ENVIRONMENTAL ASPECTS IN TUNNEL DESIGN

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ABSTRACT

Designers of infrastructure are aware that the government, owners and users become more and more concerned about negative environmental impacts of tunnels, so environmental aspects of tunnels are becoming an issue in the process of tunnel design of increasing importance.
An inventory of the environmental aspects of all types of tunnel constructions was performed and these aspects were ranked to importance for the tunnel design process. Further a method and a tool were developed to facilitate the decisions in the tunnel design process to select the most cost-effective measures that decrease the environmental impacts of a tunnel. Indirect costs of environmental impacts are taken into account in this method, which assumes that the consequences of environmental impacts can be monetarised. The method is presented here and is, as an example, applied to select the most cost effective (set of) measures to abate the impact of noise from tunnel portals.

1. INTRODUCTION

This study was performed in the framework of the DARTS (Durable and Reliable Tunnel Structures) project. The objective of the DARTS project was to develop operational methods and supporting practical tools for a pro-active decision-making process for selecting the economic most optimal tunnel construction. It is obvious that in this decision making process the technical qualities, safety precautions, service life and environmental aspects are equally important since the decisions should ensure the choice for the most sustainable and durable design in combination with the lowest costs. This article deals with the environmental aspects of decision making in the design process.
Environmental issues pop up during all phases of the design process and must be assessed to provide the stakeholders with the adequate information so that they can take the right decisions and can foresee the consequences of these decisions. DARTS developed a straightforward and simple model for the design process in which the moments that stakeholders make decisions on the tunnel designs during the design process is visualized. Four phases are distinguished in this model, each consecutive phase represents a more detