods, some selected discrete and continuous multi-criteria methods will be presented. In the last few years, multi-criteria decision applications have become popular particularly in project evaluations because of the possibility to take into account a great number of non comparable criteria and of different alternatives.

# 6.3.1. Multi-criteria decision analysis methods typology

Multi-criteria decision analysis (MCDA) methods are defined as methods which allow to choose better alternative, taking in account evaluation of preference by many non comparable criteria. For Figueira *et al*. (2005a), MCDA and multi objective programming (MOP) are complementary areas of multiple criteria decision making (MCDM), MCDA being decision-maker driven and MOP mathematics-based.

According to Roy (1996, p. 241) or Guitouni and Martel (1998), multi-criteria decision aid methods can be assigned to one of the three following categories: (i) the single synthesizing criterion approach without incomparability, (ii) the outranking synthesizing approach ("with incomparabilities" according to Roy), and (iii) the interactive local judgements with trial-and-error approach. While the first two groups embody a clear mathematical structure, the third one is not referred to any formalised or automatic procedure.

Janssen and Munda (1999) propose a classification into quantitative methods, which require quantitative information about scores of each evaluation criterion (such as weighted summation or value and utility analysis) and qualitative methods, which only require qualitative information on scores or a mixture of quantitative and qualitative scores (such as Evamix or Regime, see sections 6.3.2.2 and 6.3.2.3).

Another possible classification refers to two groups of multi-criteria methods, namely discrete and continuous methods, depending resp. on whether the set of alternatives is finite or not (De Montis *et al*., 2005). Discrete methods include i.a. single synthesizing criterion methods with tools such as Analytical hierarchy process (AHP), Multi attribute utility theory (MAUT), or Evaluation matrix (Evamix), and outranking methods with tools such as ELECTRE, Regime or NAIADE. Continuous methods typically include programming methods such as multi-objective-programming, goal programming and their different variants.

The typology of De Montis *et al*. (2005) is taken as a reference to structure the presentation of multi-criteria methods in section 6.3 and Table 44.

A list of frequently use multi-criteria methods according to application aims, including an overview addressing inputs, outputs, decision types, interaction with the decision makers, underlying assumptions and tools / software, is given in Annex 13.

**Table 44. Typical characteristics of MCDA methods (De Montis *et al.*, 2005)**

|  | **Characteristics** | **Examples** |
|---|---|---|
| Discrete methods | | |
| Single synthesizing criterion methods | - convert impacts concerning the different criteria into one criterion or attribute;<br><br>- are based on strong assumptions, i.a. the existence of utility functions and additivity. | - MAUT<br><br>- AHP<br><br>- Evamix |
| Outranking methods | - are based on less 'strong' assumptions than single criterion methods;<br><br>- encourage interaction between model and decision maker by avoiding complete ranking being identified too early;<br><br>- do not so much aim at identifying an optimal solution but rather at facilitating the identification of compromise solutions in a transparent and fair way. | - ELECTRE III<br><br>- PROMETHEE<br><br>- Regime<br><br>- NAIADE |
| Continuous methods | | |
| Programming methods | - do not choose from a finite number of alternatives, but the alternatives are generated during the solution process on the basis of a mathematical model formulation. | - MOP<br><br>- GP |

# 6.3.2. Discrete MCDA methods

## 6.3.2.1. Principles and goals of discrete MCDA

According to Funtowicz *et al.* (1999) and O'Neill (1993), it is possible to distinguish between the following basic principles:

- *strong commensurability*: the common measure of the different consequences of an action is based on a cardinal scale of measurement (e.g. students in a class may be ranked according to a scale by which one student gets '10', another one gets '8.5', the next one gets'7', etc.);

- *weak commensurability:* the common measure is based on an ordinal scale of measurement (e.g. students in a class may be ranked be an ordering, as 'first', 'second', 'third'...).;

- *strong comparability*: there exists a single comparative term by which all different actions can be ranked (present value in money terms of costs and benefits, including externalities);

- *weak comparability*: an irreducible value conflict is unavoidable but compatible with rational choice employing practical judgement (in a socialist economy, where e.g. two economic plans for a coal plant are compared, the answer to whether coal-intensive or labour-intensive methods should be used may depend e.g. on whether one thinks that

hydraulic power may be sufficiently developed or that solar heat might come to be better used. If however one is afraid that when one generation uses too much coal thousands will freeze to death in the future, one might use more human power and save coal. Such and many other non-technical matters determine the choice of a technically calculable plan. There is no possibility of reducing the production plan to some kind of unit and then to compare the various plans in terms of such units).

Whereas CBA is based on the concept of strong comparability, the concept of weak comparability can be considered as the philosophical foundation of multi-criteria evaluation (see Table 45).

**Table 45. The principles of comparability and commensurability, and corresponding concepts, theories and methods (Martinez-Alier *et al*., 1998; Funtowicz *et al*., 1999)**

| Principles | Corresponding concepts, theories and methods (examples) |
|---|---|
| Strong comparability | |
| Strong commensurability of values | - weak sustainability<br>- cost-benefit analysis<br>- contingent valuation and similar methods<br>- ecological footprint |
| Weak commensurability of values | - cost-benefit analysis (with ordinal rankings only)<br>- compensatory multi-criteria evaluation based on utility functions |
| Weak comparability | |
| Incommensurability of values | - strong sustainability<br>- non-compensatory multi-criteria decision aid |

Typically, discrete MCDA methods aim at one of the following four goals (Kunicina, 2008):
1. find the best alternative
2. group the alternatives into well-defined classes
3. rank the alternatives in order of total preference
4. describe how well each alternative meets all the criteria simultaneously

**Table 46. Structure of a typical decision matrix (Wang and Triantaphyllou, 2008)**

| Alternatives | Criteria | | | |
|---|---|---|---|---|
| | $C_1$ | $C_2$ | … | $C_n$ |
| | $(w_1)$ | $(w_2)$ | … | $(w_n)$ |
| $A_1$ | $a_{11}$ | $a_{12}$ | … | $a_{1n}$ |
| $A_2$ | $a_{21}$ | $a_{22}$ | … | $a_{2n}$ |
| … | … | … | … | … |
| $A_m$ | $a_{m1}$ | $a_{m2}$ | … | $a_{mn}$ |

Discrete MCDA methods consist of three components which can be integrated in a typical decision matrix: alternatives A; criteria C; weights of criteria w. The typical discrete MCDA problem consists in ranking a finite number of decision alternatives, each of these being explicitly described in terms of different characteristics (also often called attributes, decision criteria or objectives) which have to be taken into account simultaneously. Usually, the performance values (or value of the criteria $C_k$) $a_{ik}$ and the criteria weights $w_k$ are viewed as the entries of a decision matrix as shown in Table 46, for the $i^{th}$ alternative in terms of the $k^{th}$ criterion (Wang and Triantaphyllou, 2008).

Criteria are the ways to express, with more or less precision, the preferences of the decision-maker for evaluating a system or an alternative (Barba-Romero and Pomerol, 1997) and can either be described on an ordinal or on a cardinal scale. On a purely ordinal scale, the gap between two degrees does not have a clear meaning in terms of difference preferences. This is the case with:
- verbal scale, when nothing allows us to state that the pairs of consecutive degrees reflect equal preference differences all along the scale;
- numerical scale, when nothing allows us to state that a given difference between two degrees reflects an invariant preference different.

Other types of scaling, especially interval scales, are applicable in special cases.

## 6.3.2.2. Single synthesizing criterion methods

MCDA methods using a single synthesizing criterion method aim at converting impacts related to the different criteria into one criterion or attribute, which builds the base for the comparison of alternatives (De Montis *et al.*, 2005). Common methods using a single synthesizing criterion approach are multi-attribute utility theory (MAUT), analytical hierarchy process (AHP) or EvaMix, which are briefly described below.

### 6.3.2.2.1. Multiple attribute utility theory (MAUT)

As indicated by its name, multi-attribute utility theory (MAUT) is based on utility theory (explained in section 6.2.5) and relies on the basic von Neumann and Morgenstern (1947) axioms of preference. MAUT allows to compare risky outcomes through the computation of expected utility (De Montis *et al.*, 2005; Annex 13).

MAUT uses directly assessed preferences with general aggregation, which involves direct questioning of the stakeholders and choice based on an aggregate measure for each alternative. The preparation of a multi-attribute decision by use of MAUT includes the following steps (Dillon and Perry, 1977; De Montis *et al.*, 2005):
1. Specify the project alternatives (including combinations) as discrete entities,
2. Elicit the decision maker's set of probability distributions for outcomes associated with each project alternative in each attribute if there is risk,

3. Elicit the decision maker's utility function *u (xi)* for the range of outcomes on each attribute,
4. Use the appropriate global multi-attribute utility function *U(x)* to find the expected utility of each project alternative, and
5. Choose the project or project combination with the highest expected utility; thus the function U should be maximised.

According to Dyer (2005), multi-attribute utility theory covers several multi-attribute models of choice based on alternate sets of axioms and should be better addressed by the more general term 'multi-attribute preference theory'. To differentiate between theories for preference based on the notions of ordinal comparisons and strength of preference versus theories for risky choices, Dyer (2005) refers to the term 'value function' and 'utility function', respectively. Amongst others, Keeney and Raiffa (1976) applied the 'utility function' in decision making for large infrastructure objects building projects.

Amongst others, Dyer (2005) points at the following specific characteristics of multi-attribute preference theory:

• Multi-attribute preference theory provides an axiomatic foundation for choices involving multiple criteria. As a result, one can examine these axioms and determine whether or not they are reasonable guides to rational behaviour.

• Multi-attribute utility theory can be based on different sets of axioms that are appropriate for use in different contexts. Specifically, the axioms that are appropriate for risky choice do not have to be satisfied in order to use multi-attribute models of preference for cases that do not explicitly involve risk. Much of the work on multi-objective mathematical programming, for example, does not require the consideration of risk, and many applications of the Analytical hierarchy procedure are also developed in the context of certainty.

• Third, many existing approaches to multi-criterion decision analysis can be viewed as special cases or approximations to multi-attribute preference models.

In case of interval scale of preferences on a set of actions without forcing evaluators to produce direct numerical representations of their preferences the MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) approach is useful to use before MAUT application. MACBETH is a multi-criteria decision analysis approach that requires only qualitative judgements about differences of value to help an individual or a group to quantify the relative attractiveness of options.

### 6.3.2.2.2. *Analytical Hierarchy Process / Analytic Network Process*

AHP (Analytic Hierarchy Process), which was originally developed by Saaty (1980), is an approach that uses pairwise comparisons along with expert judgments to deal with the measurement of qualitative or intangible criteria. A description of the approach is given in Annex 13, and an application example can be found in Annex 11.

AHP is related to multi-attribute utility theory, but allows decision makers to make their own decisions on whether inconsistency in preferences and rank reversals should be permitted and, if so, the amount of permissible inconsistency. From a procedural point of view, AHP consists of three phases (De Montis *et al.*, 2005):

1. develop suitable hierarchies of entities identified by the human mind;
2. establish priorities (weights) between elements of the hierarchies by means of pairwise comparisons;
3. check logical consistency of pairwise comparisons.

The development of hierarchies allows to break down complex systems into simple structures that can be handled by the human mind, which typically is unable to simultaneously perceive all the factors affected by an action and their interrelations. The simplest model of hierarchy consists of three levels: the first one coincides with the main objective (called the "goal") of the decision making problem; the second and third ones include criteria and alternatives.

In the evaluation phase, the different criteria are compared with regard to their satisfaction of the overall goal, and the different alternatives are compared with regard to their satisfaction of each criterion. The comparison is carried out with the so called 'Saaty scale', which assigns the values 1 to 9 (for example, '1' means that two elements have "equal" importance, and '9' means that an element is favoured by at least an order of magnitude) when comparing pairs of elements on each level with respect to an element on the next higher level. The comparison results in a matrix, from which a priority vector can be calculated by normalising the principal eigenvector, so that its elements sum to one. The priority vector gives the relative importance of the different criteria in achieving the overall goal.

The consistency of pairwise comparisons is checked by calculating a consistency ratio from the maximum eigenvalue. If this ratio is sufficiently small, typically 10 % or less, the data is accepted. Sources of inconsistency are e.g. lack in information or inconsistencies in the real data.

Analytical Network Process (ANP) is a complementary tool to AHP that was developed to automatically take into consideration the quality and number of alternatives. According to Kone and Burke (2007), the key concept of the ANP is that influence does not necessarily have to flow only downwards, as it is the case with the hierarchy in the AHP. Influence can flow between any two factors in the network.

### 6.3.2.2.3. Evamix

The Evamix method, which was developed by Voogd (1983), allows to use quantitative as well as qualitative data and consists of the following five main steps (De Montis *et al.*, 2005):

(1) Construct an evaluation matrix E composed by *eij* scores of a number *n* of alternative scenarios with respect to *m* criteria.

(2) Calculate dominance scores for all ordinal and cardinal criteria, which reflect the degree to which an alternative dominates another for ordinal and cardinal criteria, respectively.

(3) Standardise the dominance scores for all ordinal and cardinal criteria. The ways in which this can be done are the subtractive summation technique, the subtracted shifted interval technique and the additive interval technique.

(4) Calculate the overall dominance scores.

(5) Calculate appraisal scores.

The method is typically used to cope with decision making problems at different geographical scales. Evamix supports stakeholder participation: Different social actors are invited to assign weights to the evaluation criteria, and the different weights given by each actor are not integrated but used to show the different points of view represented by the involved stakeholders (De Montis *et al*., 2005).

## 6.3.2.3. Outranking methods

Outranking methods are based on outranking relations. An outranking relation S is a binary relation between two options $A_1$ and $A_2$ (Pomerol and Barba-Romero, 2000). Two options satisfy an outranking relation S ($A_1$ S $A_2$) if there are enough arguments to decide that $A_1$ is at least as good as $A_2$, and there is no essential argument to refute that statement, relatively to the n criteria of interest. The outranking relation holds if one of the following relations is fulfilled (Guitouni and Martel, 1998; Giannoulis and Ishizaka, 2010):

- $A_1$ is strictly preferred to $A_2$: $\quad a(A_1) - a(A_2) \geq p \qquad$ [eq. 15]
- $A_1$ is weakly preferred to $A_2$: $\quad q \leq a(A_1) - a(A_2) \leq p \qquad$ [eq. 16]
- $A_1$ and $A_2$ are indifferent: $\quad a(A_1) - a(A_2) \leq q \qquad$ [eq. 17]

where a ist the performance of an alternative $A_m$, p the preference threshold and q the indifference threshold.

In addition, there is also the possibility for incomparability between two options.

Compared to dominance relations, outranking relations are less strict: A dominance relation can be obtained from an outranking relation by putting the threshold $q_j$ equal to zero for all j. Satisfaction of a dominance relation implies satisfaction of an outranking relation, the converse however does not hold.

The purpose of all multi-criteria methods is to enrich the dominance graph, i.e. to reduce the number of incomparabilities. When a utility function is built, the multi-criteria problem is reduced to a single criterion problem for which an optimal solution exists. This relies on quite strong assumptions and completely transforms the structure of the decision problem. For this reason, Roy proposed to build outranking relations including only realistic enrichments of the dominance relation (Roy, 1985; Roy and Bouyssou, 1993).

Because outranking relations allow tradeoffs between performance on the different criteria, this makes them more appropriate for use in decision algorithms.

According to Figueira *et al*. (2005b), the methods which most strictly apply to the definition of outranking relation are the ELECTRE (Élimination et choix traduisant la réalité) methods. These are very important in many respects, not least historically, since ELECTRE I was the first outranking method. Another type of outranking methods are the PROMETHEE (Preference Ranking Organization METHod of Enrichment Evaluations) methods. The PROMETHEE method leads to the development of an outranking relation that can be used either to choose the best alternatives (PROMETHEE I) or to rank the alternatives from the most preferred to the least preferred (PROMETHEE II) (Spronk *et al*., 2005). Both types of methods, ELECTRE and PROMETHEE, are applicable for partial aggregation of criteria (Adolphe, 2007).

### 6.3.2.3.1. The ELECTRE family methods

The ELECTRE family methods are directed to the decision of problems with already set criteria (Wang and Triantaphyllou, 2008). Unlike the AHP method (Saaty, 1994) the quality parameter for each alternative is not defined quantitatively, and only a condition of superiority of one alternative above another is established. As mentioned in Belton and Stewart (2001), the concordance index $N_i$ for each pair of alternatives $(A^i_n, A^i_k)$ is either

$$N_i = 1 \text{ if } z_i(A^i_n) + d_i(z_i(A^i_n)) \geq z_i(A^i_k)$$
$$= 0 \text{ if } z_i(A^i_n) + p_i(z_i(A^i_n)) \leq z_i(A^i_k)$$

or any linear interpolation between 0 and 1 when $z_i(A^i_n) + d_i(z_i(A^i_n)) < z_i(A^i_k) < z_i(A^i_n) + p_i(z_i(A^i_n))$, where $d_i$ and $p_i$ are indifference and preference values for criterion $N_i$.

As mentioned in Chakhar and Mousseau (2008), with the second family criteria are aggregated into a partial binary relation S, such that $A^i_n S A^i_k$ means that $A^i_n$ is at least as good as $A^i_k$.

The best known method in this family is ELECTRE (Roy, 1968). To construct the outranking relation S, for each pair of alternatives $(A^i_n, A^i_k)$ a concordance index $N_i(A^i_n, A^i_k) \in [0, 1]$ measuring the power of criteria that are in favour of the assertion $A^i_n S A^i_k$, and a discordance index $N_D(A^i_n, A^i_k)) \in [0, 1]$ measuring the power of criteria that oppose to $A^i_n S A^i_k$, are computed (Chakhar and Mousseau, 2008). Let's define n and d as given levels of concordance and discordance, also called concordance and discordance thresholds. Alternative $A^i_n$ is better than alternative $A^i_k$ if:

$$N(A^i_n, A^i_k) \geq n \text{ and } N_D(A^i_n, A^i_k) \leq d$$

If it is not possible to comply with this condition, the alternatives are not comparable.

Often an exploitation phase is needed to "extract" from S information on how alternatives compare to each other. At this stage, the concordance $N_i(A^i_n, A^i_k)$ and discordance $N_D(A^i_n, A^i_k)$ indices are used to construct an index $r(A^i_n,$

$A^i_k) \in [0, 1]$ representing the credibility of the proposition $A^i_n \, S \, A^i_k$, $\forall (A^i_n, A^i_k) \in A \times A$. The proposition $A^i_n \, S \, A^i_k$ holds, if $r(A^i_n, A^i_k)$ is greater or equal to a given cutting level, $k \in [0.5, 1]$.

Outranking relation-based decision rules mainly differ in the way the outranking relation S is constructed and the way the credibility index is calculated.

According to Figueira *et al.* (2005b), ELECTRE II is a method for dealing with the problem of ranking actions from the best option to the worst. ELECTRE III was designed to improve ELECTRE II. This purpose was actually achieved, and ELECTRE III was successfully applied during the last two decades onto a broad range of real-life applications. The novelty of ELECTRE III is the introduction of pseudo-criteria instead of true criteria. Pseudo-criteria, which are constructed taking into account indifference and preference thresholds, allow to consider imprecision, uncertainty and indetermination in complex decision problems. True criteria instead, which are the simplest and traditional form of criterion, do not have thresholds. Here, only the difference between the scores on the criteria is used to determine which option is preferred (Giannoulis and Ishizaka, 2010).

ELECTRE IV arose from a new real-world problem related to the Paris subway network.

ELECTRE TRI is designed to assign a set of actions, objects or items to categories and allows to compare between actions and a stable reference. As pointed out by Adolphe (2007), the main specificities of the ELECTRE TRI method are incomparability and overranking. The decision making process requires to evaluate concordance and discordance per criteria, relation and structure of "flou" overrranking in case of optimistic / pessimistic affectation, thresholds of preference for each criterion, degree of credibility and weighting. The advantages of the ELECTRE TRI method are that it allows for a ranking and for a consideration of thresholds (i.e. non-substitutability). Its disadvantages are the restricted readability, transparency and comparability.

In Figueira *et al.* (2005b), a modification of the valued outranking relation used in the ELECTRE III and ELECTRE TRI was proposed. The modification requires the implementation of the discordance concept. ELECTRE TRI deals with following generalization of the ELECTRE method:
−   in the conjunctive rule: Replace, in the condition "on each criterion" by "on a sufficient majority of criteria and in the absence of veto"
−   in the disjunctive rule: Replace, the condition "on at least one criterion" by "on a sufficient minority of criteria and in the absence of veto"

An atypical ELECTRE method called 'meaningful compensation method' (Figueira *et al.*, 2005b) was created to deal with the problem of highway layout in the Ile-de-France region. The method was based on substitution rates.

### 6.3.2.3.2. The PROMETHEE family methods

Another type of outranking methods are the PROMETHEE methods (see e.g. Brans and Maréchal, 2005). The preference structure of PROMETHEE is based on pairwise comparisons.

The information requested by PROMETHEE is particularly clear and easy to define for both decision-makers and analysts. It consists in a preference function associated to each criterion as well as weights describing their relative importance.

Modifications of PROMETHEE are PROMETHEE V, which includes a procedure for multiple selection of alternatives under constraints, PROMETHEE VI which includes a sensitivity analysis procedure and PROMETHEE Group Decision Support System (GDSS).

### 6.3.2.3.3. Regime

The Regime method belongs to the family of qualitative multi-criteria evaluation methods. Similar to the Evamix method, an evaluation table composed by $e_{ij}$ scores of a number $n$ of alternative scenarios with respect to $m$ criteria is given. Regime allows to use cardinal as well as ordinal data in the evaluation table (De Montis *et al*., 2005).

Compared to e.g. ELECTRE III, Regime has a simpler structure of the preference model, since it allows to process mixed data, i.e. qualitative and quantitative data can be used for criteria. Because the Regime method does not admit incomparabilities among alternatives, it shows all the benefits of the outranking relationship for modelling the individual preference system coupled to the possibility of yielding a set of completely comparable alternatives (De Montis *et al*., 2005).

## 6.3.2.4. Utility functions-based approaches (UTA method)

Utilities Attribute (UTA) methods are based on the aggregation-disaggregation approach and use linear programming (Siskos *et al*., 2005). They refer to the philosophy of assessing a set of value or utility functions, assuming the axiomatic basis of MAUT and adopting the preference disaggregation principle. UTA methodology uses linear programming techniques in order to optimally infer additive value / utility functions, so that these functions are as consistent as possible with the global decision-maker's preferences (inference principle).

According Beuthe and Scannella (2001), the problem is to compare, rank and evaluate a set of actions, or projects, with respect to N different criteria which measure the favourable consequences of the projects. The measurements of these consequences are given by the vector $g(a)=(g_1(a); g_2(a); ... ; g_N(a))$ for any project a belonging to A. As an example, for a highway project, the $g_i(a)$ could be the cost-benefit ratio, its favourable impact on safety, on the environment, etc. The existence of an additive utility function is assumed:

$$U[g(a)] = \sum_{i=1}^{N} u_i[g_i(a)] \qquad \text{[eq. 18]}$$

with $u_i(g_i) \geq o$ and $\dfrac{du_i}{dg_i} > 0$,

which satisfies the classic axioms of decision theory, namely the axioms of comparability, reflexivity, transitivity of choices, continuity and strict dominance. The additivity implies in particular that the partial utility of a criterion $u_i(g_i(a))$ depends only on the level of that particular criterion. For a discussion about the additive utility functions see for instance Keeney and Raifa (1976).

The utility function provides an aggregation of the criteria in a common index to compare, rank and assess the projects. UTA estimates the function U on a set of reference projects A' by approximating the utility of each alternative $a \in A'$ by:

$$U'[g(a)] = \sum_{i=1}^{N} u_i[g_i(a)] + \sigma(a) \qquad \text{[eq. 19]}$$

with $\sigma(a)$ being a non-negative potential error relative to the utility of each alternative a.

This is done by the method of linear goal programming proposed by Charnes and Cooper (1977), which provides an approximation by linear intervals of the non-linear functions. The objective function of UTA, to be minimised, is the sum of these errors:

$$F = \sum_{a \in A'} \sigma(a) \qquad \text{[eq. 20]}$$

## 6.3.2.5. Modifications and extensions of discrete approaches

Since the early 1990s, multi-criteria analysis has been coupled with geographical information systems (GIS) for an enhanced spatial multi-criteria decision making (see Malczewski, 1999). Outranking methods may be useful in spatial decision problems, especially when ordinal evaluation criteria are implied. A framework to facilitate the incorporation and use of outranking methods in geographical information systems has for example been proposed by Chakhar and Mousseau (2008). The framework is composed of two phases. The *first* phase allows to produce a planar subdivision of the study area obtained by combining a set of criteria maps, each representing a particular vision of the decision problem. The result is a set of non-overlapping spatial units. The *second* phase allows to construct decision alternatives by combining the spatial units. Point, line and polygon feature-based decision alternatives are then constructed as an individual, a grouping of linearly adjacent or a grouping of contiguous spatial units. This permits to reduce considerably the number of alternatives, which enables to use outranking methods, which typically are unsuitable to problems implying a high number of decision alternatives die to computational limitations (Chakhar and Mousseau, 2008). The framework is illustrated through the development of a prototype and through a step-by-step application to a corridor identification problem.

The following approaches are modifications or extensions of multi-attribute utility theory (MAUT): Stochastic dominance concepts, primarily in the context of pairwise comparisons of alternatives; The use of surrogate risk measures such as additional decision criteria; And the integration of MCDA. Risk measures such as additional decision criteria could be introduced in a typical decision matrix (Table 46). The decision making could me made in statistical data conditions, in risk conditions or in uncertainty conditions. Stewart (2001) and Miettinen *et al*. (2009) mostly use MAUT for decision making in Pareto optimality conditions (when there is a set of decisions, which are equivalent, and there is no single decision). Decision making in risk condition means that for every alternative the probability of results is known and that the range of final results is ultimate or eventual.

Other variants of discrete multi-criteria approaches are fuzzy set methods, as implemented e.g. in the software NAIADE (Novel Approach to Imprecise Assessment and Decision Environments) (Weistroffer *et al.*, 2005). NAIADE provides an impact or evaluation matrix that may include either crisp, stochastic, or fuzzy measurements of the performance of an alternative with respect to an evaluation criterion. A peculiarity of NAIADE is the use of conflict analysis procedures integrated with the multi-criteria results. NAIADE can give rankings of the alternatives with respect to the evaluation criteria (leading to a technical compromise solution), indications of the distance of the positions of the various interest groups (possibly leading to convergence of interests or to coalition formation), and rankings of the alternatives with respect to the actors' impacts or preferences (leading to a social compromise solution).

The discrete MCDA methods are evaluated with regard to their performance in assessing environmental sustainability in section 6.4.2 on page 245.

## 6.3.3. Continuous programming methods

Continuous approaches include programming methods such as Multi-Objective Programming (MOP), goal programming and some applications of Artificial Intelligence (e.g. multi-agent systems). Programming methods do not choose from a finite number of alternatives of transport project development (example: road parameters), but the alternatives are generated during the solution process on the basis of a mathematical model formulation. In artificial intelligence, genetic programming is an evolutionary algorithm-based methodology inspired by biological evolution to find computer programs that perform a user-defined task. Genetic programming is a specialization of genetic algorithms (GA) where each individual is a computer program. Therefore it is a machine learning technique used to optimize a population of computer programs according to a fitness landscape determined by a program's ability to perform a given computational task.

In the last few years, genetic programming and artificial intelligence approaches have been used more widely in some decision makings (also transport) contexts (see e.g. Stewart *et al*., 2004). Genetic programming allows to develop better alternatives, taking in account the special structure of some elements. A Genetic algorithm is a searching technique used in computing to

find solutions for optimization and search tasks. Artificial intelligence approaches can be categorized according to their global search heuristics (Russel and Norvig, 2002):

− *Clustering algorithms* is the classification of objects into different groups, or more precisely, the partitioning of a data set into subsets (clusters);
− *Neural networks* are used for solving artificial intelligence problems without necessarily creating a model of a real biological system;
− *Knowledge based systems (expert system)* are programs for extending and/or querying a knowledge base;
− *Natural language recognition* studies the problems of automated generation and understanding of natural human languages;
− *Bayesian rules* describe probabilities in terms of beliefs and degrees of uncertainty;
− *Markov chain* gives the present state, base on current state.

Combined with computer based networks and information technologies, continuous programming methods allow to realise on-line control of systems, e.g. intelligent transport systems (ITS). Some examples of ITS technologies are: electronic license plate matching, cellular phone tracking, global positioning system, loop detectors, video imaging, automatic vehicle location, automatic vehicle identification and micro simulation (Zietsman *et al*., 2006; Zietsman and Rilett, 2008). ITS allows to make predefined decisions in emergency cases, in heavy traffic situations, during repairing works and in other situations. Applying ITS allows to control traffic online and to make decisions immediately, when it is needed. ITS can be used as a data source for existing situations in view of long term decision making. Simulations of traffic system performance are useful to define the alternatives to transport plans or projects.

According to De Montis *et al*. (2005), MOP and particularly goal programming are the most frequently applied multi-criteria methods. Their popularity can be explained by their flexibility; They can account for a diversity of variable types (continuous, integer, Boolean, etc.) as well as constraints and objective functions (linearity, convexity, differentiability, etc.). MOP and goal programming are considered in more detail below. The continuous programming methods are evaluated with regard to their performance in assessing environmental sustainability in section 6.4.2 on page 245.

## 6.3.3.1. Multi-objective programming (MOP)

Multi-objective programming is a part of mathematical programming dealing with decision problems characterized by multiple and conflicting objective functions that are to be optimized over a feasible set of decisions. Such problems are commonly encountered in many areas of human activity including engineering, management, and others (Ehrgott and Wiecek, 2005). Some pioneering work on multi-objective programming has been done by Keeney and Raiffa (1976).

MOP can be considered as pertaining to situations where feasible alternatives are available implicitly, through constraints in the form of mathematical functions. An optimization problem (typically a mathematical

program) has to be solved to explicitly find the alternatives. In contrast to this, decision problems with multiple criteria and explicitly available alternatives are treated within multi-criteria decision analysis (MCDA). MOP and MCDA complement each other within multi-criteria decision making (MCDM) (Ehrgott and Wiecek, 2005).

According to De Montis *et al*. (2005), the application of MOP basically includes two steps:

1. Finding the non-dominated, Pareto-efficient solutions. Prerequisite for this is that the problem is formulated as a task of simultaneous maximisation / minimisation of several objects subjected to a set of constraints.

2. Choosing the most preferred solution, i.e. the solution preferred by the decision maker to all other solutions. Since in multi-criteria problems always a number of conflicting goals are faced, the solution is never optimal (or ideal), but a compromise. Regarding the amount of knowledge on the decision maker's preferences, different variants of the method have been developed: Those that need knowledge of the decision maker's preference, those in which the decision makers' preferences are pre-emptively determined ant those that progressively reveal the preferences of the decision maker through man-machine interaction.

According to De Montis *et al*. (2005), MOP is very appealing theoretically, however for large problems and particularly if non-linear functions are included, often no optimal solution can be found.

*Fuzzy MOP*

Multiple objective programming problem with fuzzy coefficients is one of practical approaches to make decision for transport development alternatives selection. Following Inuiguchi (2005), in multiple objective programming problems, parameters such as coefficients and right-hand side values of constraints are assumed to be known as real numbers. However, in real world problems, we may face cases where the expert knowledge is not so certain as to specify the parameters as real numbers and cases where parameters fluctuate in certain ranges. In stochastic programming approaches, we should estimate proper probability distributions of parameters. However, the estimation is not always a simple task because of the following reasons: (1) historical data of some parameters cannot be obtained easily especially when we face a new uncertain variable, and (2) subjective probabilities cannot be specified easily when many parameters exist. Moreover, even if we succeeded to estimate the probability distribution from historical data, there is no guarantee that the current parameters obey the distribution actually (Inuiguchi, 2005).

On the other hand, it is often that we can estimate the possible ranges of the uncertain parameters. In such cases, it is conceivable that we can represent the possible ranges by fuzzy sets so that we formulate the problems as multiple objective programming problems with fuzzy coefficients. From this point of view, many approaches to the problems have been proposed. Since we treat the uncertainty as well as multiplicity of objectives, we should discuss not only the

solution procedure but also the treatment of the problem (see and example of application in Caballero *et al*., 2005).

## 6.3.3.2. Goal programming

Goal Programming (GP) was originally proposed by Charnes *et al*. (1955). As noted by Charnes and Cooper (1977) in a review of the field, this approach to multiple objective optimization did not receive significant attention until the mid-1960's. However, during the past forty years, we have witnessed a flood of professional articles and books dealing with applications of this methodology (Dyer, 2005).

In GP one is interested in achieving a desirable goal or target established for the objective functions of the MOP. The vector of these goals produces a reference point in the objective space and therefore GP can be viewed as a variation of the reference point approaches (Ehrgott and Wiecek, 2005).

According to De Montis *et al*. (2005), two major subsets of GP can be distinguished: In the first type it is assumed that decision makers attempt to achieve a set of relevant goals as close as possible to the set of targets established. The methodology rests on the following basic scheme:

(1) set the values one wishes to attain on each criterion (the objectives);
(2) assign priorities (weights) to these objectives, which in practice is sometimes done with pairwise comparison (AHP);
(3) define (positive or negative) deviations with respect to these objectives;
(4) minimise the weighted sum of these deviations; and
(5) perform a sensitivity analysis.

In the other subset, the deviational variables are assigned into a number of priority levels and minimised lexicographically. The procedure of a lexicographic method consists in comparing all the alternatives with repect to the important criterion, and proceed with the next one until only one alternative is left (Guitouni and Martel, 1998).

# 6.4. General evaluation of joint consideration methods

In section 6.4, the methods presented in section 6.2 and 6.3 are evaluated with regard to their performance in assessing environmental sustainability of transportation from a general perspective, i.e. under abstraction of their specific application context.

# 6.4.1. Methods for building aggregated or composite indicators

In section 6.2, methods for building aggregated and composite indicators have been presented. According to Chapter 4, such indicators can be evaluated with the consolidated criteria presented in Table 25 on page 126 just as this has been done with the indicators presented in Chapter 5: see the result in Table 47. The aggregated indicators considered here are assumed to measure overall environmental sustainability.

**Table 47. General evaluation of indicators assumed to measure overall environmental sustainability and resulting from the application of methods for building aggregate or composite indicators**

| Indicator | Category | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Representation | | | Operation | | | Application | | | |
| | Validity | Reliability | Sensitivity | Measurability | Data Availability | Ethical concerns | Transparency | Interpretability | Target relevance | Actionability |
| Ecological Scarcity method (for Switzerland) | xxx | xxxx | xxx | xxx | xxx | xxxx | xxx | x | xxx | x |
| ReCiPe (for Europe) | xxx | xxx | xxx | xxx | xxx | xxxx | xxx | x | xx | x |
| Ecological footprint | x | xx | xxx | xx | xxx | xxxx | xxx | x | x | x |
| MIPS | x | xx | xx | xx | xxx | xxxx | xxxx | xx | x | x |
| Economic approaches (stated preferences) | xxx | xx | xxx | xxx | xx | xxxx | xx | xx | xxx | x |
| Economic approaches (revealed preferences) | xxx | xxx | xx | xxx | xx | xxxx | xx | xx | xxx | x |
| Economic approaches (damage oriented) | xxx | xxx | xxxx | xxx | xx | xxxx | xx | xx | xxx | xx |

x=poor; xx=limited; xxx=good; xxxx=excellent

## 6.4.1.1. Ecological Scarcity

The data and policy goals underlying the Ecological Scarcity method specifically apply for Switzerland (see section 6.2.2.1 on page 208). An application of the Ecological Scarcity method outside of Switzerland would require an adaptation of method, which has been done for older versions (Doka, 2002).

According to the evaluation for Swiss conditions, compared to the other methods the Ecological Scarcity has a particularly high target relevance and reliability. Besides these and ethical concerns, the highest scores are obtained

for validity, sensitivity, and data availability, the lowest scores for interpretability and actionability.

## 6.4.1.2. ReCiPe

The data underlying the ReCiPe method (described in section 6.2.2.2 on page 209) specifically apply for Europe (an application elsewhere would require an adaptation). Besides ethical concerns, the highest scores for the ReCiPe method are obtained for validity, sensitivity and data. The lowest scores are obtained for interpretability and actionability.

## 6.4.1.3. Ecological Footprint

The ecological footprint concept (described in section 6.2.3 on page 211) is increasingly used, particularly because of its choice of a practical and concrete assessment unit, i.e. land surface area. It is therefore a powerful public awareness tool to make people aware of resources consumption.

According to Amekudzi *et al.* (2009, p. 341), there is a growing number of applications of the ecological footprint concept in infrastructure decision making: for county-level transport network (Chi and Stone, 2005), ports (Carrera-Gomez *et al.*, 2006), building construction (Bastianoni *et al.*, 2006), fuels (Holden and Hoyer, 2005), and also at the policy level in a city-region (Browne *et al.*, 2008). But the ecological footprint is first widely used to calculate mankind's pressure on the planet through comparisons. Most of these studies show that western countries exceed the use of ecologically-productive land and marine area from the earth's biosphere: Europe, for example, has been running an ecological deficit since the 1960s, and its ecological footprint is rising faster than both its biocapacity per person and the world average available per person (WWF, 2007). The ecological footprint differs by an order of magnitude between developed and developing countries (e.g. 9.6 gha/cap in USA, 0.5 in Bangladesh). It used widely in discussions on sustainable development and system sustainability (see e.g. van Vuuren and Smeets, 2000; Boutaud, 2005).

The wide usage therefore makes the analysis of the ecological footprint method particularly suitable. It has received some criticism, most of which concerns the representativeness of the ecological footprint per impact, i.e. per land use type, and the aggregation of land use indicators.

### 6.4.1.3.1. *Critics of the ecological footprint per land type*

One of the critics of the footprint per impact considers the major role of hypotheses through the equivalence factors, especially:
– the equivalence between marine area and land based on the salmon and beef productivity
– the equivalence between marine area and inland water area.

Finally, from the only point of view of indicators per impact (i.e. per land use type), the ecological footprint seems quite accurate, for what it measures really, the uses of land, except for the fossil fuel footprint.

Another point of criticism aims at the way fossil fuels are taken into account. The method to calculate the fossil fuel land is essential, because it plays a major role in the global footprint. Figure 26 shows that, globally the 2005 ecological footprint amounts to 0.62 planet without considering carbon uptake, and to 1.31 with carbon uptake. In the period between 1961 and 2005, the increase of the ecological footprint is due to 82 % to the carbon uptake. According to van Vuuren and Smeets (2000), the carbon uptake accounts for 50 % of the ecological footprint in the case of developed countries, but only for 20 % for developing ones. Hails (2008) showed that in 2005, it accounts for 68 % in North America, 55 % in Europe, but only 23 % in Latin America, the Caribbean and Africa. Therefore the world overshoot is mainly due to the carbon uptake, which explains in addition a main part of the differences between countries.

**Figure 26. World overshoot according to the 2008 edition of the National Footprint Accounts (Ewing *et al*., 2008b, p. 11)**
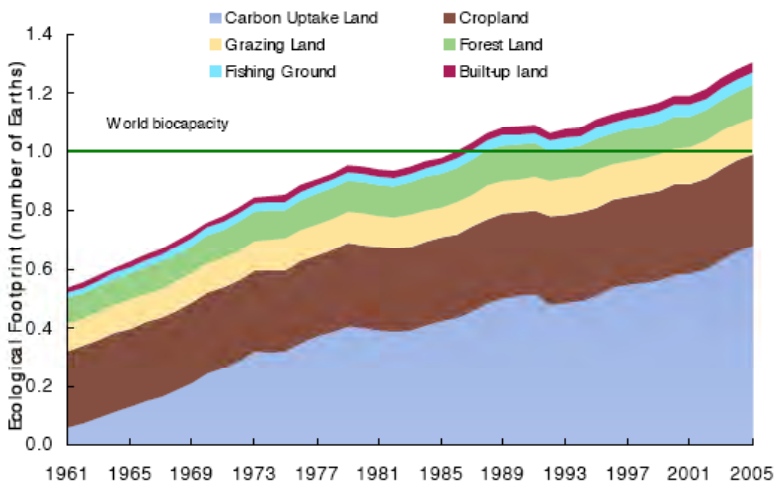


The fossil fuel land footprint is usually based on the forest land needed to uptake anthropogenic carbon emissions, i.e. a pure assumption. In addition there is no logical link between the use of fossil fuels as non-renewable resource and the carbon uptake: The issue of non-renewable resource use is the disappearance of such resource, but the carbon uptake is linked with the climate change issue. The fact that burning of fossil fuels reduces the availability of a resources *and* emits gases leading to climate change shows only that the same activity has two different impacts on the environment. However both impacts are not intrinsically linked. The consideration of the land necessary to produce alternative energy (through biomass or solar energy for instance) is more appropriate to take into account a resource issue and is used by some footprint studies.

### 6.4.1.3.2.  *Critics of the ecological footprint all land types included*

The aggregation of footprints per impact (as described in section 6.2.3.2) is relatively straightforward, as all the indicators are expressed in the same unit

(global hectare). According to its authors (Ewing *et al*., 2008b, p. 2), the footprints per impact can be added up to obtain an aggregate indicator of ecological footprint or biocapacity. The summation of impact footprints should be meaningful.

Nevertheless the aggregate ecological footprint merge biocapacities of different kinds: Most of the impact footprints represent renewable lands (used every year for similar production), but the surface theoretically used to uptake anthropogenic carbon emissions cannot be used in the future for other purpose than wood production, and especially it cannot be used again as a carbon sink. It is therefore a non-reversible use of a land, while the other land uses are reversible. This makes carbon uptake and other use lands fundamentally different and limits the additivity.

The fossil fuel land and the other impact footprints differ also in terms of actuality: If all impact footprints except the fossil fuel one represent really an actual land surface easily comparable to the Earth surface (even both expressed in global hectares), the translation of the fossil fuel consumption into a land surface is based on pure assumptions and therefore difficult to compare to the earth surface.

In conclusion, it appears that the carbon footprint and the other impact ecological footprints are not really additive.

Besides that, the indicator aggregation should also be evaluated according to what the aggregated indicator is supposed to represent. The ecological footprint method has been criticized by several authors with regard to this issue (Van den Bergh and Verbruggen, 1999; Boisvert, 2005; Ledant, 2005; von Stokar *et al*., 2006; Fiala, 2008; Venetoulis and Talberth, 2008; Franz and Papyrakis, 2009), in particular:

– The low number of impacts on the environment taken into account. Compared to the list of chains of causalities (see section 2.4.3), only three chains are taken into account, namely
  – chain 31 (loss of natural habitat due to land take), through the use of continental land, and land and maritime water
  – chain 39 (non renewable resource use), very partially through the consumption of fossil fuel
  – chain 42 (greenhouse effect), partially through the emission of $CO_2$

Noise and vibrations, accidents, air pollution, soil and water pollution, most of the impacts on land, most of the non renewable resource uses and waste handling, 'other' impacts, however, are not taken into account. The ecological footprint fails to allocate space for the needs of non-human species (Venetoulis and Talberth, 2008).

Qualitative aspects and aspects difficult to quantify, such as sweet water consumption, damages due to pollutant or losses in biodiversity are not considered or only indirectly considered, which leads to an underestimation of the ecological footprint and an overestimation of biocapacity (von Stokar *et al*., 2006).

– The method is not sensitive to changes in the environment. Only when an overuse has lead to clear impacts, e.g. when the productivity has been lowered due to erosions, is the result visible. This is why the ecological footprint cannot be considered to be an early warning indicator (von Stokar *et al.*, 2006).

– The non-taking into account of the long term, and the lack of taking into account of the debates on discount rates – see section 6.2.5.3: The short and long term are considered equally (Boisvert, 2005).

– The ecological footprint fails to distinguish between sustainable and unsustainable land use (van den Bergh and Verbruggen, 1999; Venetoulis and Talberth, 2008).

The term 'ecological footprint' refers to an impact on the earth (especially when considering the title of one of the first publications of Wackernagel and Rees in 1996, "Our ecological footprint: Reducing human impact on the Earth"; Ledant, 2005), or according to a common definition referring to *'resource consumption and waste production'*. However, the ecological footprint is far to represent that. Therefore, in addition to the above mentioned additivity problem, the summation does not allow to calculate what is usually understood through the term 'ecological footprint'. The authors of the footprint answer that the ecological footprint is for this reason an underestimation of the real ecological footprint. But as 50 % of the calculated ecological footprint (in average: the carbon uptake land – see section 6.2.3.2) is established on an assumption very open to criticism, this underestimation is questionable, and the gap between claim and reality seems to be quite wide.

According to von Stokar *et al.* (2006), data sources, assumptions and choice of variables and factors are not yet transparently described, and a handbook of the methodology is missing.

When assessing in Table 47 the ecological footprint method globally according to criteria defined in Table 25, it turns out that the highest scores are obtained for sensitivity, data availability and ethical concerns. The lowest scores are obtained for validity, interpretability, target relevance and actionability.

## 6.4.1.4.  MIPS

According to Ritthoff *et al.* (2002), MIPS is a practical, comprehensive and harmonised indicator, which is suitable for precautionary environmental protection (see its presentation in section 6.2.4 on page 214). Indeed, the idea behind the MIPS concept is simple and its application straightforward, as all material inputs considered are accounted for with mass units which are summed up without any weighing. Furthermore, MIPS changes the perspective from a reactive, symptom oriented view focused on environmental impacts towards a proactive, precautionary view focused on resource efficiency.

At the same time, however, the focus on the resource perspective and the absence of any weighing might lead to wrong conclusions. The MIPS indicator is not an indicator for the environmental impacts associated with a product or a

service, as sometimes suggested (see e.g. Burger *et al.*, 2009), and even as a resource consumption indicator it might be misleading, as it does not consider any qualitative differences between the different resources, e.g. their geophysical availability, and might be dominated by the most common or heaviest resources independently of their scarcity. Burger *et al.* (2009), for instance, investigating the environmental aspects of three different pairs of products – two types of lights bulbs (low energy and common), two types of spinach (deep-frozen and fresh baby-leaf) and two types of packaging for mineral water (recycled PET-bottle and PET-bottle), found that water consumption accounted for 95 to 98 % of the MIPS (96 % in average).

When assessing in Table 47 the MIPS method according to criteria defined in Table 25, it turns out that the highest scores are obtained for data availability and ethical concerns. The lowest scores are obtained for validity, target relevance and actionability.

## 6.4.1.5.  Economic indicators

The purpose of an external cost valuation is to take the environmental impacts of a human action into account in the assessment of its costs and advantages. Such a valuation can be stated with various methods, which can be classified into three main families depending on (1) the observation of real behaviours (revealed preferences), (2) surveys revealing stated behaviours in hypothetical situations (stated preferences) or (3) a first systematic assessment of the impact chain involved and of the costs of each impact (damage oriented methods): see section 6.2.5 on page 215. These methods tend to focus on different cost component, from the use and the option values to the existence value. They could then be considered as more complementary than opposite if the boundaries of their application fields could be better defined.

When assessing in Table 47 the three economic appraoches according to criteria defined in Table 25, it turns out that:

- validity: the 3 indicator families focus on different components of the external costs, and have an excellent validity if they are correctly used.

- reliability: the results of stated preference methods depend on a high number of factors and their reliability is still not very excellent. Revealed preferences and damage oriented methods give better figures on that criteria.

- sensibility: the 3 methods are both sensitive to damage variations, but revealed preferences show that the population perception of the environmental damages is sometimes limited and the damage oriented methods helps to take them into account – as the stated preferences, if the damages are explicated during the survey process.

- Measurability and data availability: the measurability is correct for the 3 methods, with specific difficulties to build the data.

- Ethical concern: no problem if confidentiality agreements are respected to use the survey results.

- Transparency: the external costs seem transparent on their scientific basis. But when they are used to justify public action, without discussion with the stakeholders, they appear not clear to people. Obviously, it remains very important to elaborate political procedures to obtain transparent and democratic compromise on collective official values. In such a scheme, the economic external costs valuations give big elements to the debate, but are not enough for political transparency.

- Interpretability: the principle of external cost is easy to understand, but the fact that many different components of the cost could be focused on, depending on the methodology is far to enlighten the interpretation.

- Target relevance: the external costs are strongly adapted to their purpose of economic public action assessment.

- Actionability: the economic indicators are not really conceived to follow changes and to measure the impact before and after a policy action. Damage oriented approaches are more explicitly linked to physical damages, which can be measured and followed, and are better adapted to that criteria.

## 6.4.2. Multi-criteria methods

In the context of transport and (environmental) sustainability, MCDA methods (presented in sections 6.3 on page 223) have been evaluated by several authors, amongst others:

- Guitouni and Martel (1998), who performed general evaluations of MCDA methods and proposed some tentative guidelines to help choosing an appropriate MCDA method.

- Tsamboulas *et al*. (1999), who applied four criteria (transparency, simplicity, robustness and accountability) to evaluate selected multi-criteria methods (Regime, ELECTRE, MAUT, AHP, ADAM) in the context of transport infrastructure projects.

- Janssen (2001), who analysed the role of MCDA methods in environmental impact assessment for the Netherlands.

- Omann (2004), who evaluated MCDA methods (weighted sum combined with MACBETH and PROMETHEE) with regard to requirements related to sustainable development, the criteria being related to system characteristics, sustainable development principles and the decision procedure.

- Borken (2005), who applied five criteria (iteration, participation, transparency, data insecurity, non-substitutability) to evaluate selected multi-criteria methods (AHP, Evamix, ELECTRE III, Regime, NAIADE and MOP/GP) in the context of sustainable transport.

- De Montis *et al*. (2005), who proposed a quality criteria framework with 22 criteria to evaluate MCDA methods with regard to their performance in

sustainable development contexts and applied them to selected methods (MAUT, AHP, Evamix, ELECTRE III, Regime, NAIADE and MOP/GP).

Following, results from these evaluation as well as an own evaluation based on the consolidated criteria from Chapter 4 are presented.

## 6.4.2.1. Evaluation according to Guitouni and Martel (1998)

Guitouni and Martel (1998) compare 29 different MCDA methods, subdivided into elementary methods (e.g. weighted sum, lexicographic methods, maximin method, see also Annex 13), single synthesizing criterion methods and outranking methods, with respect to seven tentative guidelines. These guidelines address, amongst others, issues such as group decision making, the cognition of the decision maker, the decision problem to be addressed, the compensation degree the decision maker accepts and the understanding of the fundamental hypotheses of the method. They conclude that the results of their comparison are, from a practical point of view, far from being completely satisfactory since they do not allow to make an unequivocal choice.

## 6.4.2.2. Evaluation according to Tsamboulas *et al*. (1999)

In study by Tsamboulas *et al*. (1999), a panel of experts examined the merits and shortcomings of some competing multi-criteria methods in the context of three infrastructure projects in Greece. The following main positive and negative aspects of the methods considered were identified:

- Additive methods are the most straightforward - close to human, rational - methods to treat transport decision problems. There is a variety of decision tools using utility or value functions (MAUT and AHP) or the notion of the ideal point (ADAM type). The additive models are usually linear and allow for complete compensation. However, this is not desirable in all decision situations.

- Regime is useful when ordinal information is available for criteria weights and projects' scores. The method is a powerful tool with the ability to manage a large variety of evaluation problems. The number of criteria plays an important role in determining the implementation difficulty.

- The ELECTRE methods are based on the partial comparability axiom. ELECTRE I may lead to inconsistent results when ''non transitive'' outranking relations are used. Most of these problems, however, have been solved in later versions.

## 6.4.2.3. Evaluation according to Janssen (2001)

In his paper, Janssen (2001) presents examples of the use of multi-criteria analysis (MCA) in Environmental impact assessment (EIA) and lessons learnt from their application in the Netherlands.

Janssen concludes that the fear that stakeholders will perceive the MCA as a 'black box' and, therefore, reject its results, leads to the use of simple straightforward methods, such as weighted summation, and limited interest in sensitivity analysis. Moreover, in many EIA processes, a shift from analysis / evaluation to communication can be observed. This shift leads to glossy, well-designed evaluation reports, information bulletins and public presentations. Furthermore, the importance of the MCA results for the final decision is not always clear. In many cases, the political decision process following the submission of the EIA report results in compromise alternatives, usually based on a mixture of elements from the original alternatives. These alternatives are usually not compared with the original alternatives. In several cases stakeholders have tried to make their own calculations. Usually, this results in enormous effort and wrong results, which then enter the public participation discussions.

For Janssen (2001), the main methodological challenge hence does not lie in the development of more sophisticated MCA methods, but in the support of problem definition and design. In particular, methods should be developed that provide a more systematic support for building a consistent evaluation framework.

## 6.4.2.4. Evaluation according to Omann (2004)

Omann (2004) suggests to evaluate MCDA methods with regard to criteria related to system characteristics, sustainable development principles and the decision procedure. According to her, criteria which are typically well fulfilled by MCDA methods are i.a.:
− addressing all dimensions and objectives;
− addressing different levels;
− addressing trade-offs (not all MCDA methods allow for incomparability);
− coping with different forms of data;
− focus on process and result;
− transparency of the process;
− bridging the gap between research and policy actions;
− interdisciplinary research group (indirectly required by MCDA).

However, for several criteria their fulfilling can range from weak to excellent, depending on the method chosen and the way it is applied. Examples for such criteria are:
− incommensurability and incomparability (depends on the method);
− addressing of self-organisation and evolutionary character;
− respecting and integrating multiple perspectives (largely depends on person in charge);
− allowing and supporting learning (depends on the approach);
− allowing non-agreement (depends on the approach);
− degree of acceptance of result (depends on degree of participation);
− flexibility of approach (depends on how the facilitators apply MCDA).

Criteria which are typically badly fulfilled are, among others:

− Mechanisms to address uncertainty (not all MCDA methods can address uncertainty);
− Irreversibility (cannot be addressed by decision aid);
− Consideration of hierarchies (depends on the methods used);
− Supporting strong sustainability (depends on whether method is compensatory);
− Understanding of process and result (depends on the method used and analysts);
− Understanding of language (depends on how facilitators apply MCDA).

According to Omann, the fulfilment of some criteria lies fully in the hands of the persons responsible for the decision process. Omann concludes that, in general, MCDA methods are able to fulfil nearly all necessary requirements and hence are able to successfully support decision making for sustainable development, and that they represent an appropriate tool to operationalise sustainability criteria.

## 6.4.2.5.  Evaluation according to Borken (2005)

According to Borken (2005, p. 5 ff.), methods to evaluate environmental impacts of transport in the context of the normative concept of sustainable development have to fulfil the following specifications:

1. iterative and open for development;
2. open for a participation of different actors;
3. as transparent as possible;
4. able to handle uncertain or imprecise (fuzzy), and qualitative data;
5. able to limit compensation between criteria, and upper and lower limits;
6. able to identify incomparabilities, if no sufficient decision criteria.

These specifications are not fulfilled by several well established evaluation methods, in particular by methods related to a single evaluation criterion (Borken, 2005, p. 6). Established methods of transport planning such as cost-benefit analysis and utility analysis are subject, amongst others, to the following criticisms:

− They are aggregating on a one-dimensional scale, which is based on a substitution.
− As long as an unrestricted substitution of different effects is allowed, they do not allow to cope with defined standards.
− Offsetting contradictory effects conceals trade-offs. Not only is transparency reduced, but also an improvement and adaptation of the considered alternatives.
− They often operate with evaluations which originate from empiricism (e.g. willingness to pay). However, to pursue certain goals, a normative approach is needed, which cannot be derived from observation (see Moore's 'naturalistic fallacy').
− A standardisation of weighting via generalized utilities or costs impedes a case-specific evaluation.

According to Borken (2005, p. 8), the specifications defined can only be met by multi-criteria methods, which are able to cope with fuzziness (specification 4). Most of these methods fulfil the specifications 1-3, and it is rather difficult to

identify the best option among them. The reason for this is that because the decisive criterion for the evaluation of these methods cannot be their 'correctness', procedural elements such as their suitability for the (decision making) problem, the involved stakeholders, the input data etc. determine the quality of the method.

From a limited number of methods (AHP, Evamix, ELECTRE III, Regime, NAIADE and MOP/GP), Borken (2005, p. 8) identifies the ELECTRE III method to be the most adequate.

According to Borken (2005, p. 140), ELECTRE III is particularly well suited for strategic (e.g. strategic environmental assessment) or prospective applications (e.g. prospective technology assessment) evaluations, when there are great data uncertainties, developments are more quantitative than qualitative, and the details are not yet determined.

In ELECTRE III, to compare the different criteria or indicators between each other, weights are assigned, which reflect the subjective evaluation of the stakeholders involved in the decision process with regard to the importance of one aspect *relative* to the other. The weights are hence not understood to be 'given' (which corresponds to a descriptive approach), but rather to be fixed by the involved stakeholders (in the sense of a constructive approach). This means that they are a priori bound to the context, the specific issue to be addressed, the criteria chosen, the involved stakeholders, the input data and the resources (Borken, 2005, p. 13 ff.).

In contrast to e.g. a simple weighted sum method, in ELECTRE III, the weight of a criterion cannot be changed by the magnitude of its characteristics: As soon as the significance threshold is exceeded, the criterion is considered in the evaluation. A greater exceeding of the significance threshold does not change anything to this (Borken, 2005, p. 20 ff). ELECTRE III is based on an ordinal, i.e. not a cardinal logics: not the absolute values of the criteria (which is not identical with 'indicator' representing the criterion) are relevant, but their weights. Hence, in ELECTRE III it is also easily possible to change, substitute or complement an indicator without changing the weight of the criterion (Borken, 2005, p. 15, 32).

Whereas a simple weighted sum method may emphasize extreme values, ELECTRE III is considered to have a systematic tendency towards compromise and attenuation of such extremes. This is why it has been qualified as a method, which could have advantages in political decision making processes, where strong interest groups not capable of winning a majority are involved (Borken, 2005, p. 20 ff.)

The goal of the ELECTRE method is to consider disparate criteria and to rank alternatives, i.e. to address the question 'Is alternative A better than alternative B?'. To answer this question, a joint consideration which includes all criteria and pairwise comparisons is necessary. From the final result, however, it is not possible to derive which criteria play a particularly relevant role, i.e. the transparency of ELECTRE III is limited. For an application of ELECTRE III, Borken (2005, p. 32 ff.) suggests to involve an experienced user, who – in coordination

with the stakeholders and decision makers – has to structure the process, model the relevant criteria and possibly also moderate the pairwise comparisons.

## 6.4.2.6.  Evaluation according to De Montis *et al*. (2005)

De Montis *et al*. (2005) propose a framework to evaluate MCDA methods with evaluation criteria organized into the following three groups:
   1) operational components of MCDA methods,
   2) applicability of MCDA methods in the user context, and
   3) applicability of MCDA methods considering the problem structure.

The first group addresses theoretical aspects related to the evaluation criteria (such as interdependencies between criteria, completeness, allowance of non-linear preferences), the weighting (transparency of weighting, transparency of process, meaning) and the solution finding procedure. The second group deals with straightforward issues like project constraints (costs, time) or the structure of the problem solving process (stakeholder participation, the way of structuring the problem, the applicability as a tool for learning, transparency or actor communication). The third group considers indicator characteristics (geographical scale, micro-macro-link, societal / technical issues, methods combinations) and the data situation (type of data, risk / uncertainties, data processing amount, non-substitutability).

### 6.4.2.6.1.  Sustainability evaluation

In view of a general evaluation of selected MCDA methods (MAUT, AHP, Evamix, ELECTRE III, NAIADE, Regime) with regard to sustainability issues, De Montis *et al*. (2005) apply four perspectives related to specific criteria from their criteria framework. The perspectives and related criteria (in brackets) which they apply are the following:
   (1) possibility to deal with complex situations (i.a. evaluation criteria, consideration of different scales or aspects (e.g. geographical scales), micro-macro-link, societal / technical issues, type of data, uncertainties);
   (2) possibility to consider non-substitutability (i.e. strong sustainability) issues,
   (3) possibility to involve more than one decision maker (stakeholder participation, actors communication, and transparency), and
   (4) information of stakeholders in order to increase their knowledge and change their opinion and behaviour (problem structuring, tool for learning, transparency, type of weights).

Following, some main outcomes of the application of these perspectives on common MCDA methods are summarized.

### (1) Possibility to deal with complex situations

Common MCDA methods show similar performance with regard to the aspects and scales that can be considered, however they show weaknesses regarding criteria related to operational components. In particular:

- Only AHP allows for an interdependence of evaluation criteria, while only MAUT and NAIADE allow for non-linear preferences. Evamix, ELECTRE III, and Regime do not permit any of both characteristics.

- For all methods, the data which can be addressed can be quantitative and qualitative. In ELECTRE III, qualitative data have first to be transformed into a quantitative scale.

- Additionally, some of the methods like GP/MOP and NAIADE include features to deal with fuzzy data and stochastic numbers which is the way for these methods to deal with risk and uncertainties. MAUT allows to deal with risk (not uncertainty) concerning the outcomes of the alternatives by assigning probabilities to the utility functions (von Neumann-Morgenstern utility functions). All of the methods provide the possibility to carry out a sensitivity analysis or to apply qualitative data to consider uncertainties and risks.

*(2) Possibility to consider non-substitutability (i.e. strong sustainability) issues*

Non-substitutability aspects could best be considered by using ELECTRE III or GP/MOP, which both allow to set constraints and thresholds explicitly. MAUT and Evamix have acceptable performance in general, however lack important aspects crucial for sustainability issues, namely the ability to account for uncertainty and non-substitutability.

*(3) Possibility to involve more than one decision maker*

For MOP/GP there are tools for group decision making, which are, however, scarcely used. Some methods like AHP support consideration of preferences of several decision makers; in practice, each decision maker is asked individually. NAIADE does not allow to assign weights explicitly, however it is the only methodology which provides an explicit structure for stakeholder participation. Concerning MAUT, each of the persons involved in decision making is asked for his or her single utility function for any attribute. The single functions are then aggregated to n multi-attribute utility functions. If they are in conflict with each other, group solutions are possible, but are not really treated by the literature about MAUT.

*(4) Information of stakeholders in order to increase their knowledge and change their opinion and behaviour*

MAUT, AHP and Evamix provide good transparency and allow to give weights explicitly. For MOP/GP, ELECTRE III and Regime, the transparency only is of medium quality, which hinders stakeholder participation. Evamix, ELECTRE III, and Regime only provide satisfactory performance for complex situations, so they are not the first choice with regard to information of stakeholders

NAIADE supports the involvement of more than one person in the decision making process, namely with reference to their different interests, which allows for an explicit conflict analysis. An important aspect in group decision making is how transparent the decision making process is, because this enhances possibilities of participation and goal-oriented discussion within the group.

### 6.4.2.6.2. Application guidelines

From their application of perspectives and qualitiy criteria, De Montis *et al*. (2005) derive the following rough guidelines for methods application in the context of sustainability:

− If the respective decision problem is such that relying upon social welfare theory and its assumptions is possible, and if the data to build utility functions is available (risk and qualitative data are possible), then MAUT is a good choice.
− If working with different conflicting interest groups is important for the case, NAIADE and AHP provide the best performance.
− If the involved decision makers should primarily learn from the application of the MCDA tool, it is advisable to use MAUT or AHP.
− If thresholds and constraints are central for the problem under investigation, which means that there is non-substitutability of some criteria, ELECTRE III or GP/MOP should be chosen.
− If the problem is a continuous one, i.e. there is not a discrete number of alternatives which comes out of the specific situation, GP or MOP should be chosen.
− If a complete ranking of the given alternatives as result of the analysis is indispensable, MAUT, AHP, Evamix, or Regime should be applied.

## 6.4.2.7. Synopsis

MCDA methods provide a generic, formal framework to consider the preferences of stakeholders in view of generating alternatives or choosing between them. Many different such methods have been developed in the last decades, each with specific underlying assumptions and hypotheses. Typically, the methods are implemented in software tools which support the application of the methods in a specific decision making situation, including simplified web-based applications (see e.g. Giannoulis and Ishizaka, 2010).

Existing evaluations of specific MCDA methods in the wider context of transport and (environmental) sustainability show that general recommendations for their application are difficult to establish. Rather, the choice of the method will depend on the specific application context, including the preferences and possibilities of those who structure and moderate the modelling process and the stakeholders. Every case hence requires careful evaluation and application of existing methods and tools for each step in the decision making process. A method successfully applied in one context cannot be automatically applied to another context, without thorough reflections and investigations.

Nevertheless, some general recommendations and guidelines for the application of MCDA methods have been given, e.g. by De Montis *et al*. (2005). As also stated by others (see e.g. Borken, 2005), methods allowing to consider uncertainties and to set thresholds and constraints (e.g. veto ability, as with ELECTRE III or ELECTRE TRI) appear to be particularly suitable in the context of (strong) sustainability. Among the issues which have to be considered when choosing and applying a method are the following:

- There is a considerable risk that the limitations of the different methods are not always considered by the practitioners, as the methods are typically complex and difficult to understand in their implications, which might lead to the application of inaccurate methods;

- The fear that stakeholders might perceive the more sophisticated MCDA methods as 'black boxes' and, consequently, might reject their results, could lead to the use of (too) simple straightforward methods, such as weighted summation, and limited interest in sensitivity;

- The systematic approach supported by MCDA method may be questioned or even counteracted in the course of the decision making process, e.g. if new sets of alternatives are developed which originally had not been considered.

It is important to keep in mind that the aim of the application of MCDA methods is a better decision, not the more sophisticated or innovative methodology. This aim may e.g. require that alternatives change during the process, which means that flexibility must be present in the method, in its use or, at least, in the framework of application. MCDA should not just consist in applying a well-formulated mathematical model providing a solution based on the unrealistic assumption that the decision-maker's preferences are made perfectly explicit, but rather to construct or create a framework which is 'liable to help an actor taking part in a decision process either to shape, and/or to argue, and/or to transform his preferences' (Roy, 1990). As stated e.g. by Stagl (2004), decision-making in a world characterized by complexity, uncertainty, indeterminacy and multiple legitimate perspectives can only be perceived as an adaptive, participatory process, allowing the actors involved to continuously learn. Hence, the largest potential of multi-criteria evaluation appears to lie in the implementation of multi-criteria algorithms in combination with participatory techniques, guaranteeing mutual exchange of arguments and information, providing all participants with opportunities to add and challenge claims, and creating active understanding among them. However, it has to be considered that with public participation mixing democratic-like procedures into the processes of administrative agencies, which are themselves responsible to democratically elected officials, public lines of deciding may become crossed."

# 6.5. Joint consideration of indicators in practice: Appraising some selected cases

In this section, selected case studies are discussed with regard to how they apply methods for a joint consideration of indicators and to which strengths and weaknesses can be identified. The case studies were evaluated by authors of the Report, independently of the authors of the case studies. Hence, they may not reflect the opinion of the authors of the respective studies. The evaluation is basically performed along the following questions:
− What was the decision making context for the study?

− What was the goal of the study regarding the joint consideration of environmental and other impacts?
− Which approaches and methods have been applied to jointly consider impacts?
− How have these approaches / methods been implemented?
− Which have been the main strengths and weaknesses in the methods for joint consideration of indicators?

The following case studies were considered:

• The case study of a by-pass around the Czech city of Kralupy n/V, where a multi-criteria decision analyses method, AHP, was applied (section 6.5.1).

• The case study of the environmental assessment of biofuels, where a fully aggregating method, the Eco-Indicator '99 Life Cycle Assessment method was applied (section 6.5.2).

• The Egnatia motorway case study in which the development of social, environmental and transport features of the areas served by the Egnatia Motorway and all adjacent and vertical road links was assessed by experts (section 6.5.3).

• The Stockholm trial case study, a goal achievement process where some costs and benefits valuable in monetary terms were aggregated using a cost-benefit analysis and other impacts were jointly considered in terms of the attainment of goals (section 6.5.4).

• The COSIMA approach to transport decision making, which consists in the combined application of cost-benefit analysis and multi-criteria decision analysis (section 6.5.5).

# 6.5.1. Case study 1: A by-pass around the Czech city of Kralupy n/V

The discussion of this case study is based on the description of the project in Annex 11.

## 6.5.1.1. The decision making context

This case study has its origin in an attempt to improve transport environmental impact assessment (EIA) exercises in the joint consideration of impacts.

## 6.5.1.2. Goal of the study regarding joint consideration of indicators

The specific case study under consideration is based on an environmental impact assessment (EIA) of three alternatives for a by-pass around the city of Kralupy n/V., Czech Republic. The research was undertaken to highlight which

and how indicators were used in the environmental assessment of transport projects.

### 6.5.1.3. Approaches for joint impact consideration and their implementation

In order to improve the objectivity of the EIA-based analysis, the application of the analytical hierarchy process (AHP: see section 6.3.2.2.2) approach involved pre-selected indicators to be used in an electronic questionnaire. Pair-wise comparisons of the indicators were required from transport experts (22 persons) and the public at large (83 persons) with the aim to assess possibilities of AHP to be used under regional road conditions; to obtain significance weights for indicators; and to compare views of public and the experts.

The information gathered for the actual EIA-based analysis included numerical (aggregated) values for impacts on different (environmental) parameters selected in accordance with Calderon *et al*. (2009a) recommendations. Those impacts were labelled as:
− Impacts on residential households
− Impacts on surface water
− Noise impacts on residential housing (compared to baseline situation)
− Impacts linked to waste
− Impacts on flora and fauna
− Impacts on landscape
− Impacts on residents
− Impacts on archaeological sites
− Other impacts

The results of the application of the questionnaire through three models (one step, two steps weighted and two steps un-weighted) show different levels of correlation for average values of significance allocated to the individual criteria (see e.g. Figure 51 on page 367).

Conclusions put forward in this case study seem to indicate that pair-wise comparison is only meant to rank variants in accordance with the selected impact indicators listed in Table 59 on page 362. In any case there are no clear explanations about how these impacts are jointly considered / added for each variant in order to come up with a more or less preferred alternative.

### 6.5.1.4. Strengths and weaknesses

The method is an interesting application of the AHP methodology which can surely provide an aid to decision makers. The following strengths have been identified:

• The exercise was based on an environmental impact assessment of the projects under consideration, which implied an objective initial approach to the joint consideration of all effects, drawing on prescriptions in the EIA Directive, as transposed to the Czech legislation.

- The involvement (public participation) of experts and the public at large was guaranteed from the onset, in an effort to assess possibilities of AHP to be used under regional conditions, to obtain significant scores for indicators, and to match the views of experts and the public.

- The questionnaire used was tested through three different models which provided a certain sensitivity analysis of the significance allocated to the individual criteria.

From the point of view of possible improvements, and disregarding possible linguistic problems, a few issues appear evident in the initial EIA-based appraisal, some of which seem to have been carried over to the AHP approach:

- Impact categories described are not entirely disjoint, which leads to duplications of impacts.

- There is already some form of aggregation in the values put forward for each variant, with no indication of the way the value of the indicator (index) show for each variant has been compiled.

- The numerical values associated to the three variants are both positive and negative, something which introduces a new dimension, as no ideas are provided regarding trade-offs between impacts of opposite sign.

- Criteria used for impact assessment (impact categories) are not homogeneous. Out of the list of 15 elements used in AHP method, as provided in Annex 11, some can be labelled as final targets, whereas others look rather as midpoint impacts or as aggregation of chains of causality due to a same source component.

A critical appraisal of the EIA-based methodology used shows there was no objective method of aggregation and values assigned to each of the proposed criteria (in fact, environmental parameters) were highly subjective. The final selection of the preferred alternative (Variant B) was again conducted without an objective allocation of significance factors or a sensitivity analysis, let alone ideas on how to trade-off positive and negative impacts upon the different environmental parameters.

# 6.5.2. Case study 2: Assessment of biofuels

The discussion of this case study is based on the executive summary of the final report of the study (Zah *et al*., 2007).

## 6.5.2.1. The decision making context

The objective of this study was to evaluate the environmental impacts of the entire production chain of fuels made from biomass and used in Switzerland. Results were meant to be used as a basis for granting an exemption from the excise duty on fossil fuels.

### 6.5.2.2. Goal of the study regarding joint consideration of indicators

The study based on the Swiss life cycle inventory database "ecoinvent" (Frischknecht *et al.*, 2007; Jungbluth *et al.*, 2007) is intended to allow for a comparison of the environmental impacts of biofuels based on a life cycle assessment (LCA) approach. The results refer to average values from the year 2004 in the respective production countries.

**Figure 27. Schematic diagram of the environmental indicators used in the case study 2 along the path of proliferation and causation**
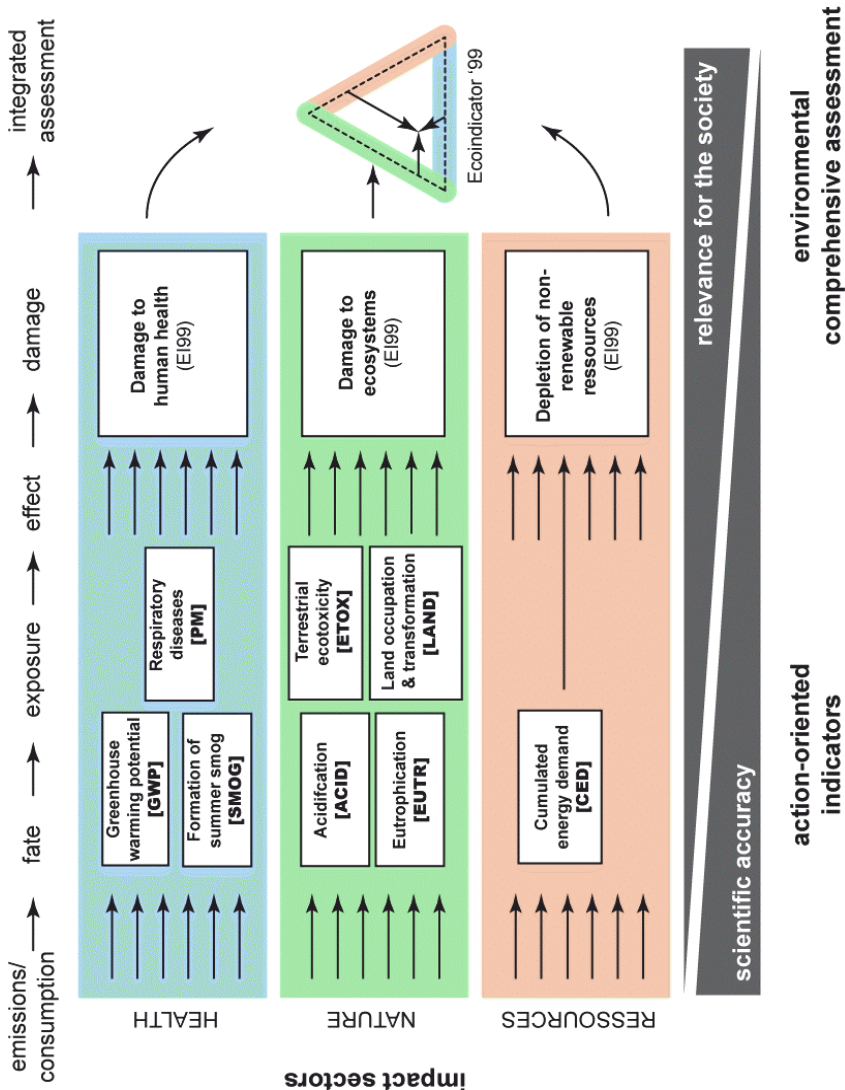
## 6.5.2.3. Approaches for joint impact consideration and their implementation

In order to determine the effects of biofuels on the environment as exactly as possible, the methodology of life cycle assessment (LCA) was chosen. This methodology entails evaluating the energy and resource consumption and all pollutant emissions over the entire life cycle needed to satisfy a defined function (e.g. filling up a car tank with 1 MJ of energy at a Swiss filling station).

The impacts on the environment were first determined with the aid of *action-oriented indicators*, which were represented by midpoint indicators according to the CML method (Guinée *et al*., 2001). Secondly, an environmental *overall assessment* was undertaken with the Eco-indicator '99 method by partially (in terms of damage to human health, to ecosystems and to non-renewable resources) and fully aggregating the environmental impacts. This was complemented by a full aggregation with the Ecopoints method (UBP '06, for Umweltbelastungspunkte '06, called the Ecological scarcity or Eco-Factors 2006 method: see section 6.2.2.1 and Figure 27).

By applying different life cycle impact assessment methods (CML - Guinée *et al*., 2001; Eco-indicator '99 – see section 6.2.2.2 – and UBP '06) and considering different levels of aggregation, the project tried to take into account, amongst others, that each life cycle impact assessment method applies different classification, characterisation, normalization and weighting procedures, and hence has its own specific limitations.

The study shows that with most biofuels there is a trade-off between minimizing greenhouse gases (GHG emissions), and lowering total environmental impacts. It is true that GHG emissions can be reduced by more than 30 % with a number of biofuels. However most of these supply paths show greater impacts than petrol for various other environmental indicators.

## 6.5.2.4. Strengths and weaknesses

The methodology provides a systematic, comprehensive comparison of bioenergy forms considering the whole production chain and is suitable for partially and totally aggregating environmental impacts. It allows to survey a large number of impacts, notably impacts from
- cultivation and processing of renewable resources
- excessive use of fertilizers
- acidification of soils
- loss of biodiversity
- land use conflicts (food producing uses, nature conservation…)

When interpreting the results of this case study, the following limitations have to be considered:

- The assessment was limited to comparing relative environmental impacts and refers to a functional unit (e.g. filling up a car tank with 1 MJ of energy at a Swiss filling station);

- The methodology of life cycle assessment (LCA) analyses the environmental impacts of material and energy flows. This neither includes the economic costs of biofuels nor the social consequences of their production are evaluated. However, this was not the goal of the research in this study.

- Most of the results refer to existing process chains, and thus cover the reference year 2004; possible future developments are not evaluated. However a glimpse on those possible future developments is provided by the sensitivity analyses and possible optimization potentials.

- Since many allocations have been calculated from sales revenue, and revenue depends on market dynamics, the results of this study are not "chiselled in stone" and may have to be verified at some later point in time.

- The process chains investigated represent only a subset of all production processes; many more production paths are conceivable. The paths chosen, however, were considered especially relevant for the current situation in Switzerland.

- The study does not tackle in detail the future consequences of a shift to renewable fuels, e.g. the consequences for the environment if agricultural products were to be grown on such a large scale for energetic utilization that agricultural production as a whole had to be intensified, or as to any possible "rebound effects". In case an increase in fuel consumption should result from the introduction of biofuels because biofuels were regarded in the eyes of consumers as "environmentally friendly", and thus as unproblematic.

# 6.5.3. Case Study 3: A Motorway in Greece

## 6.5.3.1. Background information

The information obtained in connection to this case study (AUT, 2007) is quite limited and completed only through a personal communication[3]. Hence, only scant details concerning methodological approach and attained results are included here.

In accordance with description in the text reviewed, indicators were used to relate "social and environmental development", as well as "transport features" in the area served by the Egnatia Motorway and all adjacent road links.

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[3] with A. Mouratidis, Aristotle Univ. Thessaloniki, Laboratory of Highway Engineering, Thessaloniki, Greece.

### 6.5.3.2.  The decision making context

Egnatia Motorway is one of the first large-scale public works in Greece to apply a system of environmental management, that is, a method of organising and implementing environmental protection measures in the design, construction, and operation stages of the project.

### 6.5.3.3.  Goal of the study regarding joint consideration of indicators

The Study attempts to carry out an estimation of the development of social, environmental and transport features of the areas served by the Egnatia Motorway and all adjacent and vertical road links. The monitoring and evaluation of the spatial impacts from the operation of the motorway is based on a system of indicators defined in accordance with the current European practice. The indicators fall into three main classification groups: a) transport and road-network operation indicators, b) environmental indicators and c) socio-economic indicators.

### 6.5.3.4.  Approach for joint impact consideration and their implementation

30 indicators have been selected. They have been described and (jointly) assessed by evaluators with the aim to minimise those impacts and introduce remedial measures.

### 6.5.3.5.  Strengths and weaknesses

The following strengths have been identified:

- The study has been targeted to the application of a system of environmental management.

- A great deal of studies and abatement measures have been put in place to minimise environmental impacts of the motorway

- This has implied the individuation of significant indicators and the design of corrective measures. Indicators were selected to relate "social and environmental development", as well as "transport features" in the area served by the Egnatia Motorway and all adjacent road links.

Weaknesses encountered in this case study were:

- Some of the surveyed indicators seem to categorise direct impacts whereas others apply to indirect ones. It is not clear what selection criteria have been used, nor is the geographical area or the time horizon of the evaluation evident.

- From the documents submitted, no aggregation method seems to emerge. Mention is made about remedial costs to offset some

environmental impacts. These involve landscape restoration measures and protection of archaeological sites.

## 6.5.4. Case study 4: The Stockholm Trial

The discussion of this case study is based on Hugosson *et al*. (2006).

### 6.5.4.1.  The decision making context

On 2 June 2003, the Stockholm City Council adopted a proposal to conduct a trial implementation of congestion charging. The Stockholm Trial consisted of three parts: expanded public transport, environmental charges / congestion tax and additional park-and-ride sites in the city and in the rest of the county. These have been evaluated continuously from a number of different perspectives.

### 6.5.4.2.  Goal of the study regarding joint consideration of indicators

The stated goals of the project were:
− To achieve a 10-15 % reduction in the number of vehicles that cross the inner city segment during morning and afternoon rush hours.
− To improve access on the busiest roads in Stockholm traffic.
− To reduce emissions of carbon dioxide, nitrogen oxides and particles in inner city air.
− To enhance the quality of street-level environment perceived by people in the inner city.

### 6.5.4.3.  Approach for joint impact consideration and their implementation

The sheer formulation of goals imposes a goal achievement approach to assess results, and, hence, no formal method of integrated aggregation has been attempted.

Issues covered were not limited to the environment. Actually, among indicators used in the ex-post assessment, the following are mentioned:
− number of vehicles crossing the inner-city segment during the morning and afternoon rush hours
− travel times for private vehicles and bus services
− emissions of carbon dioxide and particles
− noise levels
− changes in public transport patronage
− road accidents.

The method involved the carrying out of an extensive range of studies, that not only cover travel patterns and effects on motor traffic and public transport, but also environmental consequences, effects on trade and industry, pedestrian and cycle traffic, changes to the city environment as well as macro-economic

impact and effects on the regional economy. Many of the effects of the trial are very dependent on factors in the surrounding world, such as the economic evolution in the region and country.

It should be remarked that the main goal of the Study was to assess the achievement of stated policy goals, so the approach used for the joint consideration of consequences can be described as a "goal-achievement" method. Hence, the indicators are used to measure the ex-post situation after the trials

## 6.5.4.4. Strengths and weaknesses

The following strengths could be identified:

- The assessment of effects on the three main targeted policy areas, namely public transport, accessibility to inner city, and environmental enhancement have been widely documented.

- Secondary and indirect effects have also been taken into account (effects on trade and industry, on pedestrian and cycle traffic; macro-economic impacts, etc. ). Likewise, the surveyed area for some impacts has been the region, and sometimes, even the whole country.

- Although the approach used, as stated above, has been based on a goal achievement methodology, the ex-post evaluation conducted includes an attempt to aggregate results obtained by valuing some of them in money terms, in a simplified cost-benefit analysis.

- Uncertainty in the allocation of prices to environmental effects is acknowledged.

- Both positive and negative effects are jointly considered.

On the other hand, the following weaknesses emerge:

- The evaluation spans over a wide range of fields (see section 6.5.4.3), that are very dependent on economic factors.

- The consequences of the trial are affected by other external factors, not contemplated in the implemented strategy. For instance, significant changes occurred during the trial period as a result of decisions made in the city and region, such as the switch to flat fares in public transport.

- Traffic and the trial's effects also varied during the six months of the trial, but most studies only present a snapshot of the situation at one point in time.

- Although "winners and losers" of the strategy were identified, equity issues seem to have been ignored in the overall assessment and no attempt has been made to jointly consider ones and the others. In fact, the major winners in the Stockholm Trial were professional and service road users, who made substantial travel time savings that were worth more than the congestion tax they paid. The net effect for private individuals depends entirely on how the congestion tax revenue is used.

- No integrated aggregation exercise is attempted although a reduced cost-benefit analysis is included.

## 6.5.4.5.  Overall results attained

A review of goal achievement shows, among other things, that traffic in selected links has indeed been reduced. However, the degree of improvement of the city environment goal is more difficult to assess. Furthermore, effects varied for different times and routes: Traffic decreased on most major roads, but increased on others.

The Stockholm Trial reduced local emissions of both carbon dioxide and particles. However, seen across the county, it can only be regarded as one of several measures required to achieve national climate objectives. Moreover, as the reduction in traffic took place in densely populated areas, it brought a major health benefit to a large share of the country's population. This health benefit is about three times higher than the benefit that would have been gained had the reduction occurred through an increase in fuel prices.

The Stockholm Trial only had a marginal impact on noise levels.

The expanded public transport during the trial did not reduce motor traffic to a demonstrable extent. However, effective public transport is deemed necessary to cope with increasing levels of patronage.

The regional economy was not affected to a great extent, and it is not likely that it would have been in the long-term.

In an attempt to jointly consider those groups who obtained a larger benefit from the congestion charges, the following could be pinpointed:
- those public transport passengers who received a larger selection of services
- those who were exempted from charges
- those who drove a car without driving across the charge zone and thus achieved shorter travel time at no cost
- cyclists (who seem to have received a better traffic environment)
- those who value their time and feel a time gain is worth the money
- commercial drivers (bus drivers, taxi drivers, truck drivers, etc., who received a better work environment)

Likewise, essential losers from the congestion charges were those who drove a car across the charge zone and for various reasons could not adapt their travel, but still don't think the time gain was worth the money

## 6.5.4.6.  Some conclusions

It can easily be concluded that the implementing authority has not conducted an aggregated evaluation of positive and negative impacts. These were, rather, put forward in isolation without any attempt to jointly consider the overall effect of the strategy. As it was hinted at the beginning, the goal achievement approach prevailed in the assessment of the Stockholm Trial.

A further conclusion points to the consideration of secondary and indirect effects, and not only those directly linked to the proposed strategy or affecting to the transport sector.

The ex-post evaluation conducted includes an attempt to aggregate results attained by valuing those in money terms, in a simplified extended cost-benefit analysis. The following figures were put forward (1 SEK ~ 0.10 euro):
− Shorter travel times were valued at SEK 600 million annually.
− Increased road safety were valued at SEK 125 million annually.
− Health and environment effects at SEK 90 million annually.
− The revenue from the congestion tax is estimated to be about SEK 550 million annually. For every SEK collected in congestion tax, there is a cost-benefit return to the society of a further 90 SEK.
− The expanded bus service is estimated to be economically unprofitable, both during the trial and if it were to be made permanent. The benefits are expected to be in the region of up to SEK 180 million annually, compared with a economic cost of operation of SEK 520 million annually.
− The price level and evaluation of both road safety and the environment are characterised by considerable uncertain factors.

It should be noted here that some policy decisions were deemed necessary in any case, and hence, they may be considered as alien to the implemented strategy. This is particularly so for public transport improvements. Again, some equity issues do arise, as the revenue loss of the (needed) overall overhauling of the public transport system should not be charged on the Stockholm Trial strategy.

A wrap-up of conclusions in the ex-post assessment highlights the following issues:
− The assessment methodology is based on the achievement of policy goals
− Indicators are used to measure the ex-post situation after the trials
− No integrated aggregation exercise is attempted although a reduced CBA is included
− Uncertainty in the allocation of prices to environmental effects is acknowledged
− Benefits and losses are not accrued by the same societal groups

# 6.5.5. Case study 5: The COSIMA approach to transport decision making

The discussion of this case study is based on Leleur *et al*. (2007).

## 6.5.5.1. Background information

The current case study covers a methodological approach and its application to seven transport situations in Denmark. Unfortunately, the information obtained does not provide comprehensive details on those transport strategies. However, both the approach and the (limited) information on applicability have been considered interesting so as to deserve to be described here.

## 6.5.5.2.  The decision making context

The exercise is an attempt to compare in an integrated way all the consequences of seven transport projects in Denmark. These consequences cover effects that can be valued in money terms, those that can be quantified in sundry units, and even those that can be qualitatively described.

## 6.5.5.3.  Goal of the study regarding joint consideration of indicators

The stated goals of the COSIMA approach include:
− To move forward in the description and measuring of effects
− To find a rational and trustworthy method to compare and assess impacts
− To examine a project where a mix of cost-benefit analysis (CBA) and non-CBA effects have been found relevant to be included in the appraisal study

## 6.5.5.4.  Approach for joint impact consideration and their implementation

The COSIMA approach argues some relevant impacts in transport infrastructure planning can be included in CBA. These are calculated before the actual COSIMA method is applied, and they do not change during the whole procedure. The next task is to determine the MCDA impacts of relevance, where possible measured in a appropriate quantitative unit.

Effects that cannot be measured quantitatively must be described by judgement (e.g. using a numerical scale) or compared by pairs (analytical hierarchical process - AHP) with a score allocated to each.

COSIMA assigns rating values or scores to effects. The quantitative units and the points and AHP scores are then translated into a final rating or score (0 to 100) by using value functions, linear and non-linear. If it is possible to assess an effect quantitatively, the value function gives the rating for each alternative directly from the actual quantity, but other units such as the formulated point scale values or AHP scores can also be used in order to assign the value function rating.

With the CBA and multi-criteria analysis (MCA) effects specified, the importance of the MCA effects against the CBA effects, i.e. the overall MCA vs. CBA trade-off, and for the MCA effects among each other, i.e. the determination of MCA criteria weights, must be established.

After an agreement on the MCA effects and their assigned weights, COSIMA can be run. As previously mentioned, COSIMA includes the MCA effects or criteria along with those usually treated in a CBA, thereby calculating a total gross value (TV) in monetary units for alternative Ak obtained by spending the investment cost dealt within the CBA term:

$$TV(Ak) = CBA(Ak) + MCA(Ak)$$

The approach described above was applied in Denmark to seven transport alternatives. Although no detailed information on the case studies has been obtained, some practical tips are illustrative.

Seven Danish Standard CBA criteria were used: Travelling time, vehicle operating costs, accidents, maintenance costs, noise, air pollution, and severance and perceived risk. Unfortunately, no information is provided about criteria to value those CBA criteria in monetary units.

Three MCA criteria were used: Network accessibility, urban planning and landscape.

Through the use of the CBA methodology from the Danish Road Directorate, first year benefits were calculated for the seven alternatives. This information was put together with point scores for the three MCA criteria, where the point scores are determined by "thorough examination of the alternatives based on a rating protocol". The three MCA effects are assigned a value describing their performance on a scale from -5 to +5, where +5 is the best.

The scores were translated into ratings between 0 and 100 using a linear, local value function. A normalization exercise was then undertaken and normalized values were discounted. Final values for the four indicators were added together into a single total rate of return index applying equal weights to CBA and non-CBA indicators.

## 6.5.5.5.  Strength and weaknesses

On the one hand, the following strengths of the Cosima approach could be identified:

- The Cosima method is based on the commonly accepted CBA experience of the Danish Directory for Roads together with a remarkable practical attempt to assess non-monetary effects through multi-criteria decision analysis.

- The Cosima approach provides interesting tips for future improvements in the (subjective) assessment of non-monetary effects.

- The Cosima method is a clear step forward in putting into practice a great deal of theoretical considerations. In particular it is noteworthy that some of the intermediate steps (weights) are agreed upon through "conferences" (participatory exercises) and that the application of sensitivity analysis provides some ground for democratic decision-taking. The use of local value functions is also noticeable.

On the other hand, the following weaknesses emerge:

- The application to the Cosima methodology to particular case studies shows high degrees of subjectivity, notably:
− In the (limited) number and selection of non-CBA criteria (e.g. urban planning?).
− In the format of the value functions (linear).
− In the allocation of scores to non-CBA criteria.

− In the weights allocated to non-CBA effects: Weights are the same in the two examples surveyed, even though effects are different.
− In the trade-off coefficient applied to compare CBA and non-CBA effects (however, a sensitivity analysis is later applied).

However, some of those issues have been subject to participatory processes, something which has been considered a "strength" further up, as those processes, while local in scope, can provide reference for further assessment exercises.

• Likewise, some methodological hypotheses are, apparently, debatable:
− The use of first year benefits as an indicator of economic performance, mainly for public financed infrastructural programmes, albeit this can be a standard procedure for the Danish Administration.
− The "calibration procedure", as a method to transform scores into monetary values.
− The definition of total rate of return as total gross value in economic terms over the total investment cost.
− The normalization method / definition of scales.
− Discounting non-monetary figures.
− Sensitivity analysis seems to be inconclusive and one may wonder whether an ELECTRE approach provide more sound results.

Admittedly, none of these issues are entirely typical of the COSIMA method: indeed, some of these questions are equally applicable to standard CBA.

## 6.5.5.6. Some final conclusions

As previously stated, the COSIMA method provides useful theoretical advances but, moreover, tips about practical implementation of those theoretical proposals, notably in the form of participatory exercises and the application of sensitivity analysis to partly offset the subjectivity of factoring of impacts.

However, arguably the method does not yet provide a definite breakthrough into the evaluation of transport alternatives as it retains some highly subjective elements throughout the evaluation process, which may render the decision debatable.

# 6.6. Conclusions

In Chapter 6, the joint consideration of environmentally sustainable transport indicators has been addressed. After the discussion of some boundary conditions for joint consideration of indicators, methods for building aggregate or composite indicators and multi-criteria decision analysis methods were characterized and evaluated from a general perspective. In order to consider the influence of the specific application context, these evaluations were completed by a discussion of the strengths and weaknesses of selected joint consideration approaches in specific application contexts.

# 6.6.1. General reflections

From a the perspective of the decision-making process, important factors that determine the joint consideration of indicators are the level of decision, the socio-economic context, the type of decision making process and the quest for sustainability.

Other aspects related to joint consideration of indicators appear to be subjectivity and value judgments, uncertainty, transparency and information value for decision-makers. According to the discussion on these aspects, it is difficult to determine which type of indicator offers decision-makers the best information about the situation they are making decisions about. As Table 39 on page 202 concludes, indicators become more uncertain, less transparent and leave more of the subjective value considerations in the hands of the experts as aggregation levels increase. On the other hand, the number of indicators are reduced. Based on the discussions in Chapter 3, it can be argued that what is the better approach to indicator construction will be context dependent and situation driven. In some contexts a highly aggregated indicator will be better, while selected representative indicators would be preferable in another context.

A most critical element of the environmental assessment appears to be the determination of the significance of environmental impacts. In the context of joint consideration of indicators, significance includes the relative importance assigned to each individual impact respective of all others. Techniques for determining significance should involve: expert judgement, dialogue with stakeholders, reference to legislation and regulations, as well as existing environmental thresholds, risk assessment, ranking and weighting procedures, some notion of environmental capacity, trends analysis, literature reviews and consulting with professionals.

# 6.6.2. Joint consideration by aggregation

Advantages of the aggregation of impacts are amongst others easier interpretation, assessment of the evolution of environmental impacts or facilitation of the communication with the general public. Disadvantages are, amongst others, that they may invite for simplistic policy conclusions or lead to inappropriate policies if dimensions of performance that are difficult to measure are ignored.

Weights typically have a great impact on the results of an aggregation This is why weighting models need to be made explicit and transparent. At the same time, weights are value judgements and hence have the property to make explicit the objectives underlying the aggregation.

A necessary prerequisite for an aggregation to an indicator is to bring incommensurable indicators to the same scale. This is done by normalization. Common normalization methods are ranking, standardization, re-scaling, distance to reference measure, categorical scales, cyclical indicators or balance of opinions. The selection of a suitable normalization method to apply to the

problem at hand is not trivial and deserves special care; different normalization methods will supply different results.

The evaluation of indicators resulting from the application of typical environmental sustainability aggregation methods has shown that they differ in their performance:

– Life cycle assessment (LCA) methods such as the Ecological scarcity and the ReCiPe method appear to be medium to good performers regarding representation and operation issues and lower performers regarding application issues. LCA methods are designed to apply a life cycle perspective, i.e. to integrate resource depletion and environmental impact issues along the relevant chain of processes. Each LCA method, however, has its specificities, which have to be considered. Amongst others, the results of LCA methods differ in their aggregation level. This is why in the application example of an LCA for the evaluation of different biofuels presented in section 6.5.2, highly aggregated indicators (based on the Eco-Indicator and methods) have been complemented with less aggregated indicators based on the CML. This allows to compensate for the typically low actionability and traceability of highly aggregated LCA indicators.

– Both the Material input per service-unit (MIPS) and the Ecological footprint methods, on the other hand, appear be good performers regarding operation issues, low to medium performers regarding representation issues and, again, low performers regarding application issues of the resulting aggregated indicators. A main advantage of the MIPS method are that it is simple and its application straightforward, as all material inputs considered are accounted for with mass units which are summed up without any weighing. However, the MIPS indicator does not really appear to be a good indicator for the environmental impacts associated with a product or an service, as sometimes suggested, and even as a resource consumption indicator it might be misleading, as it does not consider any qualitative differences between the different resources. The main benefits of the Ecological footprint method are the choice of a concrete assessment unit, i.e. a land surface area, making a powerful public awareness tool, the good representativity of a part of it, and the use of a life cycle approach. However, a main element of this indicator – the carbon footprint – is fundamentally open to criticism, and the aggregation of the different elementary footprints is not well funded. The application of MIPS and of the Ecological footprint method to build environmentally sustainable transport indicators is recommended for their operationality and the choice of a clear and well understandable assessment unit, however not for the non-additivity of their elements, at least according to what they are supposed to measure.

– Economic methods focus on the economic costs of environmental damages – the external costs, which are not expressed through a market – in order to help public decision by taking environment into account in the cost advantage analysis of public projects. However, those methods often do not measure exactly the same component of the costs, and their results could vary considerably, depending on which types of value they focus on (use, option, legacy, non-use values of a good) and the way they detect them

(damage oriented methods, stated or revealed preferences). The assumptions used to take the temporal dimension into account, through the discount process, also have a significant influence on the results. The way the external cost figures have been built should be very clear to be able to have clear conclusions. Because of that variety of assumptions and methods, these indicators do not appear to be transparent, and the political process to build collective and official values is to be considered as important as the economic methods themselves.

# 6.6.3. Joint consideration with multi-criteria methods

Multi-criteria decision analysis (MCDA) methods allow to jointly consider indicators in situations, where different alternatives have to be compared (discrete methods, e.g. with ELECTRE III) or new alternatives generated (continuous methods, e.g. genetic programming / multi-objective programming). Many different MCDA methods have been developed in the last decades, each with specific underlying assumptions and hypotheses. Typically, the methods are implemented in software tools which support the application of the methods in a specific decision making situation.

With regard to their application in the context of transport and (environmental) sustainability, several publications have been found to address the suitability of MCDA methods to compare alternatives, some of which have been presented under section 6.4.2.

Each MCDA method has its own limitations, which are a consequence of the underlying methodological assumptions and hypotheses. However, there is a considerable risk that these limitations are not always considered by the practitioners, as some of the methods are typically complex and difficult to understand in their implications, which might lead to the application of inaccurate methods. The main methodological challenge regarding MCDA methods hence does not appear to be the development of more sophisticated methods, but rather to support problem definition and design, and to adequately consider the different aspects and steps of a decision making situation.

On the other hand, the fear that stakeholders might perceive the more sophisticated MCDA methods as 'black boxes' and, consequently, might reject its results, could lead to the use of (too) simple straightforward methods, such as weighted summation, and limited interest in sensitivity analysis.

Moreover, it has to be considered that a decision making process is influenced by many factors (see section 6.1.2), and that human thinking cannot be simply modelled by logical rules and calculations. Hence, it most probably never will be possible to say that a decision is good or bad only by referring to a mathematical MCDA model. Rather, MCDA should provide a consistent framework whose principal aim is not to discover a solution, but to allow the different stakeholders taking part in the decision process either to shape, and/or to argue, and/or to transform his preferences. In the absence of a unique correct policy as the outcome of the application of MCDA methods, the focus must be on the quality of the process. Particularly, in the context of sustainable

development, this process should be participatory, in order to address the problems arising from complexity of systems, uncertainty, indeterminacy and multiple legitimate perspectives.

As a consequence, the largest potential for MCDA in decision making on sustainable development appears to lie in a combination of MCDA algorithms with participatory techniques and in their better integration into specific transport decision making contexts. This integration, however, will require a thorough, differentiated understanding of the underlying decision making processes and a discussion on how far public participation processes should be mixed with the processes of administrative agencies, which are themselves responsible to democratically elected officials.

## 6.6.4. Lessons learnt from the case studies

Five case studies have been submitted for examination and they present quite diverse characteristics in terms of information provided, scope and goals, means used, and then in terms of results. Some conclusions do clearly emerge:
− There appears to be mismatch between the theoretical considerations put forward by analysts and the applicability of those considerations in real practice.
− The reason for that may be found in the high subjectivity still associated to many of the hypothesis necessary to aggregate impacts in practice.
− While monetary evaluation of environmentally sustainable transport indicators is, no doubt, advancing for some of them, others are unlikely to lend themselves to universally acceptable significance factors, something which will continue to prevent their aggregation.
− This, however, does not exclude the possibility to reach case-by-case agreements for those factors provided a democratic planning participation process is conducted.
− Practical evaluation situations are quite case-sensitive, there included assessment goals, the legal context and local circumstances and values. This implies practical evaluation exercises, while always likely to benefit from theoretical approaches and even some general considerations in terms of societal values, will always depend on local perceptions.

# 7. Research needs

The interdisciplinary research carried out during five years on the definition of a measurable environmentally sustainable transport and more specifically on indicators of environmental sustainability in transport has allowed the participants individually and jointly to identify research needs, addressing topics for disciplinary as well as interdisciplinary research. Subsequently, research needs are identified, as suggested by various COST participants. Whilst these are not the outcome of a consensus process, all participants were provided with an opportunity to comment on or disagree with perceived needs.

### *In the field of sustainability and environmental issues*

- The concept of sustainability is still in need of further operationalization before being able to clearly define and distinguish between basic dimensions in an assessment context, Furthermore, more effort is needed to clarify how environmental impacts can be represented in other sets of sustainable development dimensions, such as human needs, long term concerns, and the role of governance. This requires inter- or perhaps transdisciplinary work building in fields such as ecology, economics, anthropology, ethics, systems theory, social theory and political science.

- The links between environmental impacts and what societies perceive and define as environmental issues need to be further explained. In this context, comparative studies of environmental concerns in different countries are needed: This includes clarification of the meaning of the concept of environment in different cultures, especially by comparing Western and traditional societies, or European, North-American, African and Asian societies.

- Possible generalisation and extension of the notion of 'chain of causalities' as developed in this report need to be further explored beyond transport to other fields of environmental analysis and assessment. 'Chain of causalities' need to be systematically explored further with structures and logics of other comprehensive environmental assessment frameworks available or proposed, such as life cycle analysis and causal networks.

### *In the field of the role of context for designing indicators*

- There are different typologies of indicators and different frameworks to organize them, but a systematic typology suitable to categorize sustainable transport indicators, and to guide selection and application of indicators appropriate for context has not been developed. Research is needed to compare, develop and combine various frameworks. In

general, the concept of 'indicator frameworks' is widely used, but poorly defined in literature and little understood in terms of how various conceptual or functional frameworks such as 'DPSIR' or 'performance measurement' helps (or not) to identify, design and apply proper representational sets of indicators for various uses or decision contexts. In other words the indicator framework concept needs to be defined, and existing ones need to be critically examined and compared.

- Questions on the various factors that are potentially able to explain the choice of indicators need to be asked, e.g. to what extent data availability and political pressure play a role next to theoretical and situational considerations. Conceptual explanatory models from, for example, evaluation research and knowledge utilization research could be combined with concepts from measurement theory to develop and test hypotheses about the actual role and use of indicators intended to use by decision makers, researchers, experts, stakeholders etc.

### In the field of the design of indicators per impact on the environment

- The identification of indicators for environmental impacts of transport is not a one time effort, considering that knowledge about the various impacts are constantly evolving and the contexts of application of indication for assessment of decision making vary in a way that requires customized procedures for indicator choice. Hence procedures to regularly review and apply indicators for environmental impacts of transport should be defined. The efforts undertaken in this work to tentatively review potential indicators using criteria should be extended and consolidated, by i) conducting expert, review or peer panels to consolidate and revise the initial assessment conducted for seven impacts in this report, ii) conducting similar panels for the remaining important impacts, iii) conducting extended panels representing both expert and stakeholder views for typical applications of indicators in transport environmental assessment. A general framework for such procedures could be extended from the models applied in this work, and research and development projects or programmes could be established in an EU or other cooperative European member state institutional setting.

In this publication, we studied environmental impact indicators for direct toxicity of air pollutants, natural habitat fragmentation, non-renewable resource use, loss of cultural heritage due to land take, noise as annoyance to humans, greenhouse effect, and waste in further detail. The following research needs were especially identified for these impacts:

- The health impacts of transport is an essential issue, but a problem is posed by the lack of health impact composite indicators that can be used easily to compare different elements of a transport system. A way to explore this further is the building of health impact indicators based on pollutant emissions (as there are widely available transport parameters) in combination with human health toxicity values.

- To evaluate the process of natural habitat fragmentation, there is a need to check the real consequences of natural habitat fragmentation on biodiversity loss, especially in large areas, and to evaluate the process of fragmentation in its global (world) dimension. In parallel, the thresholds and standardizing criteria and indicators should be defined.

- For non-renewable resource use, the most promising indicators to consider are those based on the possible future consequences of resource extraction. Here, in particular, the future availability of resource types with specific qualities and grades, and the associated extraction efforts (measured e.g. with energy as a proxy), as well as recycling options and processes should be much better investigated - under consideration of technological evolution.

- Defining an indicator in order to evaluate the loss of cultural heritage due to land uptake from transport infrastructure is complex, because especially of the integral entity, ethics, sustainability, the role of cultural heritage in the promotion of information in the decision making process, the subjective factor, the political / religious distortion factor, and the inflation factor. These need to be further studied and perhaps additional factors could be included. Further research is needed in order to evaluate the potential of the relation between ecology, equity and the possible correlations linking the interaction of flow of information under the function of decision making combined with cultural heritage / cultural equity. More specifically, the definition of 'untouchable' protected areas of cultural heritage needs to be broadened. For non protected areas or those areas with momentary suspended protection due to high national importance, the values of the indicator variables need to be determined. Furthermore, there is a need of guidance concerning how to consider various ethical aspects.

- The definition of noise indicators that are useful to decision makers is a big challenge and considerable attention has to be paid to designing them. Three main points should be considered to improve their chance of implementation, relevance, measurability and sensitivity: i) to design noise indicators more related to the annoyance to humans and to their subjective response at community level, taking into account that the same noise level has different impact on people depending on which transport mode constitutes the source; ii) to design different noise indicators for highways and urban streets; iii) and to design indicators capable of reporting differences in noise levels before and after the construction of an infrastructure.

- The design of greenhouse effect indicators which are more provocative for people, able to show the impact of a travel behaviour, is an important challenge. For instance, a 'climate footprint' could be developed, meeting the advantages of the Global temperature change potential and of the Ecological footprint. It could be based on: i) the greenhouse gas emissions of an individual or group, calculated in the same way as the Ecological footprint (based on the consumption of the individual or group), expressed in mass per year; ii) the transformation of these

emissions into a global temperature change potential; iii) the expression of the temperature change for a world population emitting the same amounts per capita as the individual or group concerned. Thereby the climate footprint would express the temperature change if all humans would emit the same mass as the individual or group concerned per capita.

- Very few indicators are developed for environmental impacts from specific waste generated by transport systems. Therefore, there is a need to conduct research for indicator development in areas such as: habitat fragmentation and degradation caused by waste; land degradation or permanently lost land due to vehicle waste disposal; bird populations affected by waste; global effects of waste on marine food chains; long-term effects of small amounts of non biodegradable waste. Indicators with comparable units allowing comparisons among impacts, modes, etc., should also be developed.

### *In the field of the joint consideration of environmental impact indicators*

- In multi-criteria methods and when designing composite indicators, indicators of environmental impact are often considered as additive and then substitutable. The acceptability by the public of such substitutability of environmental impacts should be studied in detail according to impact and social parameters (country, urban / non urban, culture, age, socio-professional category etc), in order to take public awareness more into account in the joint consideration methods.

- Further research should focus on the relationship between sustainability and evaluation with respect to the process of consensus building. In this sense, the technical features are not that important. Rather, each multi-criteria technique should be evaluated according to its capacity to foster learning processes and to allow users to become aware of society's strategic role in environmental decision making.

- A large potential of multi-criteria evaluation for decision making on sustainable development lies in the implementation of multi-criteria algorithms in combination with participatory techniques, but key questions still need to be studied. The roles and role interactions of interested and affected parties in determining the significance of impacts for various project types and in various settings should be studied further. Existing thresholds, criteria and contexts should be tested and refined in varying situations. The role of formal numerical models in decision making contexts (group decision etc) should be examined in order to improve them. In parallel, non formal mathematical methods and design methods to avoid redundancies should be developed.

# Conclusions

According to its initial title, the aim of the research was to improve the definition of a measurable environmentally sustainable transport. It has been initiated and driven by the need to provide better methods and ways to represent environmentally sustainability concerns in connection with measurement, communication, monitoring, assessment and decision making related to transport.

Rather than looking at all the evaluation methods, including the most sophisticated ones as the full modelling, we focused on the indicators able to assess or represent the impacts of transport on the environment. Therefore the main aim has been to help strengthen the scientific and methodological foundations for taking environmental sustainability into account in the transport area through the use of indicators and indices, encompassing the full scope of environmental impacts, the full range of transport modes, and the full variety of transport policy, planning and decision making situations. The focus has thus mainly been on the scientific underpinnings of indicator identification, selection, building, and use for the transport and environment area generally.

The work accomplished during five years was based on a voluntary network (a COST action). It was mainly a state-of-the-art through a wide scientific literature review, together with working group meetings, conceptual developments, indicator assessment, survey, case studies and exchanges between scientists from natural and social sciences. Interdisciplinary has been an essential component of the work, allowing to consider indicators from the dual perspectives of natural and social sciences, and from the multiple perspectives of various research disciplines. It allows to consider at the same time the large variety of impacts on the environment, the processes linking a transport project, plan, policy or technology and the final targets as the human or the ecosystems, and the context of the impact assessment, i.e. the decision making in a wide meaning, the reasons and the ways indicators are used.

The work has approached indicator methods along three complementary methodological axes:

- indicators from a measurement as well as a decision making point of view
- indicators for individual impacts as well as joint consideration across impacts
- selection as well as building of indicators

Below are the **main findings**.

When the aim is to measure the impacts of transport on the environment, the first step is to know what are these impacts. Environmental impacts of transport

include a wide variety of negative influences on the environment in connection with construction, use and disposal of transport system components. There is limited availability of frameworks to describe fully these impacts. For that purpose, we developed a new approach through the concept of 'chain of causality', defined as a homogeneous process between the transport system (or any other human activity) and a final target of the impacts on the environment, made by one or several stages or steps. 49 causal chains have been identified and these should form a core of a systematic framework of environmental description and assessment for transport. The clear definition and description of each chain is the necessary solid ground for the search for corresponding indicators: With the help of a wide variety of scientific knowledge, each chain of causalities is here characterized in terms of transport source and final target as well as pathways and processes involved. The consideration of a comprehensive list of independent causal chains allowed us to give a precise definition of the term 'environment': Such definition appears necessary today, when the environmental issue is widely taken into account from local to international scale, but often without a precise knowledge of this field. This context is also especially important when taking into account the three pillars of the sustainable development, to express our concern to environment in comparison to the social or economic issues. The main limit of this framework is cultural: It is certainly adapted to Western societies, but could not necessarily be adapted to Eastern, African or other societies where the concept itself of environment can be fundamentally different or does not exist in this shape.

Our second topic was to define what an indicator of environmentally sustainable transport is, i.e. the type of tool we aim to use. It is a variable, based on measurements, representing potential or actual impacts on the environment, or factors that may cause such impacts, due to transport systems, policies, as accurately as possible and necessary. Such indicators are often necessary, because verified scentific models to fully describe interactions between transport activity and environmental impacts are not available or because simplifications are otherwise needed. There are many different types of indicators, each of which may be suitable to measure particular aspects or help decide on specific issues. There is hardly one indicator able to represent equally well all aspects of sustainable transport. In all cases, it is necessary to consider questions such as why the indicator is needed, what is to be measured, and how it should be done. Indicators can be applied for symbolic or strategic purposes as well, and decision making contexts may differ in a way that suggests different representations of sustainable transport. For example, if only one particular impact such a noise is on the agenda, indicators of other impacts may be considered irrelevant (although in fact they are not), or if a decision on a new technology is needed at an early stage before the full environmental impacts are known, indicators for pressures and state of the environment may have to be used.

Then, the dimensions and context of decision making appeared to be a suitable basis for choosing environmental indicators, because decision making context influences the perceived and actual needs for indicators and methods, but this is hard to systematize. Critical factors are likely to include the degree of consensus versus uncertainty regarding facts and values respectively. Indeed,

conflicts were said to be a 'normal feature' of transport decision making, which were, however, more or less strong, depending on the overall consensus on values and solutions. The application of structured processes for channelling and managing conflicts was suggested to be of great importance. Whereas in concrete project situations with little or no conflict they may serve as *quasi* decision makers, in situations of great conflict they are likely to only inform actors. Possible functional criteria for selecting suitable indicators include the decision making tier and related to this the stage in the policy cycle at which decision making is happening (strategic, tactic, operational), the transport modes covered, the administrative and functional boundaries, the spatial scale of the impacts, the type of formal requirements, the users and stakeholders involved as well as the timescale.

Based on this description of the context or the field of our research, we derived criteria and methods for the assessment and selection of environmentally sustainable transport indicators. These criteria were classified into three groups: measurement or representation, monitoring or operation, and management or application. Ten criteria were highlighted and equipped with interpretation and examples: validity, reliability, sensitivity, measurability, data availability, ethical concerns, transparency, interpretability, target relevance and actionability. A general and simplified approach for assessing indicators was proposed, along with a suggestion to undertake more specific indicator assessments where concrete planning situations or needs are taken into account.

Significant variety of available knowledge and operational indicators exists across the chains of causality. We exemplified indicator selection for seven chains, chosen to be qualitatively different: Some are short and easily grasped such as "noise" or "waste disposal" whereas some are long, complicated and characterized by multiple interacting inter-relationships, such as "greenhouse effect". There is a large variability between impacts in terms of research and indicator availability: The chain "greenhouse effect" is well described since substantial scientific effort has been put into clarifying its multiple and complicated chain steps, and far-reaching consensus has been reached on the scientific underpinning of the widely used indicator Global warming potential and of more recent ones. In contrast, the chain "waste disposal" has only relatively recently become subject to deeper scientific study, and existing indicators appear to cover only some of the chain steps. This chain, together with "noise" and "non-renewable resource use", is also an example of chains where there is a wide range of indicators for different types of usage. This in contrast to "loss of cultural heritage", where no indicator seems to have existed hitherto. Nevertheless, the application of assessment criteria to the indicators studied is highly subjective and should go on.

In a last step, we reviewed the methods to consider jointly indicators of several environmental impacts, either through aggregation, or through parallel consideration. Indicators become more uncertain, less transparent and leave more of the subjective value considerations in the hands of the experts as aggregation levels increase. Weights make explicit the objectives underlying the aggregation. Because they have a great impact on the results of an

aggregation, weighting models need to be made explicit and transparent. The evaluation of indicators resulting from the application of typical joint consideration methods has shown that they differ in their performance:

- Life cycle assessment methods such as the Ecological scarcity and the ReCiPe method appear to be medium to good performers regarding representation and operation issues and lower performers regarding application issues.
- The Material input per service-unit and the Ecological footprint are recommended for their operational character and the choice of a clear and well understandable assessment unit, however not for the non-additivity of their elements, at least according to what they are supposed to measure.
- Because of the variety of assumptions and methods, the economic indicators (external costs) do not appear to be transparent, and the political process to build collective and official values is to be considered as important as the economic methods themselves.
- The main methodological challenge regarding multi-criteria decision analysis methods does not appear to be the development of more sophisticated methods, but rather to support problem definition and design, and to adequately consider the different aspects of a decision making situation. These methods should provide a consistent framework whose principal aim is not to discover a solution, but to allow an actor taking part in the decision process either to shape, and/or to argue, and/or to transform his preferences. The focus must be on the quality of the process, which should be participatory in the context of sustainable development, in order to address the problems arising from complexity of systems, uncertainty, indeterminacy and multiple legitimate perspectives. As a consequence, the largest potential for multi-criteria decision analysis in decision making on sustainable development appears to lie in a combination of corresponding algorithms with participatory techniques.

Efforts to identify, develop and apply indicators for the impacts of transport on environmental sustainability meet with a number of **major challenges**, including:

- Differing world views and paradigms e.g. with regard to sustainability. This influences especially the substitutability (or additivity) between impact indicators, and between environmental and non environmental indicators, the legitimacy of stakeholders, experts and citizens to rank or weight the impact indicators.

- Questions of legitimacy of procedures to identify, build, select, weight, and apply indicators. Lacking transparency in this aspect may lead to suspicion and underuse of available environmental information.

- Dealing with the role of context for each step. The environmental context of the impacts matters in ways that can be taken into account by developing indicators in sufficient accordance with scientific understanding of the impact chains. The social, political and cultural contexts influence the need and use for indicators in ways that are much

less well understood, as it may affect everything from the framing of theories and facts about the environmental context, to the specific application in decisions.

The research carried out and presented in this Report has nevertheless **certain limits**:

- The research did not involve a sufficient range of scientists to undertake assessment of indicators for all causal chains, only a few were assessed. This can lead to development of concept failing to cover the variety of impact processes.

- There is a need to continue and complete the assessment of indicators for all the chains, involving wider circles of researchers and possibly users in the context of methods for scientific and societal validation.

- The interdisciplinary research is a necessity in the field of indicators of environmental sustainability in transport, but needs very long exchanges between disciplines, as the ways of thinking are different. The duration of the research was maybe too short to build efficient environmental indicators based on the whole set of knowledge and paradigms involved.

Finally, we give some **general recommendations** in terms of research policy and methods to take into account environmental issue in the transport sector, beside detailed research needs given in a specific chapter.

In connection with any transport assessment and decision making situation, the full list of environmental impacts should be consulted and analysed to allow the identification of a number of potential relevant impacts to consider in detail for the specific situation. It is important not to assume in advance that only a few impacts are of relevance. It is also important not to assume that one impact sufficiently represents all impacts, without assessing this specifically.

Better indicators measuring the impact of transport on the environment should be developed for most of the impacts, meeting the representation, operation and application criteria defined in this report. The ones urgently needing attention include health impacts, impacts on biodiversity and impacts on landscape quality, amongst others.

As the direct outputs of the transport activity, which represent the second step of the chain of causalities (emissions of noise, air pollutants, material consumption including energy, land consumption at least), are quite well known scientifically, it would be of high interest to consider them as input parameters of impact indicators. This field of research should be followed.

Methods for joint consideration of transport impacts should be applied with a high concern and high explicitness with regard to the appropriateness of the method for the particular situation. Each method has its limitations and advantages. The environmental impacts of transport often involve effects that are not easily taken into account by each current method without a significant loss of accuracy. The combination of various methods to support decision

making could answer this drawback. The review of methods in the present report should be consulted in connection with situations where a joint consideration is required.

Research in the actual use and application of indicators in practice is needed in order to gain better understanding of the extent to which transport planning, decision-making and implementation is under informed or even misled by the use of environmental indicators. There is a need to further develop criteria for systematic selection and application of joint consideration methods in connection with transport decision making.

There is a need to undertake in depth case studies about what actual use is made of indicators and joint consideration methods in practice, and to compare such actual use with recommendations, in order to help understand and improve indicator application in practice.

Transport and environment assessment suffers from a weak institutional foundation. Procedures and institutional frameworks should be established for the continued systematic review and assessment of environmental impact indicators for transport. Permanent structured exchanges are needed between researchers of the whole range of natural, human and social sciences necessary to build efficient indicator frameworks. If new research works do not take place, the use of environmental impact indicators in transport is likely to remain sporadic, incomplete, contested, and potentially misleading.

# Annex 1. Glossary of key terms

The glossary contains key non-self-evident terms used frequently in this report or each of its chapters. Its function is to present what is the meaning associated with key terms used in this report, not to provide a general dictionary review of possible meanings. In some cases a term is used an a slightly different way in separate chapters. In those cases both meanings are given, and the difference is explained. In some cases the glossary entries refer to a literature (e.g. dictionary) source for the terms used, in other cases the meaning was established within the project itself.

## Aggregated indicator

An indicator, composed of several sub-indicators not sharing a common characteristic or measurement unit. There seems to be no fundamental difference between 'composite' and 'aggregated' indicator. The first one seems to be used mostly for national level indicators, the second one for a wider range of applications, but this difference is not clear.

## Aggregation

Combination of different variables into a unique one.

## Annoyance

It is described like a multifaceted concept, regarding behavioural noise effects, like global disturbance and specific interfering with intended activities, but the term is also used to evaluate aspects like nuisance, unpleasantness, and getting on one's nerves (Guski *et al.*, 1999).

## Causality

Causality is the relationship between an event (the cause) and a second event (the effect), where the second event is a consequence of the first (Random House Unabridged Dictionary).

## Chain of causalities

An homogeneous process between the transport system (or any other human activity) and a final target of the impacts on the environment (resources, ecosystems, restricted human health, human well-being, man-made heritage). The process is made by one or several stages or steps, an output of the former playing the role of an input for the next.

## Composite indicator

As mentioned in Nardo *et al*. (2005), a composite indicator is the mathematical combination of individual indicators that represent different dimensions of a concept whose description is the objective of the analysis (see Saisana and

Tarantola, 2002). A composite indicator is formed when individual indicators are compiled into a single index on the basis of an underlying model.

### DALY

Disability Adjusted Life Years, i.e. the number of human life years lost when the health is affected. It extends the concept of potential years of life lost due to premature death to include equivalent years of 'healthy' life lost by virtue of being in states of poor health or disability. In so doing, mortality and morbidity are combined into a single, common metric.

### *Ecological footprint*

The Ecological footprint represents the area of Earth's productive land and water required to supply the resources that an individual or group demands, as well as to absorb the wastes that the individual or group produces, wherever is this area, given the prevailing technology and resource management practices (Wackernagel and Rees, 1996; Rees, 1996).

### *Environment*

In a first meaning, the environment is the context or the surrounding places of something well defined. In this report, the environment names the whole natural milieu, finally all the ecological issues (Maurin, 2009), i.e. the impact of the human activities on final targets in nature. The environment also includes the man made surroundings that influence well being, such as cultural heritage.

### *Environmental impact indicator*

An environmental impact indicator is a variable based on measurements, representing an impact of human activity on the environment, as accurately as possible and necessary.

### *Exergy*

Exergy expresses the quality of an energy source and quantifies the useful work that may be done by a certain quantity of energy.

### *Greenhouse gas or GHG*

Greenhouse gas is a gas which plays a role in the greenhouse effect. Six main greenhouse gases are considered within the Kyoto protocol: carbon dioxide $CO_2$, methane $CH_4$, nitrous oxide $N_2O$, and fluorine components HFCs, PFCs and $SF_6$. But some other gases are also greenhouse gases.

### *Habitat*

The habitat of a species means an environment defined by specific abiotic and biotic factors, in which the species lives at any stage of its biological cycle (EC, 1992).

### Habitat fragmentation

Fragmentation is a process in which a habitat becomes divided into units of smaller size known as patches; It is also characterised by a reduction in the total area the habitat occupies. The resulting patches may be very similar but may also have characteristics of their own, a consequence of their size, shape and boundaries etc. (Forman, 1995).

### Impact

Effect or consequence of something.

### Indicator

An indicator is a variable, based on measurements, representing as accurately as possible and necessary a phenomenon of interest.

### Indicator of environmental sustainability in transport

An indicator of environmental sustainability in transport is a variable, based on measurements, which represents potential or actual impacts on the environment - or factors that may cause such impacts - due to transport, as accurately as possible and necessary.

### Joint consideration

Taking into account of different parameters, either by considering them in parallel, or by aggregating them.

### Multi-criteria analysis

Multi-criteria analysis is an approach to contribute to decision making when the decision maker is faced with several options, called alternatives, has several points of view (or objectives), called criteria, and works with information qualitative or quantitative. These criteria may be partially contradictory (Pomerol and Barba-Romero, 2000). Multi-criteria decision analysis (MCDA) method aims at one of the following four goals, or "problematic":
−   find the best alternative
−   group the alternatives into well-defined classes
−   rank the alternatives in order of total preference
−   describe how well each alternative meets all the criteria simultaneously

### Nuisance

A person or thing causing inconvenience or annoyance (Oxford concise dictionary). In the environmental field, an impact on the environment when it is a perception, dealing with psycho-physics.

### Parameter

Synonym of variable, especially in environment and medicine, in the expressions function of variables $f(v_i)$, or function of parameters $f(p_i)$. In other words, what does enter into the formulation of a problem or a formulae.

### Perception

What is perceived by the human senses, the ability to see, hear, smell, taste, feel or become aware of something through the senses.

### Plan

The result of a preparation process, either by a public or private body, laying out a medium term course of spatial action (mainly addressing questions of where development or action should occur).

### PM10

Particulate matter less than 10 μm in diameter.

### Policy

The result of a preparation process, either by a public or private body, laying out a long-term course of direction (mainly addressing questions of why and what development or action should occur).

### PPPP

Policy, plan, programme and project.

### Programme

The result of a preparation process, either by a public or private body, laying out a medium to short term course of temporal action (mainly addressing questions of how and when development or action should occur).

### Project

A concrete development, e.g. a road bypass or a new motorway.

### Riparian

Any species evolutionarily adapted to be born, grow and live specifically on the banks of rivers under conditions of excessive moisture in the soil and perennial streams.

### Substitutability

Formal characteristic of several parameters, able to replace each other. The additivity infers the substitutability.

### Target

Milieu or part of a milieu which is impacted by a phenomenon.

# Annex 2. An example of impact assessment: Athens restriction ring

**Authors: A. Loster-Manka, K. Karkalis and G. Arapis**

The Athens traffic restriction ring is a traffic measure in order to alleviate environmental pollution, and the traffic congestion in the centre of Athens. It means that defined central traffic roads in the city of Athens are restricted to circulation by all private vehicles according to their matriculation plate last number. The exceptions are private cars owners who live inside the ring, rented cars, private cars used for special public service or emergency and finally all hybrid cars. Taxi and public buses have free access.

The ring started to be used in 1982 as a measure for the control of smog and atmospheric pollution in the Greek capital. Together with the "traffic ring" restriction of private vehicles, the use of diesel vehicles has also restricted since 1982. Only taxis equipped with diesel engines can move in the restriction ring.

The physical boundaries of the traffic restriction ring coincide with the centre of Athens and are defined by the traffic roots / Avenues covering a surface of 14.25 km$^2$ approximately (see Figure 28).

**Figure 28. Athens traffic restriction ring: the red line shows the boundaries of the ring**

The reason for the functional validity of the Athens traffic restriction ring needs to be verified on present days, because when the restriction ring was updated in the 80s there were some 400 000 cars in Athens (Wikipedia, 2009b). This number has increased continuously within last 20 years, changing the whole traffic structure of Athens.

The main objectives of the case study were focused on:

- an analysis of the case study consisting on an assessment of environmental effects of the limited traffic intensity area in the centre of Athens;
- to check if the Athens restriction ring meets its goals, i.e. if it alleviates atmospheric pollution and the traffic congestion in the centre of Athens.

### *Methodology*

In order to achieve the above objectives, the ex-post assessment has been done and the following indices / impacts have been used:

- data of concentration of pollutants ($NO_2$, $SO_2$, PM10, CO, $O_3$) from different monitoring stations located inside, near and outside the restriction ring;
- traffic volume from different avenues near the pollution monitoring stations, (vehicle per year);
- statistical share of passenger vehicles and trucks in a total number of cars registered in Athens.

Data of concentration of pollutants (MEPPPW, 2007; ESYE, 2007) due to the traffic in the Athens region have been collected and analyzed from 1986 up to 2007 for 5 districts, inside, near (1 km) and outside the restriction ring, in order to study the possible impact of traffic volume on air pollution. A comparison with the European limit values was made.

In the same manner the data of traffic volumes from different avenues near the pollution monitoring stations were collected in order to study changes and estimate future trends in traffic volume. A statistical analysis was carried out in order to evaluate changes in traffic flow between 1986 and 2006 and to make prediction of possible traffic changes in the next two years (2009-2011).

In order to estimate the vehicle emissions inside the restriction ring, the software COPERT IV was used (GDDKA, 2006; EEA, 2007). The calculation of vehicle emission has been made to have a rough assessment of the restriction ring ability to mitigate the concentration of pollutants inside the ring. The obtained results show a correlation between vehicle emission and pollution concentration. The comparison was made for average annual $NO_2$ concentration.

### *Results*

A comparison of traffic volume data showed that despite of an increase in the vehicle fleet in the greater Athens region these past decades (1980-2007),

the traffic volumes inside the Athens restriction ring remain relatively constant. On the other hand, for those observation points situated in traffic routes outside the ring an increment of traffic volume could be expected.

As regards the levels of pollutants monitored by the urban traffic stations inside the restriction eing, air pollution in central Athens exceeded internationally recommended safety levels despite an upgrade in car fleet technology due to the European emission standards. In case of the station outside the restriction ring, the levels of pollutants are close to the legislation limits.

**Figure 29. NO$_2$ concentration and traffic volume per year observed in the monitoring station in Athinas avenue (inside the Athens restriction ring)**
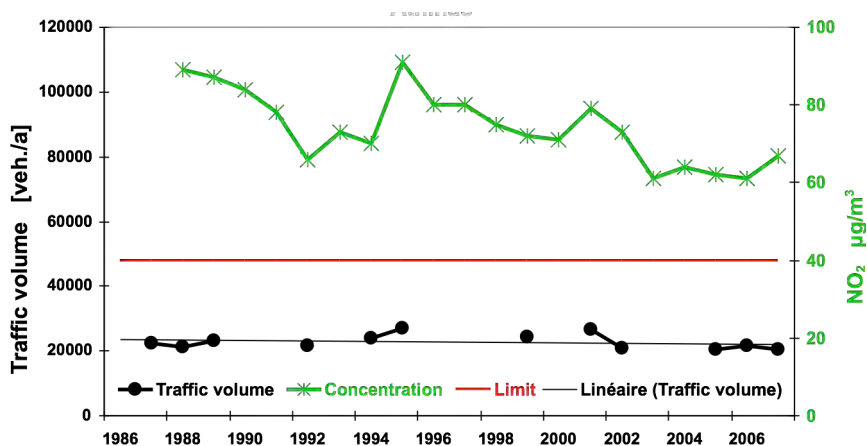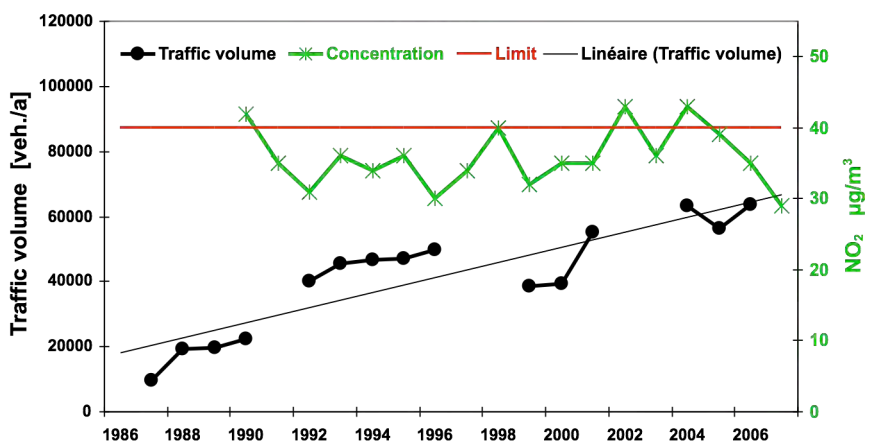


**Figure 30. NO$_2$ concentration and traffic volume per year observed in the monitoring station of Marousi (outside the Athens restriction ring)**



Comparing those data, it can be seen that the number of vehicles in central Athens has remained relatively constant while the level of concentration of pollutants exceeded the EU legislation limits. The concentration levels outside

the restriction ring are quite stable, below the EU limits while the traffic volume of vehicles seems to be increasing.

Figure 29 and Figure 30 show the above situation on the example of $NO_2$. The red line presents the legislation limit for $NO_2$.

The emission calculation shows that in central Athens there is a strong correlation between vehicle emission and pollutant concentration. The comparison was made for data (traffic intensity, average annual $NO_2$ concentration) from the same station, with a correlation factor of 0.91 (see Figure 31).

**Figure 31. Correlation between vehicle emission and pollutant concentration**
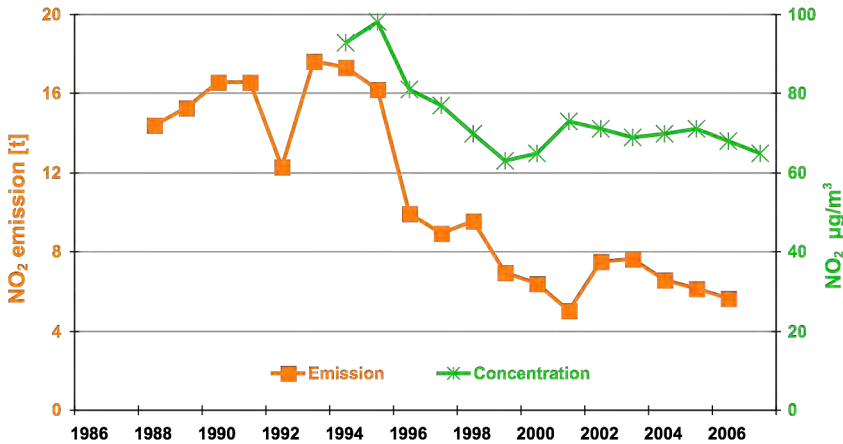


### Proposal

Regarding the Athens restriction ring as it was implemented as a policy measure in order to alleviate the environmental impacts, and based on above findings, it is proposed, instead of using an alternation of odd-even numbers, to make use of the European emission standards. Further more an improvement of the vehicles engine technology alone could prove to be insufficient in the future in Athens region, if not supported by other solutions (for example: expansion of metro lines, pedestrian zones, further development of the sustainable public transport, bicycle paths, parks).

### Conclusions

Following correlations were found: the number of vehicles in central Athens has remained constant while the concentration levels (e.g. $NO_2$), despite a significant decrease, still exceeds the EU legislation limits; the concentration levels outside the Athens restriction ring are below the EU limits while an increment of traffic volume was observed.

A strong correlation between $NO_2$ emission and $NO_2$ concentration, measured at the monitoring station located in the central Athens has been found.

Neither aggregative methods nor joint consideration methods and approaches of environmentally sustainable transport indicators in decision making were applied.

The conducted analysis showed significant environmental problems such as an increased danger caused by transport, lack of sustainable transport and sustainable understanding of transport and unconsidered management of environment in a relatively simple way.

### *Further needs*

This work must be integrated in the approach and methods of the joint consideration of environmentally sustainable transport indicators in decision making process, therefore additional data must be analyzed in this broader direction.

The study of The Athens restriction ring was considered in terms of chain of causalities (traffic volume $\rightarrow$ emission of pollutants $\rightarrow$ concentration of pollutants in the air due to the atmospheric conditions $\rightarrow$ and finally overall health effects).

The scale of transport impact on the environment was determined by the $NO_2$ concentration and then compared with the annual mean concentration value. This must be enlarged in order to take into consideration all emitted pollutants. According to sub-chapter 6.4.1 and Rabl (1999), among primary pollutants originating direct restricted health impacts on humans, the particulates (and especially PM10) are considered in most of the epidemiologic studies as the indicator of the pollution responsible for restricted direct health impacts, or in a more accurate wording, as an indicator of the cause of the impacts. There is a need to include in the study PM10 as an indicator since it would give the possibility of better evaluating health effects. However PM10 monitoring has been started recently and therefore it does not reflect as wide spectrum (20 years) as $NO_2$.

# Annex 3. The concept of sustainable transport

**Authors: P. Boulter and I. McCrae**

The Brundtland definition of sustainable development has been adapted to provide one definition of sustainable transport; for example, 'Sustainable transport meets the mobility needs of the present without compromising the ability of future generations to meet these needs.' Zietsman and Rilett (2002) described sustainable transport as an expression of sustainable development in the transport sector. Some more precise definitions of sustainable transport are given in Table 48, and these are in widespread use (often non cited) in the literature.

Much of the early work in the area of environmentally sustainable transport (EST) was conducted by OECD. In 1994 the OECD initiated an international project to define and chart a path towards EST. The overall objectives of the EST project were to provide an understanding of EST, including its implications and requirements, and to develop methods, instruments, strategies and guidelines to allow it to be realised. The so-called 'Vancouver Principles' of EST emerged at the 1996 conference *Towards Sustainable Transportation*. EST was defined as,

*'Transport that does not endanger public health or ecosystems and meets mobility needs consistent with (a) use of renewable resources at below their rates of regeneration and (b) use of non-renewable resources at below the rates of development of renewable substitutes'.*

An expanded qualitative definition would include recognition that EST is a concept for the longer term to be achieved through the attainment of several intermediate steps (OECD, 1996).

The OECD later refined the EST definition by expanding upon its basic principles and relating them to quantified international environmental and health criteria and targets (OECD, 2000). The revised definition is:

'A sustainable transport system is one that throughout its full life-cycle operation:

- allows generally accepted objectives for health and environmental quality to be met, for example, those concerning air pollutants and noise proposed by the World Health Organization (WHO);

- is consistent with ecosystem integrity, for example, it does not contribute to exceeding of critical loads and levels as defined by WHO for acidification, eutrophication and ground-level ozone; and

- does not result in worsening of adverse global phenomena such as climate change and stratospheric ozone depletion.'

## Table 48. Definitions of sustainable transport

| | |
|---|---|
| Richardson (1999) | A system in which fuel consumption, vehicle emissions, safety, congestion, and social and economic access are of such levels that they can be sustained into the indefinite future without causing great or irreparable harm to future generations of people throughout the world. |
| OECD (2002) | A system which provides safe, economically viable and socially acceptable access to people, places, goods and services while meeting generally accepted objectives for health and environmental quality, protecting ecosystems and minimising adverse impact on global phenomena such as climate change, stratospheric ozone depletion and the spread of persistent organic pollutants. Transport is environmentally sustainable if it does not endanger public health or ecosystems and meets mobility needs while using non-renewable resources below the rates of development of renewable substitutes and renewable resources below their rates of regeneration. |
| Transport Canada (2008) | A system that is safe, efficient and environmentally friendly. Sustainable transport is about integrating economic, social and environmental considerations into decisions affecting transportation activity. |
| Transportation Association of Canada (Duncan and Hartman, 1996). | A sustainable transportation system has the following characteristics:<br>(a) In the natural environment:<br>• It limits emissions and waste (that pollute air, soil and water) within the urban area's ability to absorb / recycle / cleanse.<br>• It provides power to vehicles from renewable or inexhaustible energy sources. This implies solar power in the long term.<br>• It recycles natural resources used in vehicles and infrastructure.<br>(b) In society:<br>• It provides equity of access for people and their goods, in this generation and in all future generations.<br>• It enhances human health.<br>• It helps support the highest quality of life compatible with available wealth.<br>• It facilitates urban development at the human scale.<br>• It limits noise intrusion below levels accepted by communities.<br>• It is safe for people and their property.<br>(c) In the economy:<br>• It is financially affordable in each generation.<br>• It is designed and operated to maximize economic efficiency and minimize economic costs.<br>• It helps support a strong, vibrant and diverse economy. |
| New Zealand Ministry for the Environment (2008) | Sustainable transport is about finding ways to move people, goods and information in ways that reduce its impact on the environment, the economy, and society. |
| Queensland Government (2008) | Sustainable transport allows for everyday activities such as:<br>• visiting our friends and families when we want to<br>• getting to work and conducting our business |

| | • accessing the goods, services and facilities we need. An environmentally sustainable transport system offers this in a way that benefits people while minimising the impact on the environment. |
|---|---|
| ECMT (2001) | A system which: • Allows the basic access and development needs of individuals, companies and society to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations. • Is affordable, operates fairly and efficiently, offers a choice of transport mode, and supports a competitive economy, as well as balanced regional development. • Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and uses non-renewable resources at or below the rates of development of renewable substitutes, while minimizing the impact on the use of land and the generation of noise. |

The OECD EST project ended in 2004.

According to Hall (2002; 2006) there is an international consensus that the concept of sustainable transport can be defined under the *Three E's* of environment, equity, and economy, although a wide range of issues is considered under each of the three areas (Table 49). The principles of sustainable transport are closely correlated with the definitions. The principles shown in Table 50 provide a more operational focus to the idea of sustainable transport (Hall, 2006).

A fourth 'pillar' included by Hall in Table 50 that is not explicitly identified by current definitions of sustainable transport is the role of (national, regional, and local) *governance*. Hall argued that national governance that ensures peace and development is a vital element of sustainable development. Hence, the fourth column in Table 50 identifies several core principles that can guide government action to support the objectives of sustainable transport and sustainable development.

**Table 49. A comprehensive definition of sustainable transport (Hall, 2006).**
**A sustainable transport system…**

| Environment | |
|---|---|
| *Health & environmental damage* | - minimises activities that cause serious public health concerns and damage to the environment; [a, b, d] |
| *Standards* | - maintains high environmental quality and human health standards throughout urban and rural areas; [a] |
| *Noise* | - minimises the production of noise; [b, c, d, e] |
| *Land use* | - minimises the use of land; [c, e] |
| *Emissions and waste* | - limits emissions and waste to levels within the planet's ability to absorb them, and does not aggravate adverse global phenomena including climate change, stratospheric ozone depletion, and the spread of persistent organic pollutants; [b, c, d, e] |
| *Renewable resources* | - ensures that renewable resources are managed and used in ways that do not diminish the capacity of ecological systems to continue providing these resources; [a, b, c, d, e] |
| *Non-renewable resources* | - ensures that non-renewable resources are used at or below the rate of development of renewable substitutes; [a, b, c, d, e] |
| *Energy* | - is powered by renewable energy sources; and |
| *Recycling* | - re-uses and recycles its components. [c] |
| **Equity / society** | |
| *Access* | - provides access to goods, resources, and services while reducing the need to travel; [a, c, e] |
| *Safety* | - operates safely; [a, c, e] |
| | - ensures the secure movement of people and goods; |
| *Intragenerational equity* | - promotes equity between societies and groups within the current generation, [c, e] specifically in relation to concerns for environmental justice; and |
| *Intergenerational equity* | - promotes equity between generations. [c, e] |
| **Economy** | |
| *Affordability* | - is affordable; [a, c, e] |
| *Efficiency* | - operates efficiently to support a competitive economy; [a, c, e] and |
| *Social cost* | - ensures that users pay the full social and environmental costs for their transport decisions. [a] |

[a] DoE (1996); [b] OECD (1997); [c] CSTC (1997); [d] OECD (2000); [e] European Council (2001)

## Table 50. Principles of sustainable transport (Hall, 2006)

| Environment | Equity / society | Economy | Governance |
|---|---|---|---|
| *Adopt*<br>- A precautionary and preventative approach to decision-making<br>*Avoid*<br>- Irreversible impacts<br>- Global climate change<br>- Pollution<br>*Encourage*<br>- Remanufacturing / re-use and recycling of transport vehicles and equipment<br>*Ensure*<br>- The proper disposal of transport-related toxic materials and waste<br>*Protect*<br>- Habitats / ecosystems and operate within their assimilative and regenerative capacities<br>- Biodiversity<br>- Environmental aesthetics | *Enhance*<br>- Safety<br>- Human health<br>- Social wellbeing / quality of life<br>*Promote*<br>- Equity / distributional fairness<br>- Access and choice<br>- Environmental justice<br>- Individual and community responsibility<br>- Meaningful employment in the transport sector | *Ensure*<br>- Transport services are affordable<br>- Transport is cost-effective<br>- Natural and financial resources are used efficiently<br>- Negative social and environmental costs are internalised (*i.e.* the polluter pays principle)<br>*Support*<br>- Trade and business activity that enhances productiveness and contributes to development | *Encourage*<br>- Technological innovation<br>*Ensure*<br>- Transparency and accountability<br>- Public and stakeholder participation<br>*Establish*<br>- Goals and performance objectives<br>*Support*<br>- Comprehensive and long-term planning<br>- Interagency and international cooperation<br>- The integration and co-optimisation of policy |

# Annex 4. Environmental impacts as listed by 12 references

**Author: R. Joumard**

The table gives also the correspondence with the list of processes proposed in section 2.4.2.

| Reference | Scope note | Resource impact | Climate impact | Corresponding chain in Table 13 on page 72 |
|---|---|---|---|---|
| USEPA (1996) | All impacts from transport | | pollutant emissions | |
| OECD (1996) | | use of non renewable resources | greenhouse effect | |
| Swedish EPA (1996) | | | greenhouse gases | |
| EC (2001a) | | | climatic factors | |
| OECD (2002) | All impacts from transport | use of natural resources | climate change | |
| EEA (2002) | | energy consumption | climate change | |
| Borken (2003) | | consumption of (energy) resources | climate change | |
| Ahvenharju *et al.* (2004) | | energy consumption | greenhouse gases | |
| Goger (2006a), Goger and Joumard (2007) | Impacts due to pollutant (grey: out of the scope) | consumption of solid raw materials | greenhouse effect | |
| Boy (2007) | | | climate change | |
| EC (2008) | | depletion of natural resources | climate change | |
| Calderon *et al.* (2009a) | From transport (grey: global; white: local / regional) | use of material resources / non-renewable energy consumption | climate change | 39 |
| Joumard and Nicolas (2010) | From transport (grey: irreversible; white: reversible) | non-renewable resource use, including energy | greenhouse effect | 42 |

| toxic release | highway and airport runoff | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | eutrophication of water | water | water quality | illegal / accidental discharge of oil by ships at sea | | discharge of oil, wastewater, waste at sea | eutrophication | water pollution | water pollution | water pollution | water quality / uses and regime |
| | | | | | | | runoff pollution | photochemical pollution | | | | regional air quality (smog) |
| | | urban air pollution, effects of metals, effects of POP | air, human health | air quality | photochemical smog | photosmog | emissions of air pollutants | Direct ecotoxicity | air pollution | air pollution | air pollution | local air quality |
| | | | | | human health | human health | | direct restricted health effects | | | | |
| stratospheric ozone depletion | | depletion of ozone layer | | | | stratospheric ozone depletion | | ozone depletion | | | ozone depletion | |
| | | 21, 22 | | 11 | | 12 | | 13, 14, 15, 16 | 19 | 23, 24, 25 | 26, 27, 28 | 29 |

The following is a cross-reference matrix (printed sideways on the page) comparing terminology across several reference sources. The content is grouped into three thematic blocks:

**Soil**

| Term | Reference(s) |
|---|---|
| sewage dumping | |
| release of de-icing compounds | |
| nitrogen saturation of soil | |
| soil | |
| protection of soil and landscape | |
| soil erosion | 37 |
| soil pollution | 23, 24, 25 |

**Waste**

| Term | Reference(s) |
|---|---|
| direct waste from vehicles | |
| waste | |
| non-cyclic material flows, waste and environmental hazardous residues | |
| waste | 40 |
| waste | |
| family waste, (nuclear risk?) | |
| growing waste | |
| waste production | 41 |

**Noise**

| Term | Reference(s) |
|---|---|
| noise | |
| ambient noise | |
| noise | |
| noise | |
| noise | |
| noise | |
| noise | |
| noise pollution | |
| noise nuisance / vibration | 5 |
| light and noise nuisances | 1, 2, 3, 4 |

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | light emissions | | | | | | 45 |
| | | | | | safety | | | | | | traffic accidents | traffic safety | 6 |
| roadkill, wildlife collisions | | | | | | | collisions with wildlife | | | | | | 7 |
| | perturbation of regional ecosystems | | | severance | fragmentation of ecosystems and habitat | protection of nature and landscape | fragmentation of land | | | | barrier effects / land fragmentation | | 35, 36 |
| habitat disruption and land take by infrastructure | landtake | exploitation of land and water | | | landtake | | hardening of surfaces | | | | land uptake | landuse | 31, 33 |
| | | | | | | | | | | | hydrologic / hydraulic risks | | 30 |
| | | | | | | | | sensitive pollution | | | | | 8, 9, 10 |
| | negative aesthetic effects | landscape | | visual impacts | | protection of nature and landscape | | | | landscape degradation | landscape / visual effects / aesthetics / cultural heritage | visual qualities of landscape / townscape | 38 |

| | 18, 30, 34 | 34 | 31 | 32 | 17 | 18 | 49 | 46 |
|---|---|---|---|---|---|---|---|---|
| introduction of non-native species | damages to equipments | | | | | | hazardous material incident | introduction of non-native species |
| | | | perturbation of regional ecosystems | | acidification | | | introduction and spread of alien organisms |
| | material assets | including architectural and archaeological | pressures on areas of special conserv. interests | | acidification of water and soil | | | |
| | | historical / archaeol. / nature conservation | fauna and flora, biodiversity | | | | | |
| | | | loss of biodiversity | acidification | | | | |
| | | | | | acidification | | | |
| | | | | | | | polluting transport accidents | introduction of non-native species |
| | degradation of common man-made heritage | degradation of historic man-made heritage | areas, proximity of tr. infras. to designated nature | (direct ecotoxicity) | acidification | | | |
| | | | | fauna and flora degradation | | | nuclear risks | |
| | | | | loss in biodiversity | | | natural and man made disasters | |
| | man-made heritage | | biodiversity and protected areas | | | | technological and natural hazards | |

| habitat disruption by wakes / anchors | | | | | | | damage of underwater habitats | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | 26 |
| - | - | - | - | - | - | - | - | - | - | - | - | - | 20, 43, 44, 47, 48 |

# Annex 5. Some characteristics of the main chains of causalities of environmental impacts

**Authors: R. Joumard, S. Mancebo Quintana and M. Chiron**

| Sources | | | | First step of the chain (pressure) | N. Identification | Irreversibility for individuals (II) or species (IS), distance and time scale from the source to the final impact | Chain of causalities (states and processes) and *final impact* (main scientific disciplines involved: P: Physics; C: Chemistry; LS: life sciences; HS: human and social sciences) | n | Target | | | | | |
| Infrastructure | Energy | Vehicle | Traffic | | | | | | Resource | Ecosystem | Health | Human well-being | Man-made heritage | Earth |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ** | | | *** | Emission of noise | I. Noise | km, hour | Diffusion (P), *disappearance of quiet areas* (HS) | 1 | | | | HWB | | |
| | | | | | | | Diffusion in air, absorption or reflection by surfaces (P), *annoyance to people* (HS) | 2 | | | | HWB | | |
| | | | | | | | Diffusion in air, absorption or reflection by surfaces (P), *health effects* (LS) | 3 | | | H | | | |
| | | | | | | | Diffusion in air, absorption or reflection by surfaces (P), *animal health* (LS) | 4 | | ES | | | | |
| | | ** | | Emission of vibration | II. Vibrations | 100 m, hour | Heavy traffic (HDV, trains) vibrations, mass diffusion, *damage to buildings* (P), *annoyance to people* (HS) | 5 | | | | HWB | M | |
| | | | *** | Kinetic energy | III. Accidents | II, m, - | *Human fatalities and injuries* (LS) | 6 | | | H | | | |
| | | | | | | II and IS, m, - | Fauna collision from small insects to big mammals or fish, damage by anchors. *Loss of biodiversity* (LS) | 7 | | ES | | | | |
| | ** | | *** | Emission of VOC | IV. Sensitive air pollution | 100 m, hour | Odours: Dispersion in the atmosphere (P) at short distance, *sensitive pollution perceived by smell* (HS) | 8 | | | | HWB | | |
| | * | | ** | Emission of PM | | 100 m, year | Soiling: Dispersion in the atmosphere (P) at short distance, deposition on surfaces (P), chemical reactions with materials (C), *sensitive pollution perceived by the sight* (HS) | 9 | | | | HWB | | |
| | * | | ** | Emission of PM and atmospheric pollutants | | 100 m, day | Visibility: Dispersion in the atmosphere (P) at mid distance, chemical reaction in air (C), *sensitive pollution perceived* by the sight (HS) | 10 | | | | HWB | | |

| | | | Emission of | Category | Scale / Dispersion | Effects | # | R | ES | H | M | E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | * | *** | Emission of particles and air pollutants | V. Direct toxicity of air pollutants | II, possible IS, km, day | Dispersion in the atmosphere and water (P), sometimes dispersion in food (P), | direct restricted health effects (LS) | 11 | | | H | | |
| | | | | | | | direct ecotoxicity on fauna and flora (LS) | 12 | | ES | | | |
| * | * | *** | Emission of NOx, NMVOC, CO. | VI. Photo-chemical pollution | II, possible IS, IS for cultural legacy, Mm, day | Dispersion in the atmosphere (P), chemical reaction (C) and therefore increase of photochemical pollutants as ozone, | health effects (LS) | 13 | | | H | | |
| | | | | | | | loss of crop productivity (LS) | 14 | R | | | | |
| | | | | | | | ecotoxicity on fauna and flora (LS) | 15 | | ES | | | |
| | | | | | | | deposition on surfaces (P), chemical reactions with materials (C), loss of man-made heritage (HS), destruction of archaeological, classical or historic remains (P), loss of cultural heritage (HS) | 16 | | | | M | |
| | | | | | | | Secondary effects: - greenhouse gas (see greenhouse effect) - acidification (see acidification) | - | | (ES) | | (M) | |
| * | * | *** | Emissions NOx, SO₂ | VII. Acidifi-cation | II, possible IS, Mm, year | Dispersion in the atmosphere (P), possibly wet and dry deposition, chemical reaction (C) and therefore formation of acid compounds, | (incl. secondary effect of photochemical pollution) Dispersion in air, water and soil (P), ecotoxicity on fauna and flora (LS). Decrease of ecosys-tem health, loss of biodiversity | 17 | | ES | | | |
| | | | | | | | deposition on surfaces (P), chemical reactions with materials (C). Loss of man-made heritage (HS), destruction of archaeological, classical or historic remains (P), loss of cultural heritage (HS) | 18 | | | | M | |
| * | | *** | Emissions NOx | VIII. Eutro-phication | II, possible IS, 10 km, year | Dispersion in the atmosphere and water (P), increase of plant biomass (LS), anoxia of fauna and flora (LS) | | 19 | | ES | | | |
| ** | * | *** | Emission of aerosols | IX. Dimming | 100 km and earth, day to month | Dispersion in the atmosphere (P), physical reactions (P) and sometimes chemical reactions (C), regional dimming, regional temperature decrease, global climate changes, destruction or modification of habitat for fauna, flora and humans (P), change in food chain (LS), economic losses (HS)... | | 20 | | | | | E |
| | | * | Emission of halogen compounds | X. Ozone depletion | II, earth, year | Dispersion in the atmosphere (P), chemical reaction (C) depletion of ozone layer, increase of UV on the earth (P), | health effects (LS) | 21 | | | H | | |
| | | | | | | | ecotoxicity on fauna and flora (LS) | 22 | | ES | | | |

| | | | | Category | | Scale | Effect | Impact | # | R | ES | H | HWB | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | | | * | Emission of gaseous, liquid or solid pollutants | XI. Pollution of soil, surface waters and groundwaters | II, possible IS, 100 km, year | Dispersion in the soil and water (P), | ecosystem health (LS) | 23 | | ES | | | |
| | | | | | | | | health effects (LS) | 24 | | | H | | |
| | | | | | | | | recreational areas forbidden (HS) | 25 | | | | HWB | |
| * | | ** | | Emission of liquid or solid pollutants | XII. Maritime pollution | II, possible IS, 100 km, year | Dispersion in the sea (P), | ecosystem health (LS) | 26 | | ES | | | |
| | | | | | | | | health effects (LS) | 27 | | | H | | |
| | | | | | | | | recreational areas forbidden (HS) | 28 | | | | HWB | |
| *** | | | | Land take, floods | XIII. Hydraulic changes and risks | II, possible IS, km, year | Hydraulic changes, | modification of fauna, mainly, and flora habitat (P, LS) | 29 | | ES | | | |
| | | | | | | | Hydraulic risks, | destruction of natural and human habitat (P) | 30 | | ES | | | |
| *** | * | * | | Land take by infrastructure building | XIV. Land take | II, possible IS, km, year | Waterproofing of areas, loss of natural habitats (LS) | | 31 | | ES | | | |
| | | | | | | | Waterproofing of areas, degradation of ecosystems (P, LS), loss of biodiversity. | | 32 | R? | ES | | | |
| | | | | | | | Waterproofing of areas, loss of available land for humans, modification of outdoor recreation areas (SS) | | 33 | | | | HWB | |
| | | | | | | | Destruction of archaeological, classical or historic remains (P), loss of cultural heritage (HS) | | 34 | | | | | M |
| *** | | | * | Land take | XV. Habitat fragmentation | II, possible IS, km, year | Cutting of the fauna habitat (LS). Loss of ecosystem health, loss of biodiversity | | 35 | | ES | | | |
| | | | | | | | Cutting of the human habitat, reduction of living areas of people (LS, HS) | | 36 | | | | HWB | |
| * | | | | Land take | XVI. Soil erosion | II, possible IS, km, year | Transformation of natural areas, decrease of ecosystems (P, LS). Loss of biodiversity | | 37 | | ES | | | |
| *** | | | | Land use | XVII. Visual qualities of landscape/townscape | IS, km, year | Infrastructure presence, annoyance (HS), especially if the landscape is of high quality | | 38 | | | | HWB | |
| * | * | * | *** | Non-renewable resource use | XVIII. Non-renewable resource use | IS, Mm, 100 years | Decrease of metals, fossil fuels availability for the future (P) | | 39 | R | | | | |
| ** | * | ** | | Waste disposal | XIX. Non-recyclable waste | II, possible IS, (nuclear waste), all | Includes the nuclear waste. Dissemination in the nature (P), impacts on health and ecosystems (LS) | | 40 | | ES | H | HWB | |
| | | * | | Emission of waste | XX. Direct waste from vehicles | 100 m, year | Waste thrown directly from the vehicles, accumulation. Annoyance (HS), especially if the landscape is of high quality | | 41 | | | | HWB | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | * | * | *** | Emission of air pollutants | XXI. Greenhouse effect | II, IS, earth, century | Dispersion in the atmosphere (P), sometimes chemical reaction (C) and therefore creation of secondary pollutants, increase of the greenhouse effect (P), climate change (P), sea level increase (P), *destruction or modification of habitat for fauna, flora and humans* (P), *change in food chain* (LS), *economic losses* (HS)... | 42 | | | | | E |
| * | | | * | Emission of waves | XXII. Electro-magnetic pollution | II, km, year | Diffusion in the atmosphere, absorption or reflection by surfaces (P), *health effects* (LS) | 43 | | | H | | |
| | | | | | | | *ecosystem health* (LS) | 44 | | ES | | | |
| ** | | | ** | Emission of light | XXIII. Light pollution | Possible II, Mm, min | Modification of the luminosity of the open space (P), modification of the biota behaviour (LS), *effects on biota health* | 45 | | ES | | | |
| | | | ** | Introduction of non-native species | XXIV. Introduction of invasive alien species | IS, earth | Small individuals, seeds… disperse and survive (LS), modification of biocenosis. *Loss of biodiversity* | 46 | | ES | | | |
| * | | | * | Transmission of pathogens | XXV. Introduction of illnesses | km, year | The traffic itself introduces pathogens through people and goods, *health effect and impact on ecosystem health* | 47 | | ES | H | | |
| | | | * | Risk of fire | XXVI. Fire risk | II, possible IS, 10 km, year | Fire ignition by sparks, matches… or accidents. *Destruction of natural and human habitat* (P) | 48 | | ES | H | HWB | |
| | ** | | ** | Industrial accidents | XXVII. Techno-logical hazards due to transport | II, possible IS, km to earth, day to century | Industrial accidents, included of nuclear power plants. Dispersion in the atmosphere, soil and water (P), *biological impacts on humans and biota* (LS) | 49 | | ES | H | | |

# Annex 6. Description of the 49 chains of causalities

### *Chain 1. Disappearance of quiet areas*

**C. Camusso**

The presence of transport infrastructure makes a change into the environment not only in terms of exposed residents but also in general terms of quality of urban areas and quality of soundscape. The construction of a new infrastructure or a change in the traffic condition makes an increase of noise and an alteration of the anthropic background noise level. The suggestions given by the European Directive 49 2002 to monitoring the main European cities could give information about the exposed people but also on the extension on the territory of the sound quality. In some cases the national legislation gives rules to preserve the sound quality of the territory and to reduce the noise exposure of the people. For example, in Italy the Italian norms D.M. 8/3/91 and D.P.C.M. 14/11/97 provide to classify the territory in six different acoustic classes, each with different noise limits depending on the use of the territory: residential, public, industrial, etc.

Some studies showed that the access to a quiet area or a green area could decrease the annoyance produced on the residents (Ohrstrom *et al*., 2006; Gidlof-Gunnarsson and Ohrstrom, 2007). The benefit of having access to a quiet side of one's dwelling averages 30-50 % for different disturbances, corresponding to a 5 dB reduction in $L_{Aeq,24h}$ levels at the most exposed side (Ohrstrom *et al*., 2006).

In other study the results show a strong relationship between annoyance and sound levels and that access to a quiet side of the dwelling reduces the annoyance by 10-20 %, depending on the sound level from road traffic at the most exposed side (Berglund *et al*., 2004).

In the WHO meeting (2003), the importance of the resident to access on quite areas is showed. in particular it is suggested to use the "population having access to quiet areas (within a 500 m distance)" like an indicator to describe that characteristic of the urban environment. One of the issues behind noise pollution was the ability of having access to quiet when desired. This indicator could be a tool at the disposal of local authorities, who want to establish quiet zones (WHO, 2003). The description of the indicator suggested by WHO (2003) is reported in Table 51.

## Table 51. Indicators related to the quiet areas (WHO, 2003)

| Population having access to quiet areas (in a 500 m distance) - DP**S**EEA | |
|---|---|
| **Issue** | **Noise** |
| Definition of indicator | Percentage of the population with pedestrian access to a public "quiet area" within a range of 500 metres |
| Underlying definitions and concepts | Quiet areas – areas where no major transport infrastructure and no industrial noise source exist. It has to be freely accessible to the general public. It is not necessarily an open area. A quiet area is not a silent zone, it is more to be seen as a relaxing "soundscape" area. It includes:<br>- Public parks, gardens, …<br>- Pedestrian areas<br>- Museums<br>- Riverside pedestrian paths<br>- Cultural centres, public libraries<br>- Others. |
| Specification of data needed | Noise maps;<br>Identification of quiet zones and their area;<br>Surveys of population. |
| Data sources, availability and quality | The ideal way to calculate this indicator would be with a geographical support of the city. The quiet areas have to be identified and the population living within a 500 m range has to be estimated trough the national census, questionnaires, data of the local authorities etc. |
| Computation | $$P_{qa} = \left[ \left( \sum_{qa=1}^{n} P_{qai} \right) * 100 \right] / P_{agglom}$$<br><br>$P_{qa}$ – population living in 500 m range from a quiet area<br>qa – quiet area a<br>$P_{qai}$ – estimated population living in the defined quiet areas "qa"<br>$P_{agglom}$ – total population of the agglomeration (town or city) |
| Units of measurement | Percentage of urban population. |
| Scale of application | Local. Can be translated at national level. |
| Interpretation | One of the issues behind noise pollution is also related to the ability of having access to quietness when desired. The assessment of the population exposed should be crossed with existence of quiet and easily accessible public spaces when people can "rest" and relax". This indicator could also provide a tool for local authorities to establish quiet zones. |
| Linkage with other indicators in the set | *State, Exposure*: Population exposed to various noise level ranges per source.<br><br>*Effects:* Percentage of population suffering from sleep disturbance; Percentage of the population highly annoyed by traffic noise at day time.<br><br>*Actions:* Monitoring of implementation / installation of noise barriers; Population living in areas for which there is a plan taking into consideration of acoustical aspects.<br><br>*Aggregated indicator:* Noise composed indicator. |

### Chain 2. Annoyance and sleep disturbance to people due to noise

**C. Camusso**

Noise can produce a number of social and behavioural effects as well as annoyance and sleep disturbance. These effects are often complex, subtle and indirect and many effects are assumed to result from the interaction of a number of non-auditory variables (WHO, 1999b).

The definition of the annoyance is one of the key aspects for the surveys' design and for the methodology used to describe the impact; some studies have been carried out to understand how the scientific community defines the "annoyance" (Guski *et al*., 1999).

In general the "annoyance" is described like a "multifaceted concept, regarding behavioural noise effects, like global disturbance and specific interfering with intended activities, but the term is also used to evaluate aspects like nuisance, unpleasantness, and getting on one's nerves" (Guski *et al*., 1999).

The latter, like is explained by the above authors, "seem to contain negative evaluations of the noise source as well as a feeling of tension and little power in answering the stress".

The complexity of the problem is showed by real cases where equal levels of different traffic and industrial noises cause different magnitudes of annoyance. The reason of these results is because annoyance in populations varies not only with the characteristics of the noise, including the noise source, but also depends on a lot of other variables. Some of the above variables are physical, in general easy to measure, while other are psycho-physical, more subjective, depending on the context and the characteristics of the residents, and they are not easy to interpret (Fields, 1993; Miedema and Vos, 1999).

To take into account the different human perceptions of the sounds at the different frequencies, all the noise data are evaluated in dB(A) where the "A" refers on correction (called also "filter") of the spectrum of the noise where different bands are "weighted" in different way. Other filters are used in acoustic, "B" and "C", but for environmental acoustic application the most used filter is the "A".

The correlation between noise exposure and general annoyance is much higher at group level than at individual level. Noise above 80 dB(A) may also reduce helping behaviour and increase aggressive behaviour. There is particular concern that high-level continuous noise exposures may increase the susceptibility of schoolchildren to feelings of helplessness (Evans and Lepore, 1993, as mentioned in WHO, 1999b).

Stronger reactions have been observed when noise is accompanied by vibrations and contains low frequency components, or when the noise contains impulses, such as with shooting noise. Temporary, stronger reactions occur when the noise exposure increases over time, compared to a constant noise exposure. In most cases, $L_{Aeq,24h}$ and $L_{dn}$ are acceptable approximations of noise exposure related to annoyance. However, there is growing concern that

all the component parameters should be individually assessed in noise exposure investigations, at least in the complex cases. There is no consensus on a model for total annoyance due to a combination of environmental noise sources.

Sleep disturbance is a major effect of environmental noise. It may cause primary effects during sleep, and secondary effects that can be assessed the day after night-time noise exposure. Uninterrupted sleep is a prerequisite for good physiological and mental functioning, and the primary effects of sleep disturbance are: difficulty in falling asleep; awakenings and alterations of sleep stages or depth; increased blood pressure, heart rate and finger pulse amplitude; vasoconstriction; changes in respiration; cardiac arrhythmia; and increased body movements (Berglund and Lindvall, 1995 as mentioned in WHO, 1999b). The difference between the sound levels of a noise event and background sound levels, rather than the absolute noise level, may determine the reaction probability. The probability of being awakened increases with the number of noise events per night. The secondary, or after-effects, the following morning or day(s) are: reduced perceived sleep quality; increased fatigue; depressed mood or well-being; and decreased performance (Ohrstrom, 1993; Passchier-Vermeer, 1993; Pearsons *et al*., 1995; Pearsons, 1998 as mentioned in WHO, 1999b).

For a good night's sleep, the equivalent sound level should not exceed 30 dB(A) for continuous background noise, and individual noise events exceeding 45 dB(A) should be avoided (WHO, 1999b). In setting limits for single night-time noise exposures, the intermittent character of the noise has to be taken into account.

This can be achieved, for example, by measuring the number of noise events, as well as the difference between the maximum sound level and the background sound level. Special attention should also be given to: noise sources in an environment with low background sound levels; combinations of noise and vibrations; and to noise sources with low-frequency components.

### Chain 3. Effects on human health (restricted meaning) of noise

**C. Camusso**

Some studies have been made to understand the effect of noise on health. In particular, the "Guidelines for Community Noise" edited by World Health Organization (WHO, 1999b) contains a lot of information about the noise problem. In this paragraph some of the above information are reported.

*Hearing impairment (WHO, 1999b)*

Hearing impairment is typically defined as an increase in the threshold of hearing. Hearing deficits may be accompanied by tinnitus (ringing in the ears). Noise-induced hearing impairment occurs predominantly in the higher frequency range of 3000-6000 Hz, with the largest effect at 4000 Hz. But with increasing $L_{Aeq,8h}$ and increasing exposure time, noise-induced hearing impairment occurs even at frequencies as low as 2000 Hz. However, hearing

impairment is not expected to occur at $L_{Aeq,8h}$ levels of 75 dB(A) or below, even for prolonged occupational noise exposure.

Worldwide, noise-induced hearing impairment is the most prevalent irreversible occupational hazard and it is estimated that 120 million people worldwide have disabling hearing difficulties. In developing countries, not only occupational noise but also environmental noise is an increasing risk factor for hearing impairment. Hearing damage can also be caused by certain diseases, some industrial chemicals, ototoxic drugs, blows to the head, accidents and hereditary origins. Hearing deterioration is also associated with the ageing process itself (presbyacusis).

The extent of hearing impairment in populations exposed to occupational noise depends on the value of $L_{Aeq,8h}$, the number of noise-exposed years, and on individual susceptibility. Men and women are equally at risk for noise-induced hearing impairment. It is expected that environmental and leisure-time noise with a $L_{Aeq,24h}$ of 70 dB(A) or below will not cause hearing impairment in the large majority of people, even after a lifetime exposure. For adults exposed to impulse noise at the workplace, the noise limit is set at peak sound pressure levels of 140 dB, and the same limit is assumed to be appropriate for environmental and leisure-time noise.

The main social consequence of hearing impairment is the inability to understand speech in daily living conditions, and this is considered to be a severe social handicap. Even small values of hearing impairment (10 dB averaged over 2000 and 4000 Hz and over both ears) may adversely affect speech comprehension.

*Speech intelligibility (WHO, 1999b)*

Speech intelligibility is adversely affected by noise. Most of the acoustical energy of speech is in the frequency range of 100-6000 Hz, with the most important cue-bearing energy being between 300-3000 Hz. Speech interference is basically a masking process, in which simultaneous interfering noise renders speech incapable of being understood. Environmental noise may also mask other acoustical signals that are important for daily life, such as door bells, telephone signals, alarm clocks, fire alarms and other warning signals, and music.

Speech intelligibility in everyday living conditions is influenced by speech level; speech pronunciation; talker-to-listener distance; sound level and other characteristics of the interfering noise; hearing acuity; and by the level of attention. Indoors, speech communication is also affected by the reverberation characteristics of the room. Reverberation times over 1 s produce loss in speech discrimination and make speech perception more difficult and straining. For full sentence intelligibility in listeners with normal hearing, the signal-to-noise ratio (i.e. the difference between the speech level and the sound level of the interfering noise) should be at least 15 dB(A). Since the sound pressure level of normal speech is about 50 dB(A), noise with sound levels of 35 dB(A) or more interferes with the intelligibility of speech in smaller rooms. For vulnerable groups even lower background levels are needed, and a reverberation time

below 0.6 s is desirable for adequate speech intelligibility, even in a quiet environment.

The inability to understand speech results in a large number of personal handicaps and behavioural changes. Particularly vulnerable are the hearing impaired, the elderly, children in the process of language and reading acquisition, and individuals who are not familiar with the spoken language.

*Physiological Functions (WHO, 1999b)*

In workers exposed to noise, and in people living near airports, industries and noisy streets, noise exposure may have a large temporary, as well as permanent, impact on physiological functions. After prolonged exposure, susceptible individuals in the general population may develop permanent effects, such as hypertension and ischemic heart disease associated with exposure to high sound levels. The magnitude and duration of the effects are determined in part by individual characteristics, lifestyle behaviours and environmental conditions. Sounds also evoke reflex responses, particularly when they are unfamiliar and have a sudden onset.

Workers exposed to high levels of industrial noise for 5–30 years may show increased blood pressure and an increased risk for hypertension. Cardiovascular effects have also been demonstrated after long-term exposure to air- and road-traffic with $L_{Aeq,24h}$ values of 65–70 dB(A). Although the associations are weak, the effect is somewhat stronger for ischemic heart disease than for hypertension. Still, these small risk increments are important because a large number of people are exposed.

*Mental illness (WHO, 1999b)*

Environmental noise is not believed to cause mental illness directly, but it is assumed that it can accelerate and intensify the development of latent mental disorders. Exposure to high levels of occupational noise has been associated with development of neurosis, but the findings on environmental noise and mental-health effects are inconclusive. Nevertheless, studies on the use of drugs such as tranquillizers and sleeping pills, on psychiatric symptoms and on mental hospital admission rates, suggest that community noise may have adverse effects on mental health.

*Performance (WHO, 1999b)*

It has been shown, mainly in workers and children, that noise can adversely affect performance of cognitive tasks. Although noise-induced arousal may produce better performance in simple tasks in the short term, cognitive performance substantially deteriorates for more complex tasks.

Reading, attention, problem solving and memorization are among the cognitive effects most strongly affected by noise. Noise can also act as a distracting stimulus and impulsive noise events may produce disruptive effects as a result of startle responses.

Noise exposure may also produce after-effects that negatively affect performance. In schools around airports, children chronically exposed to aircraft noise under-perform in proof reading, in persistence on challenging puzzles, in

tests of reading acquisition and in motivational capabilities. It is crucial to recognize that some of the adaptation strategies to aircraft noise, and the effort necessary to maintain task performance, come at a price.

Children from noisier areas have heightened sympathetic arousal, as indicated by increased stress hormone levels, and elevated resting blood pressure. Noise may also produce impairments and increase in errors at work, and some accidents may be an indicator of performance deficits.

*Cardiovascular diseases*

Risk assessment of cardiovascular diseases from transport noise in EU and Switzerland was showed that there is sufficient evidence for the association between community noise and *ischemic heart diseases*, and limited / sufficient evidence for the association between community noise and *hypertension*. Exposure on high levels of noise could make some increase on blood pressure, heart rate and vasoconstriction (WHO, 1999b).

## Chain 4. Noise and wildlife

**C. Camusso and A. Meszaros-Kis**

Noise and vibration are known as such an environmental impact factor on wildlife that affects several animals significantly, while it leaves others 'untouched'. Higher taxons that have developed nervous systems and communicate with voice are generally affected, although in a varying degree. Besides, noise (and vibration in the case of animals living below ground surface) is considered physiological stress factor and its signs were showed both *in vitro* and *in situ* researches. Most studies aimed at mammals and birds, hence the whole impact course was revealed firstly at these animal groups.

Some documents highlight the influence of noise among animal behaviourists and conservation biologists (Warren *et al*., 2006), the streets noise could conditions the density of some animal species around the infrastructure, in particular for some bird species (Forman and Alexander, 1998; Peris and Pescador, 2004). In the above document some hypotheses are reported on that effect: hearing loss, increase in stress hormones, altered behaviours, interference with communication during breeding activities, differential sensitivity to different frequencies, and deleterious effects on food supply or other habitat attributes.

Traffic (mainly highway) noise masks vocal communication of birds and it encumbers mate attraction, social cohesion, navigation and other basic behaviour forms. Male birds cannot keep their territories and the background noise can have influence on prey detection. Predators can approach nests and the adult birds more easily, because prey animals cannot use their hearing to detect them in time. All this results in reduced reproduction of the exposed population thus the survival chance of the community will decrease. Traffic noise seems to be serious stress factor at several mammal and bird species. The restless and distressed animals have less energy for other life functions and their individual survival chance will also decrease.

Some of the effects induced by noise on animals are indirect, for example some research had carried out that noise makes some interference on the animals' communication making problem on their "reproductive signal" or "alert signal" (Reijnen and Foppen, 2006; Bee and Swanson, 2007). Furthermore, some of songbird species start singing earlier in the morning before rush hour peaks and thus avoid unfavourable communications conditions (Bergen and Abs, 1997 as mentioned in Reijnen and Foppen, 2006).

Other studies show that, as a response to noise load, species adapt their song in terms of volume and frequencies probably to avoid the masking effect on their song (Patricelli and Blickley, 2006).

## *Chain 5. Vibrations*

### A. Meszaros-Kis

As a vehicle moves along, vibrations are generated in the road and in adjacent buildings by the interaction of the wheels and the road surface and by direct acoustic transmission through the air (Hajek *et al*., 2006).

The vehicle movement generates waves in the road, which are transmitted through the ground to adjacent buildings. The waves transmitted through the air are known to produce movements of windows and doors.

However, these movements are normally not great enough to cause structural damage but the waves may create disturbance by rattling windows and doors and the effect will be more noticeable in buildings situated close to roads (Crispino and D'Apuzzo, 2001).

It has been found that ground vibrations produced by road traffic are unlikely to cause perceptible structural vibrations in buildings located near to well-maintained and smooth road surfaces (see Table 52).

**Table 52. Ambient vibration levels due to passing trucks (averaged values)**

| Location | Peak particle velocity (mm/s) | | |
|---|---|---|---|
| | Radial | Vertical | Transverse |
| 3 metres from carriageway | 0.3 | 0.9 | 0.2 |

The ground vibration from the operation of the new road would be expected to be orders of magnitude less than that required to cause disturbance (about 1 mm/s) or structural damage (> 8 mm/s). The vibration will be less than that caused by the surfaces of the existing road.

## *Chain 6. Effect of traffic accidents on human health*

### M. Chiron

According to WHO's Global Burden of Diseases Project for 2004 (WHO, 2004; 2009a), traffic crashes caused over 1.27 million deaths that year, that is to say 2.2 % of deaths. While road traffic death rates in many high-income countries have stabilized or declined in recent decades, data suggest that in

most regions of the world the global epidemic of traffic injuries is still increasing. It has been estimated that, unless immediate action is taken, road deaths will rise to an estimated 2.4 million fatalities per year (3.6 % of deaths) in 2030.

Injuries are also an important cause of disability, for example according to the Rhône registry of road accidents casualties, the number of deaths equals the number of long-term impairments among survivors in France (12.6/100 000 per year, 1996-2004) (Amoros *et al*., 2008).

These deaths, and impairments even more, concern mostly young people.

The total amount of motorized road transport, as well as its speed have an impact both on vehicle occupants and vulnerable road users' safety. An increase in average speed is directly related both to the likelihood of a crash occurring and to its severity. Safe speed thresholds vary according to different types of road, types of collision and road users, with their inherent vulnerability. Reducing the volume of motorized traffic on roads being used by vulnerable road users can also reduce exposure to the risk of crash. Investment in infrastructure is required, that allows pedestrians and cyclists to walk and cycle safely.

The system approach to road safety recognizes that the human body is highly vulnerable to physic force and that humans make mistakes. Subsequent measures must concern safe speeds, safe vehicles (and their safety devices), safe road and road-sites, as well as road rules, education and information.

### Chain 7. Animal collision: Animal fatalities

**R. Joumard**

Aside from human safety, vehicle damage and animal welfare considerations, collisions of wild animals with the vehicles that travel on the roads may have significant impacts on animal fatalities and thus on the population dynamics of species living adjacent to roads (Malo *et al*., 2004; Saeki and Macdonald, 2004; Rampa *et al*., 2005). They can adversely affect the viability and sustainability of roadside wildlife populations (Carey, 2002). Big mammals are concerned as deers, boars or panthers, but also smaller ones, birds (Capitani *et al*., 2007), amphibians and insects.

### Chain 8. Odours

**R. Joumard**

Odours is a part of sensitive pollution, perceived by smell. Transport is a source of odours due to the emissions of $SO_2$ and of low molecular weight volatile organic compounds. The concentrations of odorous pollutants can be very low, lower than the detection threshold of analysers. The perception by smell is due to physiological, psychological and social phenomena. The level and the quality of the odour depend on the component, on its concentration but mainly on the concentration variation over time, on personal physiological parameters, on his personal history, but also on collective culture parameters (Joumard, 1982; Moch and Roussel, 2000; CNRS, 2003; Goger, 2006a).

### Chain 9. Soiling

**R. Joumard**

Surfaces of our environment are more or less dirty: It is the result of deposition on the surfaces of particles generated by man's activity but also by natural activity. It depends on the type of surface and on the meteorology. The traffic is responsible for direct particulates emission by exhaust and by wear of tyres and other vehicle components, but also for emission by recirculation of particulates present on the road by mechanical effect.

As an annoyance, this impact depends on psychological and firstly on cultural parameters. It is a sensitive pollution perceived by the sight (De Boer *et al.*, 1987; Moch and Roussel, 2000).

### Chain 10. Visibility

**R. Joumard**

The vehicles emit particulate matter made with carbon, hydrocarbons, sulphate etc. These particles are dangerous for health when they are fine or ultrafine (less than 10 $\mu$m diameter), and are then not visible. The visible particles are larger and do not impact directly health. The perception by the sight of these large particles is an annoyance: It was, with odours, one of the first causes of complaint of the urban inhabitants when diesel vehicles did emit a lot of particulates (Joumard *et al.*, 1984). It is here a short distance visibility.

An other type of visibility is the mid-distance one, present over the cities. It is due to the presence of large and fine particles together with gaseous pollutants over each big city (Mathai, 1990). Such impact is nevertheless very rarely mentioned in Europe, but is a main part of the air pollution issue in North America. As the physical presence of the pollution is similar in Europe and North America, the difference comes from a different perception between populations, due to psychological or cultural differences.

### Chain 11. Direct restricted effects on human health of air pollutants

**R. Joumard and M. Chiron**

The World Health Organization (WHO) defined in 1948 health as being "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". The restricted health can be defined as the absence of disease or infirmity, without taking into account the well-being. Therefore a health impact is termed restricted, in reference to WHO's definition, when it is a disease or infirmity. On the other hand psychological aspects are taken into account through the sensitive pollution – odours, soiling, visibility, i.e. the chains 8, 9 and 10.

An health impact is termed direct, when it is due to primary pollutants (emitted), and not to secondary pollutants, produced by physico-chemical transformations. The restricted health impacts due to photochemical pollution, acidification or ozone depletion are excluded from the direct restricted health

impacts, because the chains of causalities are very different and they are not directly due to primary pollutants. They are taken into account respectively in the chains 13, 17 and 21.

A direct restricted health impact of air pollutants is a disease directly linked to emitted pollutants.

Recently a working group of the French ministry of health selected the hazardous compounds to take into account for the health risk assessment of road infrastructures, after considering a long list of atmospheric pollutants (Chiron *et al*., 1996; Cassadou *et al*., 2004; Krzyzanowski *et al*., 2005).

A high number of components impact the human health. They are emitted mainly in the exhaust pipe, but also by evaporation of the fuel. The wear of the tyres and of other vehicle components are with the re-circulation of deposed particulates secondary sources of atmospheric pollutants. The pollutants are then dispersed in the vicinity according to the wind speed and direction, local topography and the atmospheric stability.

At an individual level, the health impacts occur mainly when the concentrations are quite high, i.e. in bad atmospheric conditions and near the main sources, and among groups at risk (e.g. pregnant women, infants, children, elderly people, but also people with specific diseases). At the community scale, the mean concentrations are much lower, but the exposed people (or the concerned days) are much more numerous. This results in the fact that most community health effects are attributable to low concentrations days or locations.

The public health impact depends thus not only on the concentration of the pollutants, but also on the density of the population exposed, the type of population exposed (groups at risk), and the toxicity of each pollutant.

### Chain 12. Direct ecotoxicity on fauna and flora of air pollutants

**R. Joumard**

The atmospheric pollutants which are ecotoxic are approximately the same than those contributing to health impacts. The literature seems not to distinguish today the long term impacts from the short term ones, probably because of the lack of available information. Among the main ecotoxic impacts, are related mainly the drop in crop output for the plants, and respiratory diseases, drop in fertility, cancers and some cases of fatalities for the animals (Huijbregts, 1999).

### Chain 13. Health effects of photochemical pollution

**R. Joumard, K. Karkalis and M. Chiron**

Photochemical pollution is characterised by the creation of photochemical oxidants. The photochemical oxidants are a secondary pollutant, which means that they are not directly emitted by transport infrastructures for example, but they are the result of photochemical reactions from primary pollutants directly emitted in the atmosphere. The pollutants originating the photochemical

pollution are the non-methanic volatile organic compounds (NMVOC), the carbon monoxide (CO) and the nitrogen oxides (NOx). The production of the tropospheric ozone and of other photochemical pollutants (aldehydes, ketones, nitric acid, peroxyacetyl nitrate or PAN) results from a non-linear chemical process (Figure 32). In particular, the ratio of VOC and NOx concentrations determines the conditions of production of the photochemical pollutants. Beyond the production of tropospheric ozone, the most important secondary impacts to be taken into account concern first the living beings, then the buildings (Derwent *et al.*,1998; Flandrin *et al.*, 2002 ; Goger, 2006a; EEA website).

**Figure 32. Scheme of photochemical pollution, and isopleths of ozone production according to NOx and NMVOC concentrations, according to Flandrin *et al.* (2002)**
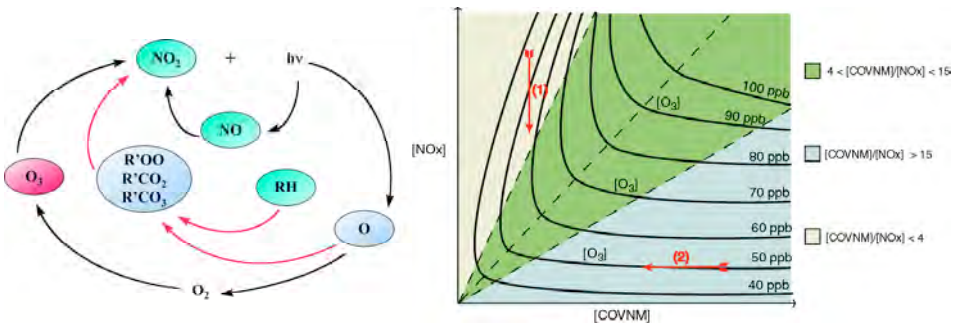


Because ozone is considered as the main indicator of the photochemical pollution, the toxicity of this pollutant for the humans is far to be the most studied (CSHPF, 1996). The oxidizing properties of this gas lead after a short term exposure to an inflammatory reaction, with the release of various pro-inflammatory transmitters, which can lead to negative effects especially on the eyes and lungs. The impacts on the subjective morbidity, i.e. the declared symptoms by the subjects, are eye irritation and nasal and throat irritation, and the appearance, especially after effort, of thoracic discomfort, breathlessness, cough, or also pains after deep inspiration. Ozone decreases for the asthmatic the reactivity threshold to allergens to which he/she is sensitive, and therefore favours asthma attacks or makes the clinical expression of the disease worse (Goger, 2006a).

### Chain 14. Loss of crop productivity due to photochemical pollution

**K. Karkalis and G. Arapis**

Photochemical pollutants (see description in chain 13 above) essentially affect population and fauna (deleterious effects on eyes and lungs), and flora (necrosis, acceleration of senescence, and influence in forest withering) (Calderon *et al.*, 2009a). Air pollutants can react in the atmosphere, forming secondary pollutants (ozone, atmospheric acids, etc.) affecting crop plant physiology (necrosis, inefficiency in carbon assimilation, acceleration of senescence, photosynthesis

disturbance, pronounced reductions in stomatal conductance, grain yield reduction, nutritional reduction of the quality of seeds etc.) (Goger, 2006a).

Photochemical pollution can reduce growth in many major crop plants (Table 53). For example low level ozone can have potential negative impacts on the agricultural production of some varieties of Maize (*Zea mays L*) even if maize is generally considered tolerant (Karkalis, 2007).

**Table 53. Low level ozone sensitive crops (Cofala *et al*., 2001)**

| Tolerant crops | Slightly sensitive crops | Sensitive crops | Very sensitive crops |
|---|---|---|---|
| maize<br>barley<br>raspberries<br>strawberries<br>leaf crops<br>cabbages<br>olives<br>sugar beet | pasture grass<br>sorghum<br>oats<br>rye<br>millet<br>rice | wheat<br>potato<br>tomato<br>sunflower<br>soybeans<br>beans<br>grapes<br>most tree fruits | melons carrots<br>cucumbers<br>onions<br>hops<br>flax<br>hemp<br>oil seeds |

## Chain 15. Ecotoxicity on fauna and flora of photochemical pollution

**K. Karkalis and G. Arapis**

The ecotoxicity on fauna and flora of photochemical pollution (see description in chain 13 above) can affect fauna (harmful effects on the respiratory system), and flora (necrosis, acceleration of senescence, and influence in forest withering). This process is also characterized by the creation of photochemical oxidants whose negate impacts are not restricted only to organism level but also to the higher levels of organization such as populations, communities, and ecosystems. Photochemical pollution can represent a negative impact on agricultural production in most major crop plants especially plants oriented where the epigeous parts of the crops are edible or destined for commercial use. The production of domestic animals can be affected as well as human health (Arapis, 1999; Arapis *et al*., 2000; Saitanis *et al*., 2004; Goger, 2006a; Karkalis, 2007).

## Chain 16. Loss of cultural heritage due to photochemical pollution

**F. Kehagia, K. Karkalis and G. Arapis**

Photochemical pollution (see description in chain 13 above) is recognized as the main agent responsible for the physical and aesthetic damage of the historic buildings by causing structural decay (CETS, 1982; Cicek *et al*., 2009). Photochemical pollution can affect paint and metals of various buildings of cultural interest. The loss in terms of cultural legacy is significant especially in southern Europe where the annual medium temperatures and sunlight are high.

### Chain 17. Decrease of ecosystem health, loss of biodiversity due to acidification

**R. Joumard and F. Kehagia**

Nitrogen oxide and sulphur dioxide are transformed into acid compounds that acidify the natural environment up to 1000 km away from the point of emission.

The acidifying pollutants are the nitric and sulphuric acids ($HNO_3$, $H_2SO_4$), which emit ions $H^+$ in the environment. The precursors of sulphuric and nitric acids come on the one hand from natural emissions of ammonia ($NH_4$), from oceanic spray ($HCl$), from volcanic emissions ($SO_2$, $H_2S$) and from volatile vegetation acids (isoprene, terpenes). They come also from the combustion of fossil fuels, giving $SO_2$ (responsible for the formation of $H_2SO_4$), $NO_x$, (responsible for the formation of $HNO_3$) and other products (responsible for the formation of $HClO_3$). The precursors can be transported up to 1000-2000 km away from the point of emission. They are trapped at the surface of the water droplets in suspension in the atmosphere or in clouds, and are transformed into sulphuric and nitric acids. The water droplets carry the acids they contain to the soil during the rainfalls (Potting *et al*., 1998).

Acidification can effect the natural environment (acidification of soil and water), flora (decrease of productivity, increase of the vulnerability of vegetal species, forest withering, loss of biodiversity), fauna and population (disappearance of certain species of fauna due to diminish or the loss of food resources, effects on eyes and lungs), and man-made environment (destruction of cultural areas) (Calderon *et al*., 2009a).

Acidification can first decrease the pH of the springs and ground waters. The animal species (batrachians, amphibians, crustaceans, fishes, molluscs, insects, micro-organisms) and the vegetal species (aquatic plants, plankton etc) have more or less serious alterations according to the environment acidity. Globally, the animal species are more vulnerable than the vegetal species. The main impacts are a decrease of the vegetal output and an increase of the vulnerability of the species to dryness, heavy winds, snow weight, insects, diseases... (Fuladi, 2002). An outstanding impact on the vegetation of acidification is its role in the forest decline, which depends also on predisposing factors (old subjects, poor soils, accumulation of acids), of inducing factors (climatic stress, especially repeated dryness) and of worsening factors (pathogenic mushrooms, pests, necrosing action of ozone at the foliaceous level) (Landmann, 1991).

### Chain 18. Deterioration of historical buildings and other cultural assets due to acidification

**F. Kehagia, K. Karkalis and G. Arapis**

Long-term exposure of acid sensitive materials (see description in chain 17) used in building construction and in monuments (e.g., zinc, marble, limestone, and some sandstone) can result in surface corrosion and deterioration. Monuments tend to be the most vulnerable because they are usually not as protected from rainfall as most building materials (Bresser, 1990; McCormick, 1997).

Photochemical pollution can have adverse atmospheric effects on marble and other calcareous stones. More in particular the concentrations of photochemically formed nitrates in the atmosphere of central Athens measured per example on the Parthenon have been found to be as high as in other polluted cities with adverse effects on human cultural legacy (Sikiotis and Kirkitsos, 1995) The negative effects of acidification are more felt in northern European cities due to the cool cloudy climate that is typical of this regions. The loss of cultural heritage is relevant but difficult to estimate.

### Chain 19. Eutrophication

**K. Karkalis and G. Arapis**

*Definition*

Eutrophication can be defined as a process of pollution that occurs when a lake or stream becomes over-rich in plant nutrient; as a consequence it becomes overgrown in algae and other aquatic plants. The plants die and decompose. In decomposing the plants rob the water of oxygen and the lake, river or stream becomes lifeless. Nitrate fertilizers which drain from the fields, nutrients from animal wastes and human sewage are the primary causes of eutrophication. They have high biological oxygen demand (BOD) (EEA website).

*Environmental effects*

Eutrophication is now recognized to be one of the important factors contributing to habitat change and to the geographical and temporal expansion of some harmful algal bloom species. Eutrophication has the main effect of tropical imbalance. The consequence is a proliferation of high levels of phytoplankton biomass in stratified water bodies, which can lead to an increased amount of algae that consume abnormal quantities of oxygen near the bottom of the water body. The nutrients involved are: nitrogen (N) phosphorus (P) silica (Si). Human activities (transport emissions included ($SO_2$, NOx, $NH_3$, and volatile organic compounds VOC) can cause an increase of these nutrients breaking the ecological balance in the water and in the aquatic ecosystems. The characteristics of the eutrophication processes in reservoir and lakes are quite specific in the semi-arid areas of the EU. Not only do the problems derived from eutrophication affect both the quality of water for irrigation and human consumption, but they also have an adverse effect on the river and reservoir fauna. An increase in nutrients (nitrogen and phosphorus), and thus eutrophication in semi-arid areas, is enhanced by temperature and light, which are the two predominant factors in biological production. Phosphorus is usually the main nutrient responsible for freshwater eutrophication, whereas nitrogen is the primary nutrient causing eutrophication of coastal areas and seas. Therefore these large transport related inputs of nitrogen and phosphorous to water bodies can lead to eutrophication, causing ecological changes that result in loss of plant and animal species, and affect the use of water for human consumption and other purposes. Near highways, for example, we have an enhancement of $NH_3$ and $NO_2$ air concentrations by up to 300 % compared to rather background sites situated at approximately 500 m from the traffic source. There are estimations of dry deposition rates, which

showed corresponding gradients of $NH_3$ and $NO_2$ (Karkalis, 2007). Eutrophication can affect also the soil. Soil eutrophication is caused by an increased content of nitrates in the soil that can lead to plant alterations and endanger many plant species (Gilbert *et al.*, 2005; Karkalis, 2007).

*Negative Aesthetic effects*

Due to Eutrophication that can immerge on large surface waters, per example by algae: *taxa Phaeocystis*, we can have a production of mucus, which when disturbed gives origin to brownish / greenish foam on the surface of the water.

## Chain 20. Dimming

**R. Joumard**

Global dimming is the gradual reduction in the amount of global direct irradiance at the Earth's surface that was observed for several decades after the start of systematic measurements in the 1950s. The effect varies by location, but worldwide it has been estimated to be of the order of a 4 % reduction over the three decades from 1960–1990 (Wikipedia, 2009a). Since the mid-1980s, visibility has increased over Europe, consistent with reported European "brightening," but has decreased substantially over south and east Asia, South America, Australia, and Africa, resulting in net global dimming over land (Wang *et al.*, 2009). It is thought to have been caused by an increase in particulates such as sulphate aerosols in the atmosphere due to human action, and especially due to the vehicle traffic. It is thought that global dimming was probably due to the increased presence of aerosol particles in the atmosphere caused by human action (Denman and Brasseur, 2007). Clouds intercept both heat from the sun and heat radiated from the Earth. Their effects are complex and vary in time, location, and altitude. Usually during the daytime the interception of sunlight predominates, giving a cooling effect; however, at night the re-radiation of heat to the Earth slows the Earth's heat loss.

## Chain 21. Health effects of ozone depletion

**R. Joumard and K. Karkalis**

The stratospheric ozone layer is located between 10 and 50 km above the Earth's surface and contains approximately 90 % of all atmospheric ozone. The main chemicals that are depleting stratospheric ozone are chlorofluorocarbons (CFCs), which are used in refrigerators, aerosols, and as cleaners in many industries, and halons which are used in fire extinguishers. The damage is caused when these chemicals release highly reactive forms of chlorine and bromine (EEA, website).

The destruction of stratospheric ozone is caused by various factors and substances. The pollutants precursors of ozone depletion are the halogenous components and mainly the chlorofluorocarbons (CFC), and their substitutes, the hydrochlorofluorocarbons (HCFC), then the hydrofluorocarbons (HFC), together with trichloroethan, halons and methylbromide. The transport sector should be responsible of less than 1 % to the ozone depletion, all sources taken

into account. The halogenous hydrocarbons are going up progressively in the atmosphere, then they are converted during the austral winter into their molecular form $Cl_2$ and $Br_2$. When the spring arrives, the molecules are quickly dissociated into chlorine and bromine atoms, destroying quickly and suddenly the ozone layer.

Most modern courtiers today have abolished or reduced the use of these substances but unfortunately the damage already done by man is calculated to persist for many years. In southern European countries in particular those that present a high frequency of clear skies and elevated temperatures, stratospheric ozone depletion can lead to increased amounts of photochemical smog

The initial impact of the ozone depletion is the decrease of the ozone layer width, mainly at the poles, which is regenerated in some years. Stratospheric ozone depletion can represent a potentially serious problem for the Earth's ecosystems, since the ozone layer in the stratosphere protects most organisms from the sun's invisible to the human eye ultraviolet radiation. If increased levels of ultraviolet radiation penetrate inside the Earth's atmosphere, this can cause various problems to the living organisms terrestrial or aquatic (Karkalis, 2007). The impacts on the human health and on the living beings generally speaking are not well known, but correlations are shown between an increasing UV B exposure and the increase of the skin cancers for instance (Académie des sciences, 1998; Goger, 2006a), specially for people engaged in open air activities.

### Chain 22. Ecotoxicity on fauna and flora of stratospheric ozone depletion

**K. Karkalis and G. Arapis**

The ultraviolet rays of the sun due to ozone depletion (see chain 21 above) can alternate the photoperiod of various plants, create genetic damage and accelerate mutations due to protein synthesis damage (Karkalis, 2007). In particular in Northern Europe if the constant stratospheric ozone depletion, could lead to an Arctic ozone hole, this would probably have negative effects on the health of plants, crop production, and domestic animal production compromising therefore the food supply (EEA, 1995; EEA website).

### Chain 23. Effects on ecosystem health of pollution of soil, surface waters and groundwater

**L. Folkeson**

Transport, industrial production and other human activities cause the emission of pollutants of various types such as: hydrocarbons and other organic compounds; oxides of carbon, nitrogen and sulphur; heavy metals; salts; and particulate matter. Some pollutants are disintegrated or transformed into other chemical compounds, others persist. Via aerial or water-borne transport, the pollutants reach environmental compartments, among others soil, surface waters and groundwater. Soil and water constitute sinks of many pollutants.

Accumulating to toxic concentrations, pollutants such as heavy metals and polyaromatic hydrocarbons may cause detrimental effects to soil and water biota and disrupt ecosystem processes.

### Chain 24. Health effects of pollution of soil, surface waters and groundwater

**L. Folkeson**

Via aerial or water-borne transport, the primary and secondary pollutants produced by human activities reach among others soil, surface waters and groundwater, that are sinks of many pollutants (see chain 23).

Toxic compounds such as heavy metals, polyaromatic hydrocarbons and salts may reach concentrations in drinking water high enough to cause effects on human health. Pollutant concentrations in crops, especially leafy vegetables, from polluted environments may reach levels toxic to humans upon consumption.

### Chain 25. Recreational areas forbidden due to pollution of soil and surface waters

**L. Folkeson**

In environments heavily contaminated by e.g. industrial activities or agriculture, toxic substances in surface waters may reach such concentrations or algal blooms resulting from eutrophication may be so abundant that the use of the waters for bathing and other recreational purposes may be constantly or temporarily restricted, or even forbidden, by authorities.

### Chain 26. Effects on ecosystem health of maritime pollution

**L. Folkeson**

Industrial production, agriculture, road traffic, shipping, sewage discharge and other societal activities may be so intense that parts of the sea become heavily polluted. Examples are the Baltic and some coastal areas of the North and the Mediterranean Seas. Nitrogen and phosphorus compounds, hydrocarbons and heavy metals are typical marine contaminants. Especially nitrogen and phosphorus compounds may cause heavy algal blooms. The break-down of the algal biomass will cause oxygen depletion, especially in deeper sea layers, which is detrimental to fish and other marine animals. Large quantities of pollutants accumulate in sediments of contaminated waterbodies. Wakes, especially from large and high-speed ships in shallow waters, and the use of anchors may cause turbulence in sediments. This mobilises pollutants again becoming available to biota. Wakes and anchors also cause direct mechanical damage to benthic biota and their habitats.

### Chain 27. Health effects of maritime pollution

**L. Folkeson**

Industrial production, agriculture, road traffic, shipping, sewage discharge and other societal activities may be so intense that parts of sea become heavily polluted. Examples are the Baltic and some coastal areas of the North and the Mediterranean Seas. Nitrogen and phosphorus compounds, hydrocarbons and heavy metals are typical marine contaminants. Concentrations of hydrocarbons

and heavy metals such as mercury in fish and other seafood may reach levels detrimental to humans upon consumption.

### Chain 28. Recreational areas forbidden due to maritime pollution

**L. Folkeson**

Where extremely contaminated, coastal areas may be so loaded with contaminants that their use for bathing, fishing and other recreational activities may be temporarily of permanently forbidden.

### Chain 29. Hydraulic changes

**L. Folkeson**

Road and railway infrastructure is often accompanied by the construction of banks and cuttings and the diversion or rerouting of streams. Also, road or rail constructions cause changes to the groundwater level and the groundwater regime. Extensive waterproofing in urban areas impedes downward transport of runoff water and contributes to water regime becoming modified. Such alterations in the hydrology may, in the short or long run, cause a permanent change of terrestrial or wetland ecosystems. Some areas may become subject to drier conditions (increased drainage), others to wetter (e.g. more frequent flooding). Such changes in the water regime may gradually cause modifications to the ecosystems, evidenced by changes in the composition of vegetation and fauna. Damage may also be caused to buildings and other constructions.

### Chain 30. Hydraulic risk

**L. Folkeson**

The occurrence, frequency and intensity of floods is influenced by climate change and also landuse changes such as deforestation. Severe floods can bring about deterioration or destruction of natural and human habitats as well as constructions such as transport infrastructure and buildings.

### Chain 31. Loss of natural habitats due to land take

**K. Karkalis and G. Arapis**

*Definition*

The area of land that is 'taken' by infrastructure itself and other facilities that necessarily go along with the infrastructure, such as filling stations on roads and railway stations (EEA website).

*Environmental effects*

The terrestrial transport land uptake has an impact on wildlife habitats. It can affect also indirectly biodiversity due to fragmentation, disturbance and barrier effects (because of infrastructure intrusion on the landscape that increases negatively from roads, fast railroads to motorways). Land uptake in the form of

sealing of the soil has a devastating impact on the soils capacity to sustain plant life in the future. Land uptake due to maritime and air transport infrastructure represents a small loss in natural habitats relatively to terrestrial transport. The biodiversity loss due to ports, airports is less relevant in respect to terrestrial transport (Seiler, 2002; Trocmé *et al*., 2003).

*Agricultural effects*

The loss of natural habitats due to land uptake can have an impact in agriculture production and especially in sustainable agriculture since the degradation of biodiversity can also lead in a lack of resistant agricultural ecotypes. The loss of the natural habitats can also be followed by an increase in plant pathogens and parasites. Land is a limited resource for which the agriculture sector, wild life designated areas, urban development and the transport sector all compete. Even if the transport sector takes relatively much less land form agriculture and the environment, it is not to be underestimated especially if it regards modern multilane highways. These structures have an effect that goes beyond their conventional physical boundaries. Sealing almost deactivates the soil for future agricultural use and can create various hydraulic problems since the surface and thus the soil beneath it is now hermetically closed to rainwater. Another factor that needs considering here is the compacting effect of various heavy duty agricultural vehicles that render the soil impenetrable to the natural elements needed to maintain soil fertility (Karkalis, 2007).

## Chain 32. Degradation of ecosystems due to land take

### K. Karkalis and G. Arapis

In resent years there has been an increase in public and political recognition of the importance of maintaining and preserving the high quality of ecosystems and the negative consequences caused by the increasing number of natural habitats sacrificed in order to make space for the various types of human activities. There is an increasing number of research in the literature, such as the Stern review, that has made it clear that the degradation of ecosystems is not only an environmental dispute but it is also an enormous threat towards human well-being, and economic prosperity. Urban development, transport, industry, intense mechanized agricultural production and biofuels are among the factors that contribute to land uptake, ecosystem degradation, loss of biodiversity, as well as an alteration of the characteristic rural social environment (CEC, 2006; EEA, 2004a; 2006). In particular regarding the transport sector and heavy mechanized agricultural production, this is caused manly due to the fragmentation of ecosystems and the intense monoculture and mechanized character of modern agronomical production systems and the possible use of artificially created species or GMOs (Seiler, 2002; Eastham and Sweet, 2002). The most significant ecosystem threat involving in particular biofuels is the possibility for biofuel production to expand agriculture's advance on indigenous plants. For example, a tepid enforcement of land protection laws like in Malaysia, Indonesia and Brazil have all probably contributed to the proliferation of industrial agricultural production with negative impacts to the natural ecosystems (Keeney and Nanninga, 2008).

### Chain 33. Modification of outdoor recreation areas, due to land take

**K. Karkalis, G. Arapis and F. Kehagia**

The loss, modification and the increasing inaccessibility of outdoor recreation areas (small parks, preservation areas, wild areas and free space) due to land uptake by transport and other more productive infrastructure can represent a significant impact on physical and mental health (Godbey, 2009). Large cities that lack significant outdoor recreation areas, pedestrian areas and bicycle lanes forcing their inhabitants to a sedentary way of life (being forced to use the car instead of walking and video games or the television instead of outdoor recreation especially for children) can lead to negative health effects like obesity, hart diseases, psychosomatic diseases, diabetes etc. Most people (and children) of the twenty-first century live in overpopulated and air polluted cities where physical activity and recreation is becoming more and more restricted (AAP, 2004; Tamburlini et al., 2002; DCR, 2007). Even in those cases where recreation areas are left with their physical boundaries unmodified by the ever increasing demand in land, these areas can still suffer a negative modification due to the surrounding air and noise pollution, and also by the degradation of the adjacent landscape due to the presence of industrial infrastructure. This tendency if not inversed will probably lead most urban populations to an increase with health problems (Lindberg-Hatzipanagiotou, 2004).

Transport and private transport in particular can have also a benevolent effect on the health and well being of populations by giving then a wider possibility to reach distant recreation areas or natural parks. Unfortunately this possibility is generally negated to underprivileged social groups who usually find them selves having to live in over populated, polluted and neglected manufacturing districts, where outdoor recreation areas are losing ground to more "productive" infrastructure. Things are not so bright even for those social groups that are considered privileged, since an increasing move towards private motorization encourage public transport infrastructure and services to be replaced by new roads and parking space to meet the demands of new private car users. This investment in road infrastructure, in turn, is further boosting road use, worsening traffic congestion and leading to greater pollution and noise instead of improving people's mobility. Further, as private transport infrastructure needs considerably more space than public transport infrastructure, an increase in private transport will lead to reduced green spaces and opportunities for walking and cycling in privileged urban areas as well as poor areas and the vicious circle continues (Dimitrov, 2004). Finally other negative effects of the loss or modification of outdoor recreation areas and free urban spaces could be the deprivation of many European cities from a valuable ally in the defence against climate change and related phenomena like heat waves, projected to become more frequent and intense in the nearby future (EEA, 2005).

### Chain 34. Loss of cultural heritage due to land take

**S. Dimopoulou, K. Karkalis and G. Arapis**

In most modern metropolis especially in Europe the demand for land is under enormous economic pressure especially near areas with high density of

cultural legacy. This can result in the loss of areas of cultural interest in order to satisfy demands for new transport or other infrastructure.

Below are the definitions of cultural heritage, architectural heritage, archaeological heritage, as defined by UNESCO and other international institutions.

*Cultural heritage*

During the International Convention of UNESCO (1972), "cultural heritage" is defined (Article 1) as the total of:

- Monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science;

- Groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science;

- Sites: works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view.

The Article 4 of this International Convention states that each State Party to this Convention recognizes that the duty of ensuring the identification, protection, conservation, presentation and transmission to future generations of the cultural and natural heritage referred to in Articles 1 and 2 and situated on its territory, belongs primarily to that State. It will do all it can to this end, to the utmost of its own resources and, where appropriate, with any international assistance and co-operation, in particular, financial, artistic, scientific and technical, which it may be able to obtain (European Cultural Convention, 1954).

*Architectural heritage*

The declaration of Amsterdam (Declaration of Amsterdam, 1975) regarding the architectural heritage emphasized the following basic considerations and defined the conservation of the architectural heritage as one of the major objectives of urban and regional planning:

a. Apart from its priceless cultural value, Europe's architectural heritage gives to her peoples the consciousness of their common history and common future. Its preservation is, therefore, a matter of vital importance.

b. The architectural heritage includes not only individual buildings of exceptional quality and their surroundings, but also all areas of towns or villages of historic or cultural interest.

c. Since these treasures are the joint possession of all the peoples of Europe, they have a joint responsibility to protect them against the growing dangers with which they are threatened - neglect and decay, deliberate demolition, incongruous new construction and excessive traffic.

d.  Architectural conservation must be considered, not as a marginal issue, but as a major objective of town and country planning.

e.  Local authorities, which whom most of the important planning decisions rest, have a special responsibility for the protection of the architectural heritage and should assist one another by the exchange of ideas and information.

f.  The rehabilitation of old areas should be conceived and carried out in such a way as to ensure that, where possible, this does not necessitate a major change in the social composition of the residents, all sections of society should share in the benefits of restoration financed by public funds.

g.  The legislative and administrative measures required should be strengthened and made more effective in all countries,

h.  To help meet the cost of restoration, adaptation and maintenance of buildings and areas of architectural or historic interest, adequate financial assistance should be made available to local authorities and financial support and fiscal relief should likewise be made available to private owners.

i.  The architectural heritage will survive only if it is appreciated by the public and in particular by the younger generation. Educational programmes for all ages should, therefore, give increased attention to this subject.

j.  Encouragement should be given to independent organizations - international, national and local - which help to awaken public interest.

k.  Since the new buildings of today will be the heritage of tomorrow, every effort must be made to ensure that contemporary architecture is of a high quality.

The declaration proceeds declaring that "The conservation of the architectural heritage should become an integral part of urban and regional planning, instead of being treated as a secondary consideration or one requiring action here and there as has so often been the case in the recent past.

A permanent dialogue between conservationists and those responsible for planning is thus indispensable. Planners should recognize that not all areas are the same and that they should therefore be dealt with according to their individual characteristics. The recognition of the claims of the aesthetic and cultural values of the architectural heritage should lead to the adoption of specific aims and planning rules for old architectural complexes."

*Archaeological heritage*

The council of London at the European Convention on the Protection of the Archaeological Heritage (revised: 1992) agreed on the following:

1.  The protection of archaeological heritage as a source of the European collective memory and as an instrument for historical and scientific study.

2.  To this end are considered to be elements of the archaeological heritage all remains and objects and any other traces of mankind from past epochs:
    i.  The preservation and study of which help to retrace the history of mankind and its relation with the natural environment;

ii. For which excavations or discoveries and other methods of research into mankind and the related environment are the main sources of information; and

iii. Which are located in any area within the jurisdiction of the Parties.

3. The archaeological heritage shall include structures, constructions, groups of buildings, developed sites, moveable objects, monuments of other kinds as well as their context, whether situated on land or under water (European Convention of the protection of the archaeological heritage, 1992).

In order to define an indicator of cultural heritage loss we need to include to all the definitions of UNESCO among other things the concept of cultural "integral entity". Another thing to consider is the inflation factor. The integral entity and inflation factor are described more in detail below.

*Integral entity*

The term cultural "integral entity" means that a monument / duelling may it be a tomb, palace, house, sanctuary, tool, etc. is defined, not only by its "physical self" but most of the time, it is also defined by its natural surroundings and also by its dynamic interrelation with other cultural entities. More in detail:

a. The integration between a monument / duelling and its surrounding natural landscape is the natural integral entity.

b. The integration between a monument / duelling and its dynamic interrelation with other cultural entity units is the socio-economic integral entity.

Natural entity and social-economic entity combined together compose the integral entity of a cultural heritage unit.

*a) Natural integral entity*

To give an example of natural integral entity, the temple of the Goddess Athena (Tholos) in Delphi (Greece) – see Figure 33 – by a strict architectural point of view is defined only by its physical volume (not more 600 $m^3$). But on a more broad cultural perspective the temple of Delphi and its cultural value is given, not only by the "physical" borders of the temple itself, but also by the surrounding nature and landscape. This was also the initial intention of the ancient craftsmen; to create a monument that would blend with nature. This is why the columns of the temple of Delphi and most Greek-Roman ancient temples resemble to tree trunks. This is also why the columns are oriented in such a way, that the light passing through them in a certain time of the day resembles to the light of the sun beaming through a forest. In the same manner, many Egyptian pyramids are constructed in a way that they blend not only with the desert landscape surrounding them but also with the sky and stars above them.

**Figure 33. Temple of Athena in Delphi "Tholos"**



picture: Stavroula Dimopoulou

The fact that these monuments mix together with their surrounding landscape means that the landscape and the monument / dwelling are not separate but are constructed in such a way that they compose together an integral entity. If, for example, a major transport artery or some other infrastructure should be constructed near a monument / dwelling or if the monument should be moved kilometres away, this would nevertheless constitute a visual and aesthetic damage and a destruction of cultural heritage even if the structural entity of the monument / dwelling remains untouched.

*b) Socio-economic integral entity*

To give an example of socio-economic integral entity, a house in a small town near a medieval castle is defined architecturally by about 200 m$^3$ but that domicile culturally is interrelated socially and economically with the castle. The house in itself is only one piece of the cultural puzzle. In order for us to appreciate the cultural value of the social / economic landscape as it is represented by a small rural home in its context, we need to consider not only the rural house in itself but also the lord's castle and a nearby water mill interacting with each other, etc. Just like natural heritage, cultural heritage is, in the bottom line, a holistic concept and this is probably the way it should be viewed.

An interesting example of an effort to combine the construction of a transport infrastructure with a means to increase the understanding of cultural assets present in the construction area is given by the Attiko metro in Athens. Archaeological excavations took place in parallel with the construction of the metro infrastructure in an area of 79 000 m$^2$ bringing into the surface more than 50 000 archaeological findings. Care was given to avoid the alteration or destruction of underground archaeological structures. Samples of archaeological findings were incorporated in various Athens metro stations where they are exhibited – see Figure 34. This example shows that with

conscious planning in connection with the construction of infrastructure, part of the cultural heritage can actually be "increased" instead of lost.

**Figure 34. Exhibition of the archaeological findings in Athens metro area in Syntagma / Acropolis**



picture: Konstantinos Karkalis

Finally we need to point out that the translocation of cultural monuments or dwellings should not always be seen as a loss of integral cultural heritage. In fact in those cases where care has been given during the translocation of dwellings / monuments in order to conserve not only the physical integrity of the constructions but also their social and cultural and natural entity, cultural heritage can actually be maintained and increased. A very good example of this can be seen in the Skansen open air museum in Stockholm (see Figure 35). The museum contains original constructions transferred from all over Sweden, often surrounded by gardens and cultivated patches that are typical of the time and place. The various plants are from different parts of Sweden and the domestic animals kept in Skansen represent different Scandinavian varieties. All this together enhances the natural, cultural and pedagogical value of the museum. It is important to point out that these monuments / dwellings are not only representatives of their era but also replicate the ways of life (socio-economic) of past times and have great cultural and educational value.

**Figure 35. Bakery and wind mill, Skansen (Stockholm) open air museum**



pictures: Stavroula Dimopoulou

The philosophy followed in the Skansen open air museum could represent a good example for those cases when an translocation of monuments is obligatory due to transport infrastructure.

*The inflation factor*

Not all regions on the earth have the same richness and density in cultural heritage. This is because some places through history have been preferred by mankind more than others as settlements and sites of action. Cities such as Cairo, Athens or Rome have a very high density of monuments on the surface and below ground. If a quantitative indicator were to be implemented in order to esteem the damage to the cultural heritage due to land uptake, these cities would seem to be exceedingly suffering from loss of cultural values due to transport infrastructure. The inflation factor makes it difficult to create a uniform indicator that would be accepted by all countries, cities and scientific communities.

*Visual impact and the calculation of the solid angle*

Another interesting method for the calculation of the visual impact and cultural value in combination with the surrounding landscape / environment of monuments / dwellings is "the solid angle" (*angle solide*). This technique presents interest whatever any aesthetic aspect or judgement (Maurin, 2006).

### Chain 35. Loss of ecosystem health, loss of biodiversity, due to habitat fragmentation

**E. Ortega Pérez and S. Mancebo Quintana**

Fragmentation involves dividing up contiguous ecosystems (or landscape unit) into smaller areas called "patches" (Forman, 1995). Ecosystem fragmentation causes (Geneletti, 2004; Rutledge, 2003; Forman, 1995): (1) increase of the number of patches, (2) decrease of the mean patch size and (3) increase of the total amount of edge, where edge is the border between patches of two different classes.

These spatial effects cause that habitat conditions will be affected:

- Less habitat surface. Larger ecosystems are typically better at conserving biodiversity than smaller ones (Geneletti, 2004), then if the habitat area decreases the populations will decrease too. In general terms, larger and heterogeneous patches can sustain more species than smaller and homogeneous ones.

- Isolating patches, increasing distance between patches of natural habitats. Patch isolation difficult interchange between individuals, and it contributes to extinction of stabilized species (Fahrig and Merriam, 1985). Habitat fragmentation can be understood as lost connectivity (Serrano *et al*., 2002). Connectivity is a fundamental characteristic in the landscape structure (Taylor *et al*., 1993), because it enables energy and material fluxes (like migratory, colonization, pollination, etc), which are basic in the ecosystem (Ortega, 2004).

- Patches shape is modified, depending on the action which causes fragmentation. Reduction of the patches size produces a higher perimeter-area ratio. It increases the permeability of the patches to external disturbances (Baskent, 1999; Saunders *et al*., 1991).

- Transport infrastructures are barriers to energy and material fluxes (Forman and Alexander, 1998) and alter the resources of a habitat. The changes in the ecosystems affect the distribution and number of species inside a patch. Linear infrastructures alter natural surfaces and its stability and recovery capacity. These changes can compromise the viability of the species.

These effects as a result of habitat fragmentation have far-reaching consequences for species survival (Nikolakaki, 2004). In particular, for area-sensitive species, the patches of suitable habitat may be too small to support a breeding pair or a functional social group (Lambeck, 1997), whereas species with low dispersal capacity are unable to recolonize the habitat patches following the extinction of their local populations (Collinge, 1996).

Figure 36 shows the chain of causality of habitat fragmentation. Its characteristics are: multiple interconnected chains, cyclic chains and the impact is a non-linear sum of effects.

**Figure 36. Chain of causality of habitat fragmentation**
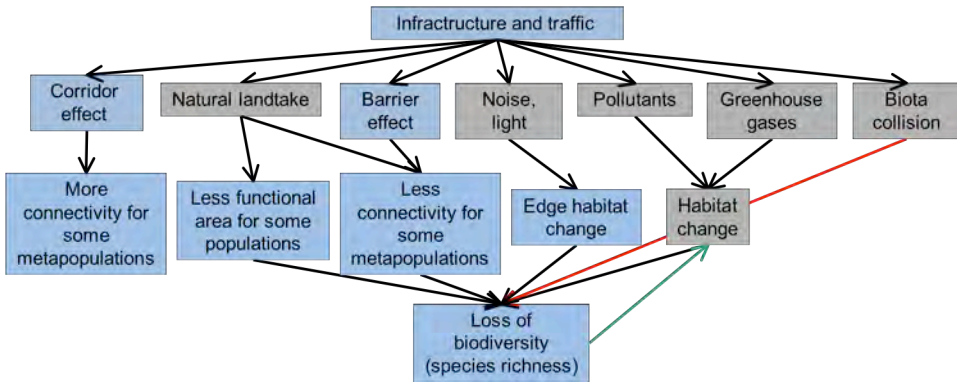


Source: Infrastructure and traffic
Pressure: Traffic (barrier because of noise, light, collision)
State: Habitat change (less functionalities, divided populations, edge habitat change)
Impacts: Loss of biodiversity (some species disappear, some reduced number of individuals

### Chain 36. Reduction of living areas of people, due to fragmentation

**S. Mancebo Quintana and E. Ortega Pérez**

Transport infrastructures affect humans because they block the freedom movement in the territory and in the cities. The infrastructures are barriers and decrease connectivity between places in which humans do their activities (Di Giulio *et al*., 2009). The effects on pedestrian movement have been usually ignored in transport planning and traffic engineering practice (Russell and Hine,

1996). The local accessibility is decreased because they have to move further to get destinations and the cost (time, resources…) is higher. The most vulnerable groups are people with restricted mobility (e.g. elderly people), school children and people without access to a personal car (Hine and Russell,1996; Di Giulio *et al*., 2009).

## Chain 37. Soil erosion

**F. Kehagia**

Roads are a key contributor to erosion processes because of the abundance of exposed soil in roadsides and on unpaved road surfaces. Disturbance during road construction can upset the often delicate balance between stabilizing factors, such as vegetation, and others which seek to destabilize, such as running water. Erosion occurs at the surface and can be described as the detachment of soil or rock particles by water or wind leading to significant consequences for aquatic systems and wildlife. Rainfall erosion processes are predominant in most areas and are a function of four major factors linked in a "universal" soil loss equation: climate, soil, topography and vegetation cover (Lal, 1994; Forman *et al*., 2003). In dry climates wind erosion often predominates (Brandle *et al*., 1988).

## Chain 38. Visual qualities of landscape / townscape

**K. Karkalis, R. Joumard and G. Arapis**

According to the European Landscape Convention (Council of Europe, 2000), "landscape" means: "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors". Despite this official definitions, landscape is still an ambiguous concept, with meanings of both the actual reality (the area) and also its perception (Ventura, 2008). Landscape is a term found in heterogeneous disciplines - see Ingegnoli (1993) or Beguin (1995) for a definition of landscape. Geographers emphasize the dynamic relationships among the physical context inhabited by man, the biological environment and the human action. Natural science and ecology examine the different forms of life in their habitat. Economists consider landscape as a support for resources or a resource itself. The landscape of the sociologist is a context for social relationships. Urban planners see landscape as a context before and after the developments they implement.

Painters or writers remind us of the holistic character of the term landscape, far from the simple collection of composite elements (where the whole is much more than the simple sum of its individual parts, *Aristotle*). A new order appears and with it new values and different sensations. Landscape is either interpreted according to the subjective sensibility and intuition of the artist (see the famous painting by Monet on Figure 37), or based on his own philosophy and mind-set. The landscape as a separate entity exists only in our minds. In nature everything is linked to everything else; This is the basic concept of the "holistic" principle.

**Figure 37. Claude Monet, Les coquelicots à Argenteuil
(*Poppies near Argenteuil*), 1873**



More over the quality of the landscape is not only an abstract aesthetical value that only humans or gifted artists can "appreciate" but it can be perceived by most living beings and it is a very important element for various functions of ecosystems, i.e. the creation of specific habitats and niches (Arapis,1999).

Historically, roads were firstly simply paths made by animals with no impact to the landscape or the environment at all. Among the ancient civilizations, the most significant road constructors were the ancient Romans. But even if the Roman road network was immense as the empire itself, it had a very low impact towards the visual quality of landscape or the functions of ecosystems. Today from our western civilizations point of view, it sometimes seems impressive how ancient man managed to coexist peacefully with nature sometimes even improving the landscape with his creations.

Before the development of the steam engine the material mostly used in transport infrastructure was mostly stone and the roads had to follow the natural topography of the landscape. Instead, railroads demanded a significant quantity of steal, stone and wood. This started creating an impact to the environment, in the form of a systematic cut down of trees in order to provide the wood to be used in the construction of the railroads or as a fuel source; or in the presence of mines in order to provide row materials. Thanks to the invention of dynamite, this new transport could now alter the landscape to its needs (tunnels, cutting through hills) (Karkalis, 2007). The technical progress allows the road or rail routes to progressively free of the territory morphology.

The transport infrastructures appear as a fundamental element of the ordinary landscapes (Dewarrat et. al., 2003). Their relationship can be questioned according to three points (Teller and Cremasco, 2009): The visual integration of the infrastructure in the landscape, the accessibility to the landscape they offer, and at last the impacts due to the peri-urbanization phenomena they induce.

The transport infrastructures are often perceived as added elements which assimilate with difficulty the natural elements. The relief has then more and

more impact through the bridges, tunnels, excavations and embankments which are developed. These side elements can then become the main modes of the landscape impact of the transport frameworks. Their footprint on the landscape is sometimes so important that they gain a true heritage value (see Figure 38).

**Figure 38. Transport infrastructure as a cultural heritage:
The Millau viaduct, the tallest vehicular bridge in the world**



picture: Vincent Kauffmann - http://earthworm.online.fr

**Figure 39. Bad integration of a transport infrastructure in the landscape
or natural environment**



picture: Rosa Arce

Unfortunately most of the sophisticated transport infrastructures of the 20th century gave very little consideration to the conservation of the local rural character of the landscape / natural environment and the beneficial influence they have on human health and the quality of life (see Figure 39). If the only visual presence of the transport infrastructures is notable, their indirect consequences are equally impressive. The mobility is intimately linked with the modalities of land using and urbanizing. The transport infrastructures, although they appear unbound from the land, shape inevitably the landscape by introducing a new relationship with time and space.

## Chain 39. Non-renewable resource use

**P. Waeger and K. Karkalis**

Non-renewable resources such as fossil fuels and metals (e.g. steel, aluminium, platinum) play, at least to this day, a major role as energy source or materials for transport infrastructure.

Fossil fuels are a resource that is being depleted much faster than it is regenerated. Indeed, transport is know to be one of the main energy consuming sectors (over 30 % of total final energy consumption), with energy use is growing at a rate of about 3 % per annum (EEA, 2000). In the EU, the transport sector is nearly fully dependent on fossil fuels (99 %). The use of renewable energies such as biofuels in the transport sector is so far very limited (EEA, 2002; 2005b). As a consequence, peak-oil, the point in time where the maximum rate of global petroleum extraction is reached, is expected for the next few years (Aleklett *et al*., 2010).

Metals such as platinum and other platinum group metals (palladium, rhodium) required for car catalysts have been extracted at much high rates in the last decades than before, and today contribute to about 50 % of the net platinum group metals (PGM) demand worldwide (Hagelüken *et al*., 2005). This has raised concern regarding the security of supply of these scarce elements and a discussion on possible counter-measures such as substitution, reduced consumption or increased recycling (NRC, 2008; Hagelüken and Meskers, 2009; Wäger *et al*., 2010).

## Chain 40. Non-recyclable waste

**M. Boughedaoui**

Transport constitutes a source of different types of waste solid, liquid, recyclable and non recyclable generated from all type of vehicles in use and at different stages of their life cycle and all equipment and materials used for their production, control and maintenance or reparation, fuel production and distribution. Vehicles in use are also considered to generate wastes when are users inside vehicles produce wastes along roads and rest places.

Some of the solid wastes would degrade or leach chemicals over time with long-term effects and then will contaminate soils, surface and underground water.

Solid waste accumulations and dumping facilities raise environmental concerns because of potential smoke from open burning, odours, insects, rodents, gaseous emissions and water pollution that might result.

The tyre waste chain in Europe is illustrated in Figure 40, and the number of scrapped cars in Europe is shown in Figure 41.

For marine transport, waste generated on-board ships and boats that is discharged or collected for disposal in ports are: oil, sewage, garbage, ballast water, anti fouling paint scraps and maintenance wastes, and contaminated dredged material.

These generated wastes are divided into four categories of sources, operational and domestic waste from ships and boats, waste from commercial cargo activities, wastes generated from maintenance activities and associated maritime industry activities and domestic waste generated by port and harbour employees and users.

The first three sources of waste could cause impacts on marine wildlife.

The latter source is not specific to ports and harbours and could be considered with domestic or commercial or general activities wastes which are managed.

**Figure 40. Treatment of waste tyres in European Union (Pirc-Velkavrh and Kristensen, 2003)**
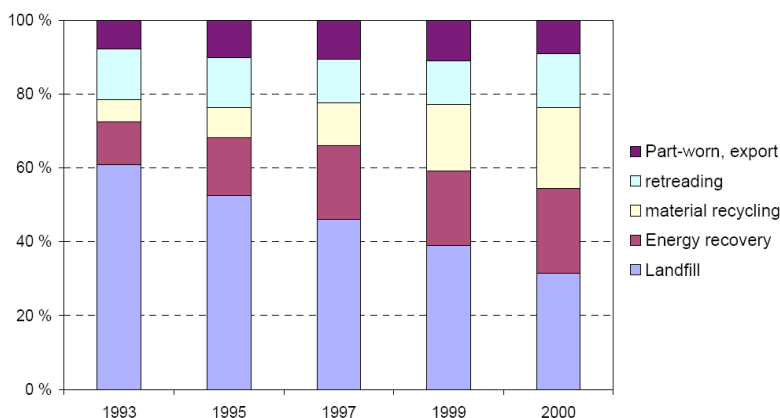


**Figure 41. Modelled estimated numbers scrapped cars per capita in selected countries in EU (EEA, 2003)**
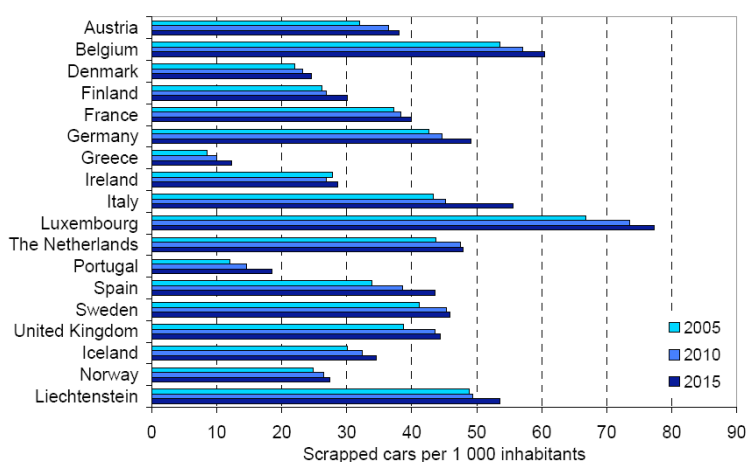


Shipping is estimated to contribute between 10 and 20 % of the world's marine debris (Sheavly 1995; Faris & Hart 1994), which makes shipping the

second largest source of debris in the marine environment after tourism (MCS, 1998).

Oil spills to marine areas have a significant impact on environmental quality affecting all aspects of marine ecosystems. The oil causes surface contamination, smothering of marine biota and acute toxic effects and long-term accumulative impacts. During clean-up operations, marine life is also affected either directly or through physical damage to marine and coastal habitats (EEA, 2004a).

Discarded fishing gear, which cannot be recovered, waste that is dumped by boats, especially fishing vessels; the leaching of wastes into the marine environment, including accumulation in the food web; often remains in the marine waters affecting wildlife for many years.

*Entanglement of marine wildlife*

Entanglement of marine wildlife tends to occur when animals feed on organisms attached to or associated with marine debris, or if they swim into marine debris floating at sea. Plastic bands or net fragments entangled around young animals' necks restrict their ability to feed properly, and as they grow, result in their strangulation and death.

Entanglement or entrapment can also occur onshore when marine wildlife such as seabirds and turtles are caught in beach debris.

*Ingestion by marine wildlife*

Debris such as balloons, plastic bags and confectionery wrappers are ingested by vertebrate marine wildlife when confused with prey species. Debris such as fishing line, plastic pieces and ropes can also be ingested when wildlife eats prey that is attached to or associated with these items.

Ingested debris may starve animals by preventing ingestion of food; reducing absorption of nutrients, resulting in internal wounds and ulceration; or by causing animals to become more buoyant, thereby inhibiting diving (Beck and Barros, 1991; Bjorndal *et al*., 1994; Sloan *et al*., 1998; EPA and QPWS, 2000). There is also the potential for marine wildlife to absorb heavy metals and/or other toxic substances through ingestion of suspended 'microplastics' (Balazs, 1985; Ananthaswamy, 2001; Mato *et al*., 2001). Microplastics are small plastic particles that are introduced to the marine environment through cosmetic additives (plastics are added as abrasives), aeroblasting materials (plastic 'sand' is used to remove paint from ship hulls) and the weathering of larger plastic items. Within marine food webs, plastic debris can serve as both a transport medium and a potential source of toxic chemicals such as polychlorinated biphenyls (PCBs), endocrine-active substances and chemicals similar to DDT (Balazs, 1985; Ryan *et al*., 1988; Bjorndal *et al*., 1994; Faris and Hart, 1995; Ananthaswamy, 2001; Mato *et al*., 2001). These chemicals are known to compromise immunity and cause infertility in animals, even at very low levels (Ananthaswamy, 2001; Mato *et al*., 2001).

### Chain 41. Direct waste from vehicles

**R. Joumard**

Cans, bottles, litter, rubbish etc are thrown out of vehicle windows along the roads. The impact is mainly an annoyance for the landscape users along the infrastructures, but also a trouble for the wildlife. This issue seems especially important in North America.

### Chain 42. Greenhouse effect

**R. Joumard**

The 2007 4th Assessment Report from the UN Intergovernmental Panel on Climate Change (IPCC) concluded that "*warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*" and also that "*most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gases (GHG) concentrations*" (Pachauri and Reisinger, 2007, p. 72 and 39). The change in the composition of the atmosphere and the resulting increase of the global temperature are just two steps in a cascade of impacts caused by human activities. Consequences of climate change include an increased risk of floods and droughts, storm intensification, sea level rise, losses of biodiversity, threats to human health, and damage to economic sectors such as energy, forestry, agriculture, and tourism (EEA-JRC-WHO, 2008).

**Figure 42. Emissions of greenhouse gases GHGs by IPCC (Pachauri and Reisinger, 2007, p. 36): (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.[5] (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of $CO_2$-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of $CO_2$-eq**



Forestry includes deforestation
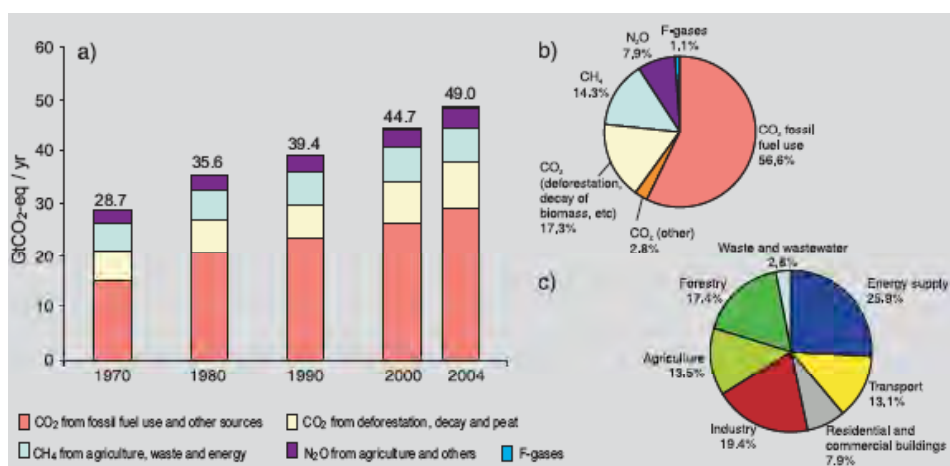
The impact of climate emissions can be regarded, in a simplified manner, as the chain: Emission changes → concentration changes → radiative forcing → climate impacts → societal and ecosystem impacts → economic "damage" (O'Neill, 2000; Smith and Wigley, 2000; Fuglestvedt *et al*., 2003).

$CO_2$ is the main responsible of the greenhouse effect – it represented 77 % of total anthropogenic GHG emissions in 2004, beside methane $CH_4$ (14 %), nitrous oxide $N_2O$ (8 %), and fluorine components HFCs, PFCs and $SF_6$ (1 %) (Pachauri and Reisinger, 2007, p. 36 – see Figure 42). According to WHO Europe and UNECE (2009), greenhouse gas emissions from the transport sector increased from 16.6 % of the total in 1990 to 23.8 % in 2006 in the 27 current EU Member States, and continue to grow. Road transport accounts for more than 70 % of these emissions.

## Chain 43. Health effects of electromagnetic pollution

**M. Hours**

Despite the lack of a known physiopathological mechanism, some experimental studies have shown that electromagnetic pollution can induce biological changes, and a few epidemiological studies raises the question of tumour appearance in given conditions. But there is no consensus on this subject (WHO, 2000; Hours *et al*., 2005; AFSSE, 2005). The extremely low frequency electromagnetic fields due to high voltage power lines are also suspected to induce annoyance, health effects and to impact ecosystems (Draper *et al*., 2005; Huss *et al*., 2009).

## Chain 44. Effects on ecosystem health of electromagnetic pollution

**K. Karkalis, G. Arapis and R. Joumard**

The effect on the ecosystems of electromagnetic pollution is even less familiar than the health effects. They are in the same way suspected: annoyance, biological changes etc. More in detail, electromagnetic pollution can produce a number of negative effects ranging from changes in cellular function: alteration in the intracellular ionic concentrations, proliferation rate, changes of gene expression, changes to cell death induction, decrease in the rate of melatonin production, partial albinism, and promotion of tumours. On the ecosystem level, we can have declination of bird and insect populations, problems in building the nest or impaired fertility, number of eggs, embryonic development, hatching percentage. Microwave radiation can produce negative effects on the nervous, cardiovascular, immune and reproductive systems, disruption of circadian rhythms (sleep–wake) by the interfering with the pineal gland and hormonal imbalances, changes in heart rate and blood pressure (Balmori, 2009; Panagopoulos and Margaritis, 2008a and b).

## Chain 45. Light pollution

**F. Kehagia**

Animals react to the lights of passing vehicles. Light energy transmission is evident in seeing a vehicle's headlights or taillights at night or an onrushing stop sign readable by reflected daylight. Light energy moves virtually instantaneously through air, irrespective of wind speed. Although roadside lighting may affect nocturnal frogs (Buchanan, 1993), little is known about the ecological effects of vehicle headlights. However, visual disturbance, in the sense of responding simply to the sight of a vehicle or vehicles, is likely to be important to wildlife (Liddle, 1997). Inappropriate street lighting and other stronger light sources killed off for instance the predaceous water beetle (family ditiscidae).

At the same time light pollution is destroying natural heritage: only in recent decades, we have tainted our natural heritage of the night sky everywhere, except in inhabited regions. People no longer enjoy the stars and the Milky Way. Humanity has lost touch with the nocturnal environment.

## Chain 46. Introduction of invasive alien species

**K. Karkalis, G. Arapis and R. Joumard**

Many non-native species are unintentionally introduced into countries via the transport of commodities, food, etc. Although only a small percentage of these non-native species will become invasive, when they do their impacts are immense, insidious and usually irreversible, and they may be as damaging to native species and ecosystems on a global scale as the loss and degradation of habitats (IUCN/SSG/ISSG, 2000; UNEP, 2006, p. 16). Invasive alien species are now considered as second only to habitat loss as a cause of biodiversity loss.

*Social-agronomical effects*

One of the best examples effects of the introduction of invasive alien species that has caused in the past devastating agriculture production and social effects, and still influences European potato and vine production can be seen in the potato disease known as late blight and phylloxera. The potato late blight disease is caused by the fungus Phytophthora infestans whose genetic origins are traced up to the highlands of central Mexico. It is speculated that the disease was brought in Europe by fast clipper ships, transported on potatoes being carried to feed passengers sailing from America to Ireland, or with a shipments of seed potatoes destined to Belgian farmers. What ever the case, the disease managed to reach Europe mostly due the use of new fast maritime technologies and vehicles that permitted faster transatlantic speeds giving the possibility to the fungus to survive during the voyage. This alien species had the effect of massive crop failures in Europe that led to the Great Irish Famine. Especially in Ireland the disease caused the death of more than one million people between the period 1845 and 1852 during which island's population dropped by 20-25 % and more than one million people had to immigrate in order to avoid famine. Similar problems of invasion of alien species have been experienced due to the species vitifoliae an insect that infects the root apparatus mostly of European vines. When

the insect was introduced in the Europe of the ninetieth century it caused the destruction of almost all the vineyards for wine grapes in France and later played a major role in the national bankruptcy of Greece today known as the "Sultanina wine grape Crisis" (Goidànich, 1975). Today the most susceptible habitats to invasive alien species have been identified as miss-managed agricultural and rural areas and wetland ecosystems. According to recent estimates, about 45 000 ha of grassland in nationally designated sites in Hungary are affected by invasive plants such as Solidago spp., Ailanthus altissima, Elaeagnus angustifolia and Asclepias syriaca. The situation is not different for aquatic marine environments where Invasive alien species are frequently introduced into marine ecosystems through maritime transport or fishery (ballast tanks, anchors) and may have a significant impact on biological diversity. Introduced species comprise 23 % of the total flora of Thau Lagoon, 20 % of the estuarine biota in the North and 18 % of the total biota in the eastern Bothnian Sea (EEA, 2006). In modern times another serious problem of invasion of alien species through modern freight and other transport modes for agronomical use along transport corridors, is taking place and probably will affect the biodiversity of wild species of agronomical importance: the invasion of artificially created species or GMOs (genetically modified organisms). This contamination of the different agronomical autochthonous ecotypes and loss in biodiversity is caused because of the movement of artificial seed and pollen during transport and other agronomical practises that involve agronomical machinery (Eastham and Sweet, 2002).

## Chain 47. Introduction of illnesses

### J.N. Poda and R. Joumard

Transport takes part in the process of disease transmission by pathogenic agents according to three modes (UNEP, 2006; Poda *et al*., 2009):
− The flows of people and goods, which are carriers of parasitic agents, bacteria, virus, mushrooms and their vectors or hosts
− The emergence or development of pathogenic agents following the environmental and socio-economic changes due to infrastructures
− The weakening (immunisation, adaptation, vulnerability) of humans living along or near infrastructures.

## Chain 48. Fire risk

### E. Ortega Pérez

Some of wildfire causes in natural and urban areas are directly or indirectly related to transport. Directly, main causes can be defined like: train sparks (4 %) and traffic accidents (0.2 %). Indirect causes are related with getting more accessibility to natural areas by drivers, getting higher fire risk by accidents and negligence (campfire, cigarette butts, etc.).

Fires have important local effects, which are commonly associated to fire frequency and intensity, which imply soil degradation, soil erosion, lost of lives, biodiversity, and infrastructures (Omi, 2005). On the other side, the fire plays an essential role in the Mediterranean ecosystem (Merino Saum, 2008).

In this way, burning vegetation supposes an important emission of carbon dioxide (26 %), methane (48 %) and nitrous oxide (26 %) to the atmosphere (Houghton, 2005).

Otherwise, vegetable bio-mass transformation to ash causes an increasing in soil pH and nutrients available to plants (burning may increase nitrogen fixation in the soil). Pyrofit plants and herbs will quickly colonize burnt surface, therefore an important landscape modification will take place as result of species succession (Omi, 2005). Later, soil acidification and nutrients loss (soil humus) will happen by surface runoff and soil erosion.

**Figure 43. Chain of causality of fire**
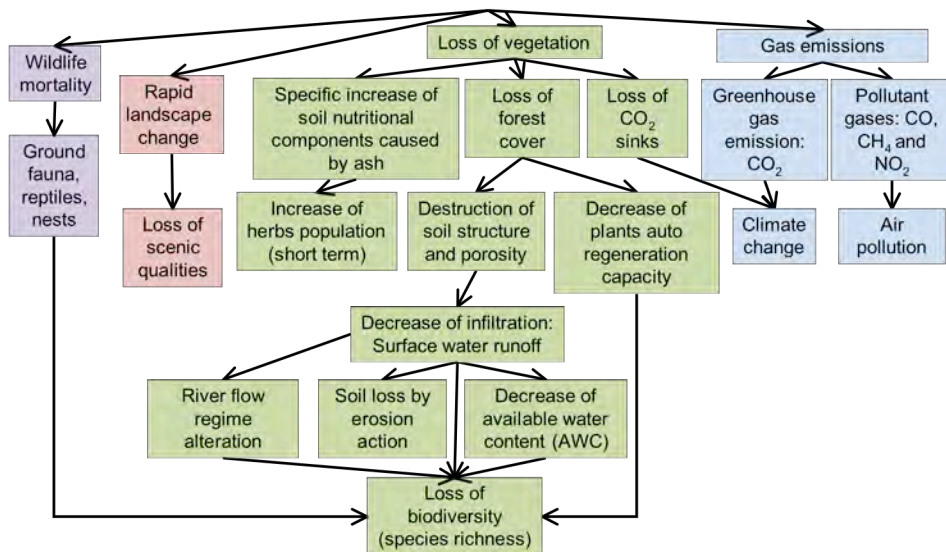


Source: Traffic
Pressure: Traffic (sparks, cigarette butts, accidents)
State: Habitat change (loss functional area, loss vegetation, loss of nutrients)
Impacts: Loss of biodiversity, loss of landscape quality, emissions

If mineral soil is repeatedly exposed due to forest covert destruction (less than 30 % of initial vegetation after fire), rain impact may clog fine pores with soil and carbon particles, decreasing infiltration rates and aeration of the soil. This situation causes an important decrease of available water content (AWC) and strong surface runoff. The hydrologic cycle change caused by fire will finally modify rivers flow regime and associated ecosystem to them. Figure 43 shows the chain of causality of fire.

Desertification phenomena, incapacity of plants regeneration, and destruction of vegetation and fauna during fire action (ground fauna, bird's nets, reptiles) produce a global and persistent loss of biodiversity on environment.

Consequently, all these effects are appreciable on landscape. After the fire, loss of scenic qualities will produce for five year at least. With pass of time and pyrofit plants and after herbs colonization, fire effects could be reversible.

Therefore, fire chain of causalities is long and complex with huge effects on local and global levels, most of them reversible if long time passes.

## Chain 49. Technological hazards

### K. Karkalis and G. Arapis

*Definition*

Any application of practical or mechanical sciences to industry or commerce capable of harming persons, property or the environment (EEA, website).

*Environmental effects*

Technological hazards due to transport can represent an increasing risk for the environment and by consequence human health and well-being. In today's global production and increased commerce in all transport modes may it be naval, air or terrestrial transport the possibilities of a major technological accident are increasing. These risks involve the release of substances due transport accident (Krejsa, 1997). These substances can affect human health or the environment by contamination and their effects on animals and plants. Examples of major transport accidents are for maritime transport the "Exxon Valdez" oil spill in the Prince William Sound, Alaska, on March 24, 1989. Thousands of animals died; including 500 000 seabirds, 1 000 sea otters, 300 harbour seals, 250 bald eagles, and 22 orcas, as well as the destruction of billions of salmon and herring eggs (Graham, 2003). In 2002 a Greek oil tanker, Prestige, sank near the coast of Galicia. The oil spill polluted thousands of kilometres of coastline in Spain and France causing great damage to the Environment. The spill is the largest ecological disaster in Spain's history.

In air transport we have the Palomares incident on 1966 where a B-52G bomber collided with a air tanker during mid-air refuelling at 10 km over the Mediterranean sea, off the coast of Spain. The non-nuclear explosives in two of the weapons exploded when the airplane crashed, contaminating 2 km$^2$ with radioactive plutonium. The cloud dispersed contaminated with radioactive material residential areas, farmland (especially tomato farms) and woods.

Finally for terrestrial transport the sector mostly involved is rail road since rail is mostly used for the transport of heavy industrial hazardous material (Grytsyuk and Arapis, 2005).

*Agricultural effects*

Accidental releases of hazardous materials, including their progressive accumulation in plants, animals, fish or entire ecosystems can involve Agricultural production mostly by the contamination of soils and underground water. The effects of nuclear heavy contamination or "light" contamination like for example Palomares incident regarding agricultural soil require in any case first an assessment of risk and if the contamination is found relevant, special restoration procedures should be used (Marti *et al*., 1990; Grytsyuk *et al*., 2006).

# Annex 7. Unconsolidated indicator selection criteria

**Author: H. Gudmundsson**

The list represents a combination of working group input and references from literature. Overlaps between criteria have not been fully addressed and definitions may not be fully consistent. According to e.g. Rochet and Rice (2005), such lists may nevertheless serve as a basis for conducting more simple assessment processes or be used as a starting point for designing a more elaborate one.

**Table 54. Long list of unconsolidated criteria**

| Cate-gory | Criterion | Proposed definition | Source |
|---|---|---|---|
| Conceptual and theoretical aspects | 1. Represen-tativity | Correlation between an indicator and the issue for which it is supposed to be a proxy | Hauge *et al.*, 2005 |
| | 2. Conceptual validity | Is the indicator based on a well understood conceptual model? 1) The definition of the indicator and the concepts that comprise it up is suitable. 2) There is a correspondence between the indicator and the factor to be quantified. 3) The interpretation and meaning of the indicator are suitable. | CGER, 2000; Cloquell-Ballester *et al.*, 2006 |
| | 3. Theoretical foundation | Is the indicator explicitly defined by appropriate statistical units of measurement and standard international terminology? A clear theoretical definition of a concept to be indicated should, 1) Identify the number of distinct aspects or dimensions of the concept. Each dimension requires a separate latent variable. 2) The theoretical definition should clarify whether the latent variable is continuous or not. 3) Each latent variable is ideally measured with several indicators. | NCHOD, 2005; OECD, 2003; Bollen, 2004 |
| | 4. Predictive validity | Does the measure correctly predict a situation which would be caused by the phenomenon being measured? | Cole *et al.*, 1998 |
| | | The degree to which data values satisfy acceptance requirements of the validation criteria or fall within the respective domain of acceptable values. Data validity can be expressed in numerous ways. One common way is to indicate the percentage of data values that either pass or fail data validity checks. | Batalle *et al.*, 2004 |

| | | | |
|---|---|---|---|
| | 5.<br>Sensitivity | An indicator must be able to reveal important changes in the factor of interest. | WHO, 2006 |
| | | Do the measurement tools and timing of results allow changes to be observed over time? | NCHOD, 2005 |
| | 6.<br>Specificity /<br>transport<br>specificity | An indicator must reflect only changes in the issue or factor under consideration. | WHO, 2006 |
| | | The indicator should identify the effect of transportation rather than providing an estimate of environmental quality that may depend on numerous sources. | USEPA, 1999 |
| Measurement aspects | 7.<br>Transparency | To which degree it is described in an understandable way how the indicator is constructed, how it varies with what it represent (the phenomenon in focus), and how it is influenced by uncertainties. This implies that input data, assumptions, methods, models and theories involved are described and justified. | Internal Working group definition |
| | 8<br>Reliability | An indicator must give the same value if its measurement were repeated in the same way on the same population and at almost the same time. | WHO, 2006 |
| | | The ability of an indicator to perform its predefined functions in routine circumstances, as well as hostile or unexpected circumstances. | Internal Working group definition |
| | 9.<br>Measurability | Be easily measured: The indicator should be straight-forward and relatively inexpensive to measure. | Dale and Beyeler, 2003 |
| | | Measurable indicators are based on data that should be readily available or made available at a reasonable cost / benefit ratio. | OECD, 2003 |
| | 10.<br>Data availability | Data that are available and accessible, accurate, comparable over time, complete with historical information and covering sufficient geographic area. | Boyle, 1998 |
| | 11.<br>Timeliness | The degree to which data values or a set of values are provided at the time required or specified. Timeliness can be expressed in absolute or relative terms. | Batalle *et al.*, 2004 |
| | 12.<br>Threshold availability | Theory allows calculation of reference point associated with serious harm. | Rice and Rochet, 2005 |
| Data analysis aspects | 13.<br>Aggregatability without loss of representativeness | How easy and to which degree indicators can be aggregated, to higher geographical levels, with other indicators etc. | Internal working group definition |
| | 14.<br>Discountability | Discounting influences people's assessment and evaluation of impacts that will be perceived in different moments of time, as well as trade-offs with other effects characterized in other moments and through other indicators. Discounting factors are affected not only but subjective perceptions but, likewise, by changes in technology and by people becoming used to situations | Internal working group definition |

# Annex 8. Formulation of habitat fragmentation indicators

**Author: E. Ortega Pérez**

**Table 55. Composition indicators**

| Number | Expression | Description |
|---|---|---|
| **Number of patches, NP** (Turner *et al*., 1989) | | Number of patches caused by fragmentation |
| **Mean patch size, MPS** (McGarigal *et al*., 2002) | $$MPS = \frac{\sum s_i}{N}$$ $S_i$ = area of patch <br> N = number of patches | Average area of a patch of a particular class |
| **Largest patch index, LPI** ( Saura and Martinez-Millán, 2001) | $$LPI = \frac{S\,(largest\ patch)}{S_t} * 100$$ $S_t$ = total area of landscape | Percentage of landscape area occupied by the largest patch of a class |
| **Patch density, PD** (McGarigal and Marks 1995; Saura and Martínez-Millán, 2001) | $$PD = \frac{N}{S_t}$$ N = number of patches <br> $S_t$ = total area of landscape | Number of patches per unit area |
| **Average patch carrying capacity, Kavg** (Vos *et al*., 2001) | $$Kavg = \sum reproductive\ areas$$ | Average of the number of reproductive areas of a species in the landscape |
| **Core area** (McGarigal and Marks, 1995; Schumaker, 1996) | $$CORE = \frac{\sum s_c}{\sum s_i}$$ $S_i$ = area of patch <br> $S_c$ = area of core of patch | Core area inside a patch and percentage of the patch that is core area |

**Table 56. Shape indicators**

| Number | Expression | Description |
|---|---|---|
| **Perimeter area ratio, P/S** (Krummel *et al.*, 1987; McGarigal and Marks, 1995) | $$P/S = \sum \frac{P_i}{S_i}$$ $P_i$ = perimeter of patch $S_i$ = area of patch | Ratio of patch perimeter to area |
| **Shape index, SI** (McGarigal and Marks, 1995; Schumaker, 1996 | $$SI = \sum \frac{P_i}{S_i} * k$$ | Ratio of perimeter to area adjusted by a constant |
| **Square pixel, SqP** (Frohn, 1998) | $$SqP = 1 - (4 \cdot \sqrt{A/P})$$ P = perimeter of patch A = square area | Measures deviation from a square shape |

**Table 57. Patch configuration indicators**

| Number | Expression | Description |
|---|---|---|
| **Nearest neighbour, $d_{ij}$** (Moilanen and Nieminen, 2002) | | Distance from a patch to the nearest |
| **Relative size of the biggest patch in the landscape, $RS_i$** (Turner, 2001) | $$RS_i = \frac{S\,(largest\ patch)}{R_i * S_t}$$ $S_t$ = total area of landscape $R_i = S_i/S_t$ ($S_i$ = area of patch) | Connectivity measure between patches of a class |
| **Connectivity index, CI** (Martín *et al.*, 2007) | $$CI_i = \frac{\sum_{j=1}^{n} \frac{S_j}{C_{i,j}}}{2\pi\,C_{max}}$$ $S_j$ = area of patch $C_{ij}$ = distance between patches i,j $C_{max}$ = maximum distance between patches | Assess the landscape resistance to be crossed by species |
| **Patch cohesion (COH) index** (Schumaker, 1996) | $$COH = \left[1 - \frac{\sum_{i=1}^{n} p_i}{\sum_{i=1}^{n} p_i \sqrt{a_i}}\right]\left[1 - \frac{1}{\sqrt{N}}\right]^{-1}$$ $p_i$ = perimeter of patch $a_i$ = area of patch N = total area of landscape | Assess perimeter-area ratio of each patch class in the landscape |
| **Integral index of connectivity, (IIC)** (Pascual-Hortal and Saura, 2007) | $$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j/(1 + nl_{ij})}{A_L^2}$$ nlij = number of links in the shortest path between patches i and j $a_i$ and $a_j$ = area of patches $A_L$ = total area of landscape | Connectivity measure between two patches in the landscape |

# Annex 9. Formulation of noise indicators

**Author: C. Camusso**

### *The Equivalent Level Leq*

The Equivalent level "*Leq*" is defined in the ISO 1996/1-1982, it is represented in the following equation:

$$L_{Aeq} = Leq_{(A),T} = 10\log\left[\frac{1}{T}\int_0^T \frac{p_A^2(t)}{p_0^2}dt\right] \text{ [dB(A)]} \qquad \text{[eq. 21]}$$

where:
   $T$ = time of the noise duration;
   $p_a$ = instantaneous pressure;
   $p_0$ = reference pressure 20 µPa.

### *The Traffic Noise Index TNI*

The Traffic noise index "*TNI*", proposed by Griffiths and Langdon (1968) as mentioned in Schultz (1972), it is an indicator used to describe the road traffic noise; its formulation is given in the following equation:

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \text{ or } TNI = 4(L_{10} - L_{90}) + L_{eq} \text{ [dB(A)] [eq. 22]}$$

where:
   $L_{10}, L_{90}$ = statistical level on the observation time of 24h;
   $(L_{10}\text{-}L_{90})$ = parameter for the variability of the noise;
   $L_{90}$ = background noise;
   *Leq* = equivalent level of the 24h.

### *The Noise Pollution Level NPL*

The Noise Pollution Level "*NPL*" is an indicator developed by Robinson at the end of the sixties (Robinson, 1969 as mentioned in Schultz, 1972); the formulation is reported in the following equation:

$$L_{NP} = L_{eq} + k \cdot \sigma \text{ [dB(A)] [eq. 23]}$$

where:
   *Leq* = equivalent level in the period of reference;
   $\sigma$ = standard deviation of the instantaneous level;
   $k$ = 2.56 constant.

### The Sound Exposure Level SEL

Another basic energetic indicator is the Sound Exposure Level "*SEL*" or "*LAE*" or "*LAX*" and it is defined by the ISO 1996/1-1982. It is used to describe the energetic emission of a single noise event in a particular context, for example a passage of a single vehicle in an empty street or a passage of a train.

The expression of the indicator is given by the following equation:

$$SEL = L_{AE} = 10\log\left[\frac{1}{t_0}\int_{t_1}^{t_2}\frac{p_A^2(t)}{p_0^2}dt\right] \text{ [dB(A)] [eq. 24]}$$

where:

$t_2 - t_1$ = interval of the event where $L_{A(t)} > L_{Amax}$ -10;
$t_0$ = reference time (1 *s*);
$p_{A(t)}$ = instantaneous pressure [Pa];
$p_0$ = reference pressure 20 μPa.

In Figure 44 the time-history of a noise event is depicted and the methodology for the evaluation of the intervals for the calculation of the *SEL* is showed.

### Figure 44. Example of time history and time interval for Sound Exposure Level evaluation
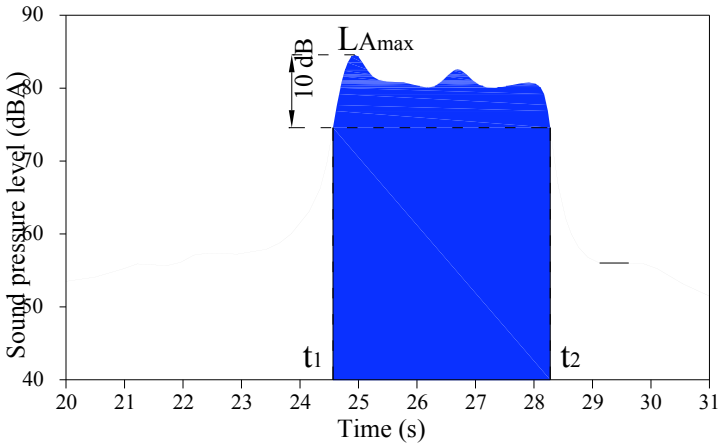


Given a time period, with many single events, it is possible to evaluate the equivalent level on the time period if we know the *SEL* of the single events.

In Italy, this indicator is typically used for the evaluation of the noise emitted by railways. The rail traffic, in fact, is characterized by different single passages of the vehicles. In an observation time period (TR), for example during a day or night reference time, if we measured the correspondent *SEL* for every event, it is possible to calculate the corresponding *Leq,* for the observation time period, generated by the source using the following equation:

$$L_{Aeq,TR} = 10\log\sum_{i=1}^{n}10^{0,1SEL_i} - k \ \text{[dB(A)] [eq. 25]}$$

where:

n = number of events in the time period TR;
$SEL_i$ = SEL value for the i-th event;
k = 47.6 dB(A) when the TR is day period;
k = 44.6 dB(A) when the TR is night period.

### The Transit Exposure Level TEL

The *TEL* is an index used to describe the noise emitted by rail; Its formulation is given by the EN ISO 3095:2005 (EN ISO, 2005) and it is represented in the following equation:

$$TEL = 10\log\left[\frac{1}{T_p}\int_0^T \frac{p_A^2(t)}{p_0^2}dt\right] \ \text{[dB(A)] [eq. 26]}$$

where:

T = is the measurement time interval in *s*;
$T_p$ = is the pass-by time of the train in seconds which is the overall length of the train divided by the train speed;
$p_{A(t)}$ = instantaneous pressure [Pa];
$p_0$ = reference pressure 20 µPa;

In Figure 45 the graphical meaning of the time intervals, *T* and $T_p$ is reported.

**Figure 45. Graphical meanings of the time interval
(elaborated from EN ISO, 2005)**
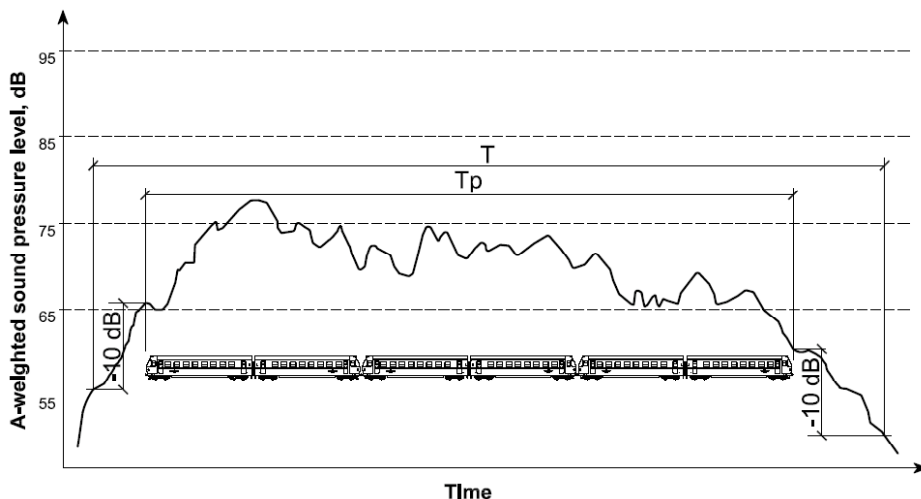
The measurement time interval *T* is chosen so that the measurement starts when the A-weighted sound pressure level is 10 dB lower than found when the front of the train is opposite to the microphone position.

The measurement is stopped when the A-weighted sound pressure level is 10 dB lower than found when the rear of the train is opposite to the microphone position.

The *TEL* is related to the single event level *SEL* and to the A-weighted equivalent continuous sound pressure level *Leq,T* according the following equations:

$$TEL = SEL + 10\log\left(\frac{T_0}{T_p}\right) \quad \text{[dB(A)] [eq. 27]}$$

$$TEL = Leq,_T + 10\log\left(\frac{T}{T_p}\right) \quad \text{[dB(A)] [eq. 28]}$$

where:
$T_0$ = is the reference time interval 1*s*.

As we can observe in equation [25], the *TEL* is not a pure energetic level like *SEL*, but it is the equivalent level of the transit plus a correction for the length of the measurement time, compared with pass-by time; this implies that a 100 m long uniform train would get about the same *TEL* as a 200 m long train of the same type.

### The Perceived Noise Level PNL

Another noise indicator is the Perceived Noise Level "*PNL*", developed by Kryter (1959). This indicator is used to describe the noise emitted by a single aircraft flying over, and is calculated as in the following equation:

$$PNL = 40 + 10\log_2 N_t \quad \text{[PNdB] [eq. 29]}$$

where:
$N_t$ = "total noy" index of the event.

The term "total *noy*" is calculated taken into account the spectrum of the event expressed on the third-octave-bands: the pressure level of every band is compared to a normalized annoyance curve to get the term $N_i$ for the i-th band.

The spectrum is reported on the normalized table (Figure 46), and the $N_i$ for the band corresponds to the "Noy" curve passing for the band spectrum level expressed in dB.

The "*total noy*" is calculated in the following equation:

$$N_t = N_{max} + F\left(\sum_i \left(N_i - N_{max}\right)\right) \quad \text{[eq. 30]}$$

where:

*F* = is a constant;

$N_{max}$ = maximum value of the "noy" evaluated on the conversion table;

$N_i$ = single value in "noy" of the i-band evaluated on the conversion table. An example of this conversion table is reported in Figure 46.

**Figure 46. Conversion table for the evaluation of noy
(Hassall and Zaveri, 1979)**
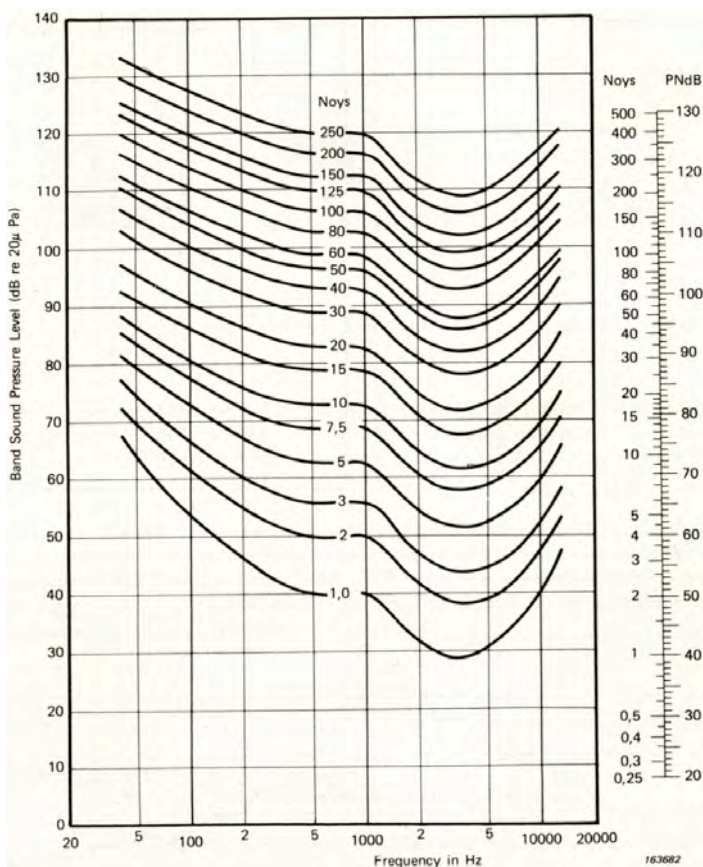


### The Effective Perceived Noise Level EPNL

An evolution of the *PNL* is the Effective Perceived Noise Level "*EPNL*" (Bishop and Horonjeff, 1967 as mentioned in Schultz,1972).

This indicator takes into account the evolution of the *PNL* during the time with an increase of the level depending on the duration of the high level. Its expression is given by the following equation:

$$EPNL = PNL + 10\log_{10}\left(\frac{\Delta t}{T_0}\right) + F \quad \text{[EPNdB] [eq. 31]}$$

where:

Δt = time interval where PNL > PNLmax-10;

$T_0$ = 15 s;

F = correction for the presence of discrete frequency components; this correction is tabulated according to the third-octave band in which the tone lies and the extent to which the tone level exceeds the mean level in the adjacent bands.

The *PNL* and *EPNL* are used to describe the noise emitted by a single event.

### The Noise Number Index NNI

This is another indicator used for the evaluation of the aircraft annoyance; it was developed in the UK and the basic measure is the Perceived Noise Level, (HMSO, 1963, as mentioned in Schultz, 1972, and DORA, 1981).

The index was developed during a social survey in the 1961 in the vicinity of the London (Heathrow) Airport. The expression of the index is reported in the following equation:

$$NNI = L_{APN} + 15\log_{10} N - 80 \text{ [PNdB] [eq. 32]}$$

where:

N = number of aircraft flyovers during the measurement period;

$L_{APN}$ = average peak noise level defined in the following equation:

$$L_{APN} = 10\log_{10}\left(\left(\frac{1}{N}\right)\sum_{i=1}^{N} 10^{\frac{L_i}{10}}\right) \text{ [PNdB] [eq. 33]}$$

where:

$L_i$ = peak noise level (in PNdB) occurring during the passage of each aircraft.

The first part of equation [29] takes into account the average level of the peak noise while the second is referred to the number of events.

### The Noise Exposure Forecast NEF

One of the global noise indicators is the Noise Exposure Forecast "*NEF*" (Bolt Beranek and Newman, 1964-1965, as mentioned in Schultz, 1972).

This indicator is proposed by the US Federal Aviation Administration for the noise emitted by plane, and the following equation expresses the indicator:

$$NEF_{ij} = EPNL_{ij} + 10\log_{10}\left(\frac{n_{D,ij}}{20} + \frac{n_{N,ij}}{1.2}\right) - 75 \text{ [eq. 34]}$$

where:

$n_D$ = number of day operations;

$n_N$ = number of night operations;

i = aircraft class;

j = take-off, landing profile.

This indicator takes into account the different events in the different periods of the day.

### The Weighted Noise Exposure Forecast WECPNL

This indicator is an evolution of the indicator *EPNL* proposed by International Civil Aviation Organisation, as mentioned by Changwoo *et al.* (2007). There are different computations of the index, in general the *WECPNL* represents a unique index for describing the noise emitted in a time period by different numbers of flights; an example of its expression is contained in the following equation (Moncada *et al.*, 1995):

$$WECPNL = 10\log_{10}\left(\frac{5}{8}10^{\frac{ECPNL_D}{10}} + \frac{3}{8}10^{\frac{ECPNL_N}{10}}\right) + S \quad \text{[eq. 35]}$$

where:
*D* = for noise level in day operations;
*N* = for noise level in night operations;
*S* = constant;
*ECPNL* = parameter (function of time period and *EPNL*).

Some studies show that this indicator is more useful than other indicators like $L_{dn}$ (Changwoo et. al., 2007).

### The Indicator LVA

It is described in the Italian norm D.M. 31/10/1997; the expression of the indicator is contained in the following equation:

$$L_{VA} = 10\log\left[\frac{1}{N}\sum_j 10^{\frac{L_{VAj}}{10}}\right] \quad \text{[dB(A)] [eq. 36]}$$

For the calculation of this indicator we take into account three periods of the year:
− from 1 October to 31 January;
− from 1 February to 31 May;
− from 1 June to 30 September.

For each of those periods we take the busiest week, for a total of *N*=21 days; for every j[th] day the daily indicator $L_{VAj}$, used in the equation [33], is calculated as in the following equation:

$$L_{VAj} = 10\log\left[\frac{17}{24}10^{\frac{L_{AVd}}{10}} + \frac{7}{24}10^{\frac{L_{AVn}}{10}}\right] \quad \text{[dB(A)] [eq. 37]}$$

where:

$$L_{VAd} = 10\log\left[\frac{1}{Td}\sum_{i=1}^{N_d} 10^{\frac{SEL_i}{10}}\right] \quad \text{[dB(A)] day level}$$
$$\text{[eq. 38]}$$

$$L_{VAn} = \left[ 10 \log \left( \frac{1}{Tn} \sum_{i=1}^{N_n} 10^{\frac{SEL_i}{10}} \right) + 10 \right] \quad \text{[dB(A)] night level}$$

[eq. 39]

where:

$T_d$ = 17 hours day period in seconds;
$T$ = 7 hours night period in seconds;
$SEL$ = level of the single event;
$N_d$ = number of events in the day period;
$N_n$ = number of the events in the night period.

## The Day-Night Equivalent Level $L_{DN}$ or DNL

For the evaluation of this indicator the 24 hours of the day are divided in two periods:
−   day period, from 6 a.m. to 22 p.m.;
−   night period, from 22 p.m. to 6 a.m.

The indicator is calculated using the following equation:

$$L_{dn} = 10 \log \frac{1}{24} \left( 16 \cdot 10^{\frac{L_d}{10}} + 8 \cdot 10^{\frac{L_n}{10}} \right) \quad \text{[dB(A)] [eq. 40]}$$

where:

$L_d$ = day equivalent level weighted A;
$L_n$ = night equivalent level weighted A + 10 dB.

As we can see, the night level is increased of 10 dB(A); this increase is used to take into account that the night period is a sensible period for the people, where they need to be safeguarded from the noise emission.

Some applications have been made to the use of the $L_{dn}$ for the description of the annoyance. For example, in Martin *et al*. (2006) is reported that $L_{dn}$ relates well to the annoyance if considering the "highly annoyed" people, but in the same study is showed that also the $L_{max}$ relates well with the annoyance if the "average" annoyance is used.

## The Day-Evening-Night Equivalent Level Lden or DENL

The last European Directive 49/2002/EC suggests for all the European countries to use two new noise indicators for all transport system; these indicators are:
−   Day Evening Night Level "$L_{den}$" also called DENL: it is used like a global annoyance indicator, its expression is given by the following equation:

$$L_{den} = 10 \log \frac{1}{24} \left( 12 \cdot 10^{\frac{L_{day}}{10}} + 4 \cdot 10^{\frac{L_{evening}+5}{10}} + 8 \cdot 10^{\frac{L_{night}+10}{10}} \right) \quad \text{[dB(A)] [eq. 41]}$$

−   Night Level "$L_{night}$" = it is used like sleep annoyance indicator.

The day is divided in three periods:
−   day period: in general from 7 a.m. to 19 p.m.;

−    evening period: from 19 p.m. to 23 p.m.;
−    night period: from 23 p.m. to 7 a.m.

The $L_{den}$ is A-weighted average level of the noise emitted in the three periods of the day, with a penalty of 5 dB(A) for the evening period and a penalty of 10 dB(A) for the night period.

The $L_{den}$ is the most recent indicator and some studies have been carried out using it to evaluate the relationship between noise and annoyance (see Miedema and Oudshoorn, 2001; or Klæboe *et al*., 2004).

Corrections on the value of $L_{den}$ have been made depending on the typologies of sound, presence of low frequencies, tonal components and the above proposed corrections are suggested to reduce the scatter on the dose-response relationship (Schomer, 2002).

In general for the traffic noise no corrections are added on the noise levels, but some analyses show that the presence of low frequencies are important in the evaluation of the annoyance and, in some cases, the use of the A-weighted curves could not be appropriated (Nilsson, 2007).

# Annex 10. Analytical expression of Miedema' dose-response relationship

**Author: C. Camusso**

**Table 58. Dose-response relationship: % of annoyed people in function of two noise indicators DNL and DENL (Miedema and Oudshoorn, 2001)**

| Measure / source | DNL or $L_{DN}$ |
|---|---|
| %LA | |
| Aircraft | $-5.741 \times 10^{-4}(DNL-32)^3 + 2.863 \times 10^{-2}(DNL-32)^2 + 1.912(DNL-32)$ |
| Road traffic | $-6.188 \times 10^{-4}(DNL-32)^3 + 5.379 \times 10^{-2}(DNL-32)^2 + 0.723(DNL-32)$ |
| Railways | $-3.343 \times 10^{-4}(DNL-32)^3 + 4.918 \times 10^{-2}(DNL-32)^2 + 0.175(DNL-32)$ |
| %A | |
| Aircraft | $1.460 \times 10^{-5}(DNL-37)^3 + 1.511 \times 10^{-2}(DNL-37)^2 + 1.346(DNL-37)$ |
| Road traffic | $1.732 \times 10^{-4}(DNL-37)^3 + 2.079 \times 10^{-2}(DNL-37)^2 + 0.566(DNL-37)$ |
| Railways | $4.552 \times 10^{-4}(DNL-37)^3 + 9.400 \times 10^{-3}(DNL-37)^2 + 0.212(DNL-37)$ |
| %HA | |
| Aircraft | $-1.395 \times 10^{-4}(DNL-42)^3 + 4.081 \times 10^{-2}(DNL-42)^2 + 0.342(DNL-42)$ |
| Road traffic | $9.994 \times 10^{-4}(DNL-42)^3 - 1.523 \times 10^{-2}(DNL-42)^2 + 0.538(DNL-42)$ |
| Railways | $7.158 \times 10^{-4}(DNL-42)^3 - 7.774 \times 10^{-3}(DNL-42)^2 + 0.163(DNL-42)$ |

| Measure / source | DENL or $L_{DEN}$ |
|---|---|
| %LA | |
| Aircraft | $-6.158 \times 10^{-4}(DENL-32)^3 + 3.410 \times 10^{-2}(DENL-32)^2 + 1.738(DENL-32)$ |
| Road traffic | $-6.235 \times 10^{-4}(DENL-32)^3 + 5.509 \times 10^{-2}(DENL-32)^2 + 0.6693(DENL-32)$ |
| Railways | $-3.229 \times 10^{-4}(DENL-32)^3 + 4.871 \times 10^{-2}(DENL-32)^2 + 0.1673(DENL-32)$ |
| %A | |
| Aircraft | $8.588 \times 10^{-6}(DENL-37)^3 + 1.777 \times 10^{-2}(DENL-37)^2 + 1.221(DENL-37)$ |
| Road traffic | $1.795 \times 10^{-4}(DENL-37)^3 + 2.110 \times 10^{-2}(DENL-37)^2 + 0.5353(DENL-37)$ |
| Railways | $4.538 \times 10^{-4}(DENL-37)^3 + 9.482 \times 10^{-3}(DENL-37)^2 + 0.2129(DENL-37)$ |
| %HA | |
| Aircraft | $-9.199 \times 10^{-5}(DENL-42)^3 + 3.932 \times 10^{-2}(DENL-42)^2 + 0.2939(DENL-42)$ |
| Road traffic | $9.868 \times 10^{-4}(DENL-42)^3 - 1.436 \times 10^{-2}(DENL-42)^2 + 0.5118(DENL-42)$ |
| Railways | $7.239 \times 10^{-4}(DENL-42)^3 - 7.851 \times 10^{-3}(DENL-42)^2 + 0.1695(DENL-42)$ |

where: - %HA is the percentage of highly annoyed people;
- %A is the percentage of annoyed people;
- %LA percentage of little annoyed people.

# Annex 11. The use of Saaty's Analytical Hierarchy Method for the assessment of environmental road transport impacts

**Authors: M. Ruzicka and H. Brozova**

Most of the present environmental impact assessments EIA / strategic environment assessments SEA do not take into account properly the variety of the environmental impacts, or are using markers, indicators, criteria and more generally tools which do not represent the impacts. A correct representation of the whole range of impacts is necessary to ensure that sustainability takes into account environmental issues to a satisfactory degree. This is especially important for the transport sector where the concerns and the stakes are important. Therefore it is so important to create and to appraise an evaluation procedure of impacts preferences (impacts characterised by criteria or by aggregated indicators) with the use of scientific methods. The Analytical Hierarchy Method (Saaty, 1980; 1999) was chosen for this purpose with the aim to verify possibilities of AHP method used for transport EIA/SEA as whole and in relation of three groups of respondents: public, informed public and transport experts. For this purpose it was necessary to map a contemporary situation in EIA/SEA of transport projects as well.

The current situation of EIA/SEA is possible to characterize on the base of research results and obtained data from the Czech Republic's information system (ISESČR, undated). The research was carried out to determine what and how indicators were used in transport projects assessment. Data were logged from 101 of road projects and 52 car parking projects of EIAs that they were carried out during the last two years in the Czech Republic. As typical example can be presented EIA that was carried out near to Prague with the aim to select the best variant of new road leading around the city of Kralupy n/V: See Figure 47.

The final impacts assessment of the example includes indicators that are listed in the Table 59. The EIA uses different indicators (aggregated) and their values are modified by a vague interpretation into value. Finally these values are summoned without any comparison, determination of weights, standardisation etc. and as the best variant is taken the one with the maximal value. In this case the variant B was recommended for the construction.

**Figure 47. Projects of road construction
(0: contemporary situation; A, B: proposed variants)**
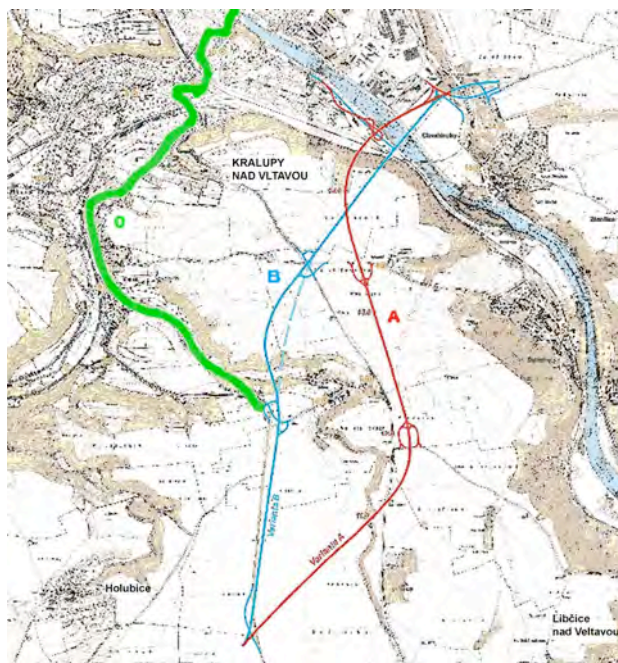


**Table 59. Comparison of EIA variants – city Kralupy n/V. 2004
(company VPÚ Deco Praha a.s)**

| Indicators | Variant 0 | Variant A | Variant B |
|---|---|---|---|
| Impacts on residential households | -2 | 1 | 2 |
| Impacts on surface water | 0 | -1 | -1 |
| Noise impacts on residential housing in comparison with existing one | 0 | -1 | -1 |
| Impacts linked with waste | -2 | 1 | 2 |
| Impacts on flora and fauna | 0 | -1 | -2 |
| Impacts on landscape view | 0 | -1 | -2 |
| Impacts on residents | -2 | 1 | 2 |
| Impacts on archaeology findings | 0 | -1 | -1 |
| Impacts of remaining (old) ecological impacts | 0 | -1 | 0 |
| Other impacts | 0 | -1 | -1 |
| Total | -6 | -4 | -2 |

As it is shown in the example the solution of the transport impacts assessment has two aspects – the first one is to determine values of indicators (aggregated indicators) and the second is to compare weights of these indicators (to weight them) to obtained quantified values. Similar problem was solved in COST 350

(Calderon *et al*., 2009a) and that is why the decision was accepted to use aggregated indicators from this research to evaluate pros and cons of their proceeding. It can be expected that similar work can be done with results of our data processing. The preliminary COST 350's result was the proposal of these main indicators and they were used in this case study (Calderon *et al*., 2009a) – 15 indicators to assess transport impacts are proposed:

1 Noise and vibration
2 Local air quality
3 Regional air quality
4 Quality and use of water
5 Protected areas
6 Waste
7 Loss of biodiversity
8 Light pollution
9 Technological hazards
10 Landscape, cultural and built heritage
11 Land use (landtake)
12 Non-renewable resource use
13 Ozone depletion
14 Climate change
15 Safety of transport users and residents.

The case study was based on the preposition of the regional road project with a design of new road construction. This proposal is described in the next part of this text. The advantage of general model is that respondents are not influenced by NIMBY effect.

The Analytical Hierarchical Process (AHP) (Saaty, 1980; 1999) is based on mathematics and psychology and serves as a mathematical solution method for individual or group decision-making with multiple criteria (indicators in out case). It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. It is used around the world in a wide variety of decision situations, in fields such as government, business, industry, healthcare, and education.

The procedure for using the AHP consists of:
− The problem hierarchy containing the decision goal (selection of the best alternative according to the given indicators), the alternatives for reaching it, and the criteria for evaluating the alternatives.
− Priorities among the elements of the hierarchy by making a series of judgments based on pairwise comparisons of the elements.
− Synthesize these judgments to yield a set of overall priorities for the hierarchy.
− Check the consistency of the judgments.
− A final decision based on the results of these processes.

*The problem hierarchy*

A hierarchy is a system of ranking and organizing people, things, ideas, etc., where each element of the system, except for the top one, is subordinate to one or more other elements.

In the world of ideas, we use hierarchies to help us acquire detailed knowledge of complex reality: We structure the reality into its constituent parts, and these in turn into their own constituent parts, preceding down the hierarchy as many levels as we care to.

*Establishing and synthesizing of priorities*

Once the hierarchy has been constructed, users can establish priorities for all its nodes. Priorities are distributed over a hierarchy according to its architecture, and their values depend on the information entered by users of the process.

Two additional concepts apply when a hierarchy has more than one level of criteria: local priorities and global priorities. Within a hierarchy, the global priorities of child nodes always add up to the global priority of their parent. Within a group of children, the local priorities add up to 1000.

*Consistence*

The calculated priorities are plausible only if the comparison matrices are consistent or near consistent. A pairwise matrix is called consistent if the transitivity and the reciprocity rules are respected. Especially for high order matrices, consistency is difficult to reach because the number of transitive rules to satisfy increase quadratically. To improve an inconsistent matrix, a user can be urged to reconsider pairwise comparisons until the consistency measure proves to be satisfactory. Feedback after the completion of the comparison matrix is frustrating to the user, because it gives no hints about the comparisons to reconsider.

*Assessment method for criteria preferences*

MS Excel was used to obtained data from different groups of respondents by the form of electronic questionnaire (file). The structure of electronic questionnaire was prepared in a way that it enabled an easy work for respondent. The MS Excel file consisted of three sheets (one of them invisible) and macro code. The first sheet contents a description of model situation: See Figure 48 a brief explanation of 15 criteria (indicators) meaning. Explanation serves as a support for public that is not informed about importance (sense) of impacts characterised by indicators.

**Figure 48. Description of model situation**
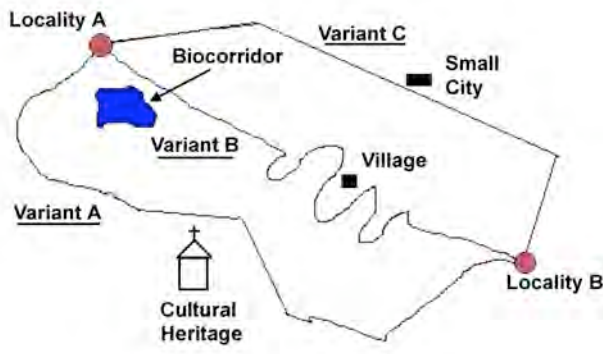
**Figure 49. Electronic questionnaire**



The second sheet contents tools (see Figure 49) that can help with pairwise comparison to respondent. Scroll bars and check boxes were used here. Next, expected transport context was described here; In this case transport context

means: transport project of regional importance – characterization, rebuilding of local or municipal roads, change or rebuilt of junction (roundabout versus traffic lights), construction of new roads (max. 7 m width, length of construction up to 3 to 5 km), structure of traffic flow with max. 20 % heavy vehicles, rush hour intensity max. 1000 unit veh./h. etc.). Respondent was asked to compare values of these 105 pairs of indicators by use of scroll bar and after it to mark a check box. The condition of questionnaire's completing was that every check box had to be marked. This condition was checked after the use of button "FINISHED". In case that every check box was marked the sheet was protected against changes and respondent was asked for saving the file. Values of scroll bars were linked with the table located on invisible (hidden) sheet (lower side of Figure 49). Values from this table were used for calculation of AHP preferences.

*Preferences Evaluation of Environmental Impact Criteria*

Evaluation method for preferences or importance uses AHP method. A hierarchical structure of criteria and experts' (respondents) preference estimation of elements on different levels can be used for calculation of quantitative weights of all primary indicators.

Two variants of model were used.

The first model variant can be called "One step comparison". This model has four levels complete hierarchy (see Figure 50):
1. The first level represents the goal – the indicators preference setting.
2. The second level consists of three groups of respondents. The first one is a group of experts, the second is a group of students of subject "Decision models", and the third one is a group of students of subject "Logistic systems", distinguished by note number 1 or 2 in the figure.
3. The third level represents the judgement of asked experts and students.
4. On the fourth level there are listed 15 environmental indicators see e.g. Figure 49.

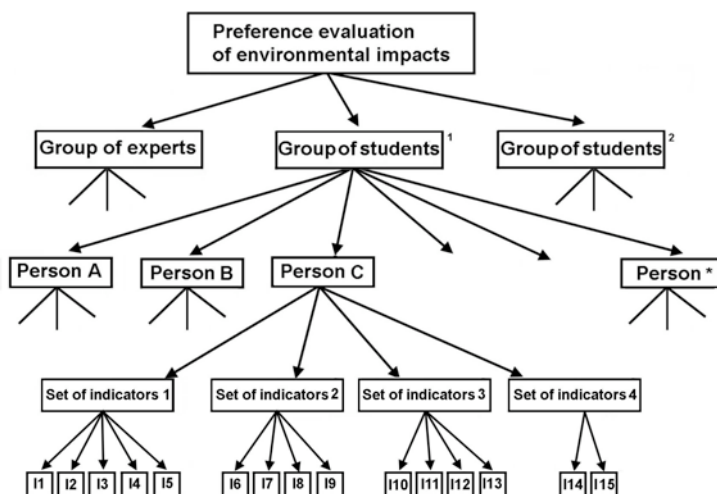**Figure 50. One step comparison hierarchy**
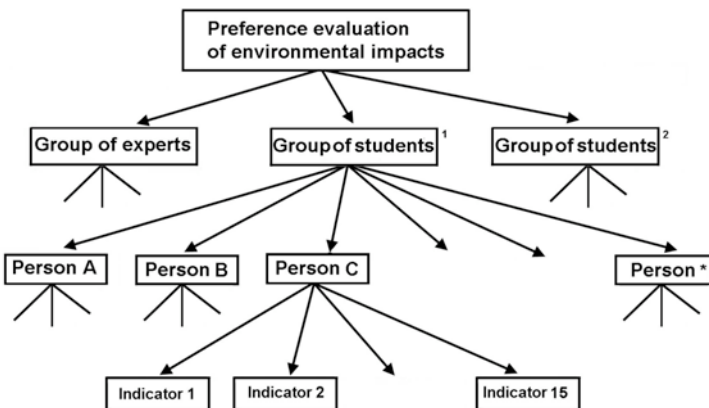
Preferences on these levels are set using Saaty method of pairwise comparison. Preferences of all indicators of environmental impacts factors are calculated as a synthesis of preferences on different levels of hierarchy.

The second model variant can be called "Two step comparison". This model has five levels complete hierarchy (see Figure 51). The three first levels are the same than above in the one step comparison. The 4th and 5th levels are:

4. The fourth level consists of 4 sets of indicators, which consist of the kindred impact factors.
5. On the fifth level there are 15 environmental impacts factors that are selected as a result of project COST 350.

**Figure 51. Two step comparison hierarchy**



Preferences on these levels are set using Saaty method of pairwise comparison. Preferences of all indicators of environmental impacts are again calculated as a synthesis of preferences on different levels of hierarchy.

*Results and discussion*

Three groups of respondent consist of 22 transport experts (people employed in transport sector), 59 students of logistic systems (so called "informed public") and 24 students of decision models (so called "public") were inquired. It is necessary to remark that this sample represents educated people without any links to specified conditions (NIMBY was excluded).

Processing of obtained data performs the check of consistency and omitting of non consistency respondents. Global synthetic preferences were carried out according to the decision hierarchy. Above described models and with these specifications were used:

• One step model
Equal preferences of group of respondents (1/3);
Equal preferences of respondents within group (1/n);

Preferences values of impacts are set using Saaty's pairwise comparison method.

- Two steps model without weights
Equal preferences of group of respondents (1/3);
Equal preferences of respondents within group (1/n);
Equal preferences of group of impacts (1/4) (model was proposed with the aim to compare it with weighted groups);
Preferences values of impacts are set using Saaty pairwise comparison method indicator groups.

- Two steps model with weights
Equal preferences of group of respondents (1/3);
Equal preferences of respondents within group (1/n);
Preferences of group of indicators according to the number of indicators in various groups (5/15, 4/15, 4/15, 2/15) - various groups were created as see Table 60.
Preferences values of criteria are set using Saaty pairwise comparison method criteria groups.

### Table 60. Various groups

| Group 1 | Local air quality | Regional air quality | Quality and use of water | Ozone depletion | Climate change |
|---------|-------------------|----------------------|--------------------------|-----------------|----------------|
| Group 2 | Noise and vibration | Waste | Light pollution | Non-renewable resource use | |
| Group 3 | Protected areas | Loss of biodiversity | Landscape, cultural and built heritage | Land use | |
| Group 4 | Technological hazards | Safety of transport users and residents | | | |

The final results are presented in Figure 52 and Figure 53. The Figure 52 presents order (rank) of indicators. These values represent average values of all respondents (excluding respondents with low consistency). It is possible to say that some indicators have a very high correspondence among every model - especially land use, light pollution, landscape and cultural and built heritage, non-renewable resources, loss of biodiversity, safety, but every criterion of these correspondences has higher values of rank i.e. its importance is lesser (lesser weight). Lesser rank correspondence between one and two step models can be seen in local air quality, regional air quality, noise and vibration. Differences of these indicators are reduced in comparison of weighted and not weighted two step models. It would be possible to say that it is easier for respondents to find conformable standpoint in more general indicators than in quality of air and noise and vibration.

Considerable differences can be only seen in indicators of climate change and safety of transport users – it can be explained by extremely different views of respondents. It possible to presume that some part of public is not persuaded

that climate change has any relation with transport and another part of public does not include safety of transport users as criterion for environmental impact. Another point of this explanation could be in regional transport context. Differences among groups of respondents are described in details in other authors' publication.
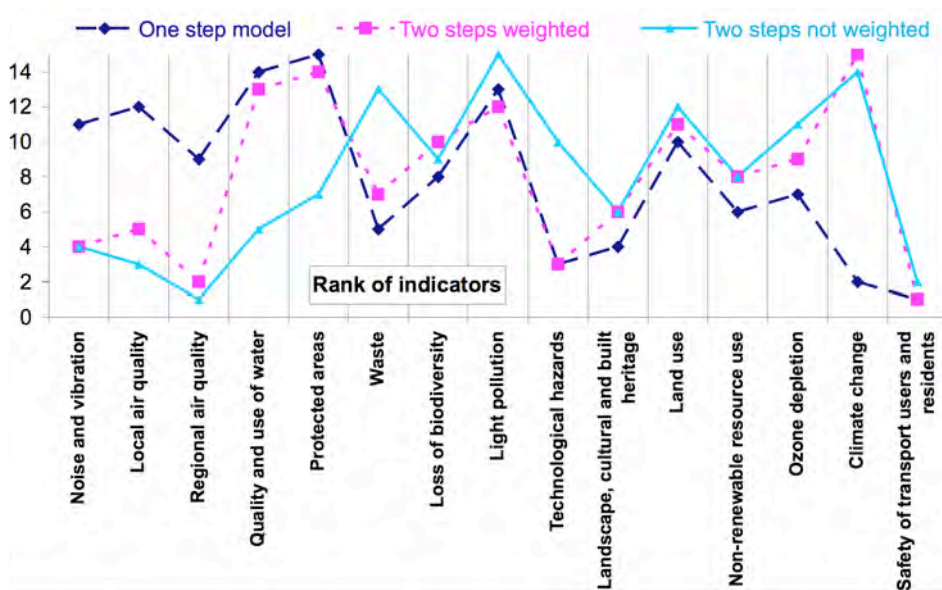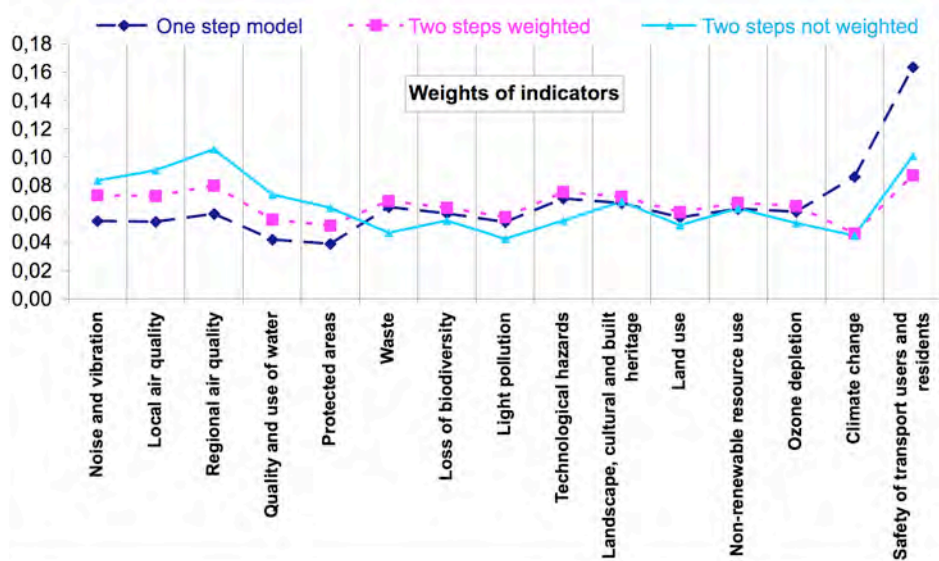
**Figure 52. Rank (order) of indicators**



**Figure 53. Weights of indicators**

*Conclusion*

The experience with the use of AHP pairwise comparison for determination of criteria (aggregated indicator) preference proved the following conclusions:

- electronic questionnaires - it is possible to recommend these questionnaires from the point of view of easy data processing (pairwise comparison value could be obtained e.g. from internet database with adequate interface and non-restricted access instead of used MS Office product).

- pairwise comparisons in case of higher number of indicators - the work attention of respondents has decreasing tendency. It is possible to recommend create groups of indicators and reduced number of necessary pairwise comparisons.

- results of indicator preference determination proves possibilities to use values of weights and AHP method for EIA/SEA instead of contemporary ways of assessment.

- the case study proves the necessity to determine quantified aggregated indicators (criteria) for enhancing EIA/SEA processes.

# Annex 12. MCDA and non-MCDA approaches

**Author: N. Kunicina**

**Table 61. Possible classification of MCDA methods and tools**

| Category | MCDA method |
| --- | --- |
| Fuzzy set analysis | Fuzzy set analysis (software TOMASO). |
| Distance to ideal point | Compromise programming |
| Pairwise comparison | Analytic Hierarchy process (AHP)/Analytic Network Process (ANP); Macbeth; Pairwise Criterion Comparison Approach (PCCA): Martel and Zaras´ method; MAPPAC; PRAGMA; IDRA; PACMAN |
| Outranking methods | ELECTRE I, Iv, IS, II, III, IV, TRI; PROMETHEE I, II, III, IV, V; IV, visual interactive module GAIA; ITIS; NTHomic; VIKTOR; PROAFTM; Suremesure; AGATHA; MAPPAC; PRAGMA; IDRA; PACMAN |
| Conjoint measurement tools | Utilities Attribute (UTA) methods |
| Particular binary relations | Qualiflex; REGIME; ORESTE; ARGUS; Evamix; MELCHIOR; TACTIC |
| Multi – criteria value function | Multi attribute utility theory (MAUT) |
| Distance to ideal point and outranking methods | Multicriterion Q analysis (MCQA I, II, III) |
| Verbal | ZAPROS |
| Distance to ideal point | EXTROM, TOPSIS |
| Others | Pert scheduling, THOR, SEMA, If 0 then analysis; NAIADE; PAMSSEM; PATTERN |

Source: Kunicina (2008)

### *Other Non-MCDA approaches*

*Negotiations (Negotiation theory).* The foundations of negotiation theory are decision analysis, behavioural decision making, game theory, and negotiation analysis. Another classification of theories distinguishes between Structural analysis, Strategic analysis, Process analysis, Integrative analysis and behavioural analysis of negotiations. The main approaches and applications are published in the journal Group Decision and Negotiation. Main standardized techniques for making decisions by negotiation are described by game theory.

The realization of special software – multi and intelligent agent systems are based on standardised negotiation paradigms. The effective tools for negotiation also named negotiation support system (see Lim, 2003) (as a part of decision support system).

*Game theory* is a branch of applied mathematics that attempts to mathematically capture behaviour in strategic situations, in which an individual's success in making choices depends on the choices of others (see von Neumann and Morgenstern, 2007). Its subject is the analysis of acceptance of optimum decisions in the conditions of the conflict.

The *''Delphi method''* is a systematic, interactive (forecasting) method, which relies on a panel of independent experts. The carefully selected experts answer questionnaires in two or more rounds. After each round, a facilitator provides an anonymous summary of the experts' forecasts from the previous round as well as the reasons they provided for their judgments. Delphi method is successfully applied for negotiation and decision making process organisation (see Ferguson *et al*., 2005).

*Clustering methods (data clustering):* is a problem of splitting of the set sample of objects (situations) on not crossed subsets named clusters so that everyone cluster consisted of similar objects, and and different objects are essentially different in clusters. Three methods were used: K-means, Self-organizing map and Genetic algorithms.

*Fuzzy sets* are setting the elements which have the degrees of membership. Fuzzy sets have been introduced by Zadeh (1965). Example of application is a priority based fuzzy goal programming approach for solving a multi-objective transport problem with fuzzy coefficients (see Pramanik and Roy, 2008).

Problem solving technique could be applied for NP hard problems (non-deterministic polynomial-time hard). In computational complexity theory, it is a class of problems informally "at least as hard as the hardest problems in NP". There are special issues of NP hard problems descriptions. A mathematical problem for which there is no simple or rapid solution is NP-hard problem. Examples of NP-hard problems include the travelling salesman, Seven Bridges of Königsberg (Euler's bridges).

NP-hard problems may be of any type: decision problems, search problems, optimization problems.

*Operational Research* is an interdisciplinary branch of applied mathematics and formal science that uses methods like mathematical modelling, statistics, and algorithms to arrive at optimal or near optimal solutions to complex problems.

Logistics problems (in case of transport) as "if – then analysis" see also Perfilieva *et al*. (2008), which allows to simulate result of innovation at computer model, instead of making a project and then see results; ABC and XYZ ranking, which allows to group of main transport roots in clusters, this technique is used also for inventory management (see also Chena *et al*., 2008) which allows to make for example traffic assignment and trip distribution (Larichev, 2000).

*Decision maps and decision trees (*Li, 2005): This method allows to find critical path in decision making, and to analyse various possible results from one decision; *Pareto set* allows to have set of equivalent area of decisions - Pareto decisions (see also example in Miettinen *et al*., 2009).

Design of *new alternatives*, based on win-win principle (Zeleny, 2006) allows to have ideal alternative, instead of choosing best decision from bad alternatives.

# Annex 13. Overview of methods for joint consideration of indicators: Multi-criteria decision making methods (MCDM)

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The following is an excerpt extracted from Malczewski (1999). The methods are only for attribute aggregation, there are more methods for objective aggregation.

*Overview*

See Table 62.

*Methods description*

*Scoring*

Scoring methods are based on the concept of a weighted average. The decision maker directly assigns weights of "relative importance" to each attribute. A total score is then obtained for each alternative by multiplying the importance weight assigned for each attribute by the scaled value given to the alternative on that attribute, and summing the products over all attributes. When the overall scores are calculated for all the alternatives, the alternative with the highest overall score is chosen. The decision rule evaluates each alternative, $A_i$, by the following formula:

$$A_i = \sum_j w_j \cdot x_{ij}$$

where $x_{ij}$ is the score of the $i$th alternative with respect to the $j$th attribute, and the weight $w_j$ is a normalized weight, so that $\sum w_j = 1$.

*Multi-attribute value*

The value function approach is applicable in the decision situations under certainty (deterministic approach). This approach assumes that the decision maker is relatively "risk neutral" or that the attributes are known with certainty. Formally, the value function model is similar to "scoring method", except that the score $x_{ij}$ is replaced by a value $v_{ij}$ derived from the value function. The value function model can be written:

$$V_i = \sum_j w_j \cdot v_{ij}$$

where $V_i$ is the overall value of the $i^{th}$ alternative, $v_{ij}$ is the value of the $i^{th}$ alternative with respect to the $j^{th}$ attribute measured by means of the value

function, and the weight $w_j$ is a normalized weight or scaling constant for attribute $j$, so that $\sum w_j = 1$.

**Table 62. Characteristics of some attribute aggregation methods**

| Method | Input | Output | Decision types |
|---|---|---|---|
| Scoring | Attribute scores, weights | Ordinal ranking | Individual decision making, deterministic |
| Multi-attribute value | Value functions, weights | Cardinal ranking | Individual and group decision making, deterministic, fuzzy |
| Multi-attribute utility | Utility functions, weights | Cardinal ranking | Individual and group decision making, probabilistic, fuzzy |
| Analytic hierarchy process | Attribute scores, pairwise comparisons | Cardinal ranking (ratio scale) | Individual and group decision making, deterministic, probabilistic, fuzzy |
| Ideal point | Attribute scores, weights, ideal point | Cardinal ranking | Individual and group decision making, deterministic, probabilistic, fuzzy |
| Concordance | Attribute scores, weights | Partial or ordinal ranking | Individual and group decision making, deterministic, probabilistic, fuzzy |
| Ordered weighted averaging | Fuzzy attribute, weights, order weights | Cardinal or ordinal ranking | Individual and group decision making, fuzzy |

| Method | Decision making interaction | Assumptions | Tool / software |
|---|---|---|---|
| Scoring | Moderate | Non-restrictive | Spreadsheets |
| Multi-attribute value | High | Very restrictive | Logical decisions, MATS, spreadsheets |
| Multi-attribute utility | High | Very restrictive | Logical decisions, HIPRE3+, spreadsheets |
| Analytic hierarchy process | High | Moderately restrictive | Expert choice, HIPRE3+, Which&why, spreadsheets |
| Ideal point | Moderate | Non-restrictive | AIM, spreadsheets |
| Concordance | Moderate | Non-restrictive | ELECTRE III and IV, spreadsheets |
| Ordered weighted averaging | Moderate | Moderately restrictive | Spreadsheets |

*Multi-attribute utility*

In the utility function procedure, the decision's maker attitude toward risk is incorporated into assessment of a single-attribute utility function (Keeney, 1980). Thus utility is a convenient method of including uncertainty (risk preference) into decision making process. The concept of a utility function is inherently probabilistic in nature. Formally, the utility function model is similar to "scoring method", except that the score $x_{ij}$ is replaced by a utility $u_{ij}$ derived from the utility function. The utility function model can be written:

$$U_i = \sum_j w_j \cdot u_{ij}$$

where $U_i$ is the overall value of the $i^{th}$ alternative, $u_{ij}$ is the utility of the $i^{th}$ alternative with respect to the $j^{th}$ attribute measured by means of the utility function, and the weight $w_j$ is a normalized weight or scaling constant for attribute $j$, so that $\sum w_j = 1$.

*Analytic hierarchy process*

The analytical hierarchy process (AHP) method, developed by Saaty (1980), is based on tree principles: decomposition, comparative judgment and synthesis of priorities. The *decomposition principle* requires that the decision problem be decomposed into a hierarchy that captures the essential elements of the problem, the principle of *comparative judgment* requires assessment of pairwise comparisons of the elements within a given level of the hierarchical structure, with respect to their parent in the next-higher level, and the *synthesis principle* takes each of the derived ratio-scale local priorities in the various levels of the hierarchy and constructs a composite set of priorities for the elements at the lowest level of the hierarchy. In this final step, the goal is to aggregate the relative weights of the levels obtained in the previous step to produce composite weights. This is done by means of a sequence of multiplications of the matrices of relative weights at each level of the hierarchy.

*Ideal point methods*

Ideal point methods order a set of alternatives on the basis of their separation from the ideal point. This point represents a hypothetical alternative that consists of the most deliverable weighted standardized levels of each criterion across the alternatives under consideration. The alternative that is closed to the ideal point is the best alternative. The separation is measured in terms of a distance metric. The ideal point decision rule is:

$$s_{i+} = \left[ \sum_j w_j^p \left( v_{ij} - v_{+j} \right)^p \right]^{1/p}$$

where $s_{i+}$ is the separation of the $i^{th}$ alternative from the ideal point, $w_j$ is a weight assigned to the $j$ criterion, $v_{ij}$ is the standardized criterion value of the $i^{th}$ alternative, $v_{+j}$ is the ideal value for the $j^{th}$ criterion, and $p$ is a power parameter ranging from 1 to ∞.

*Concordance methods*

Concordance methods are based on a pairwise comparison of alternatives. They provide an ordinal ranking of the alternatives. That is, when two alternatives are compared, these methods can only express that alternative A is preferred to alternative B, but cannot indicate by how much. The most known concordance approach is the ELECTRE method and its modifications.

*Ordered weighted averaging*

Ordered weighted averaging is an aggregation technique based on the generalization of three basic types of aggregation functions, which are: (1) operators for the intersection of fuzzy set, (2) operators for the union of fuzzy sets, and (3) averaging operators. It provides continuous fuzzy aggregation operations between the fuzzy intersection and union, with a weighted-average combination falling midway in between.

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**Summary**

This report is the final report of the action COST 356 'EST - Towards the definition of a measurable environmentally sustainable transport'. It tries to answer the following questions: How can environmental impacts of transport be measured? How can measurements be transformed into operational indicators? How can several indicators be jointly considered? And how can indicators be used in planning and decision making? Firstly we provide definition of 'indicator of environmental sustainability in transport'. The functions, strengths and weaknesses of indicators as measurement tools, and as decision support tools are discussed. We define what "environmental sustainability in transport" may mean through the transport system, the concepts of sustainable development and of environment. The concept of 'chain of causality' between a source and a final target is developed, as a common reference for indicators and assessments. As the decision making context influences the perceived and actual needs for indicators and methods, we also analysed the dimensions and context of decision making. We derived criteria and methods for the assessment and selection of indicators of environmental sustainability in transport, in terms of measurement, monitoring and management. The methods and the criteria are exemplified for seven chains of causality. Methods for a comprehensive joint consideration of environmentally sustainable indicators are analyzed and evaluated. They concerned aggregated or composite indicators as well as multi-criteria methods. Five case studies are presented. Finally, recommendations for continued research and development of indicators and joint considerations methods for assessment of environmental sustainability in transport are given.

| **Key Words** | | | |
|---|---|---|---|
| Transport, environment, impact, decision making, indicator, method, joint consideration, multi-criteria analysis. | | | |

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**Résumé**

Ce rapport final de l'action COST 356 'EST – Mesurer la soutenabilité environnementale des transports' tente de répondre aux questions suivantes : comment mesurer les impacts des transports sur l'environnement ? Comment transformer ces mesures en indicateurs opérationnels ? Comment prendre en compte conjointement plusieurs indicateurs ? Et comment utiliser des indicateurs comme aide à la décision et à la planification ? Nous définissons tout d'abord un 'indicateur de soutenabilité environnementale dans les transports'. On discute les fonctions et les avantages des indicateurs en tant qu'outils de mesure et d'aide à la décision. Nous définissons la 'soutenabilité environnementale dans les transports' par le biais du système de transports, et des concepts de développement durable et d'environnement. On développe le concept de 'chaîne de causalités' entre une source et une cible finale comme référence commune des indicateurs et des évaluations. Comme le contexte décisionnel influence les besoins perçus et réels d'indicateurs et de méthodes, nous analysons aussi les dimensions et le contexte de la décision. Nous en déduisons des critères et des méthodes d'évaluation et de sélection d'indicateurs de soutenabilité environnementale dans les transports, en termes de mesure, de surveillance et de gestion. Méthodes et critères sont illustrés pour sept chaînes de causalités. On analyse et on évalue les méthodes de prise en compte conjointe d'indicateurs de soutenabilité environnementale par le biais des indicateurs agrégés ou composites et des méthodes multicritères. On présente cinq études de cas. On fait enfin des recommandations en termes de recherche et de développement d'indicateurs et de méthodes pour évaluer la soutenabilité environnementale dans les transports.

**Mots clés**

Transport, environnement, impact, aide à la décision, indicateur, méthode, considération commune, analyse multicritère.

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How can environmental impacts of transport be measured? How can measurements be transformed into operational indicators? How can several indicators be jointly considered? And how can indicators be used in planning and decision making?

This book contains the results of an interdisciplinary group of about thirty researchers meeting regularly to discuss these questions along the period 2005-2010. The researchers were from natural as well as social sciences, and all engaged in the field of transport and environment.

The report provides analysis of the functions, strengths and weaknesses of indicators, the dimensions and context of decision making, and introduces the concept of "chain of causality" between a source and a final target. It then proceeds to derive criteria and methods for the assessment and selection of indicators, exemplified for seven chains of causality, including climate change, noise or loss of cultural heritage. Finally it includes an extensive analysis and evaluation of methods to build composite indicators as well as multi-criteria methods for assessment. The authors give a state-of-the-art overview for those interested in methods to evaluate simply, accurately and efficiently the impact of transport on the environment. They conclude with a series of recommendations and research needs.

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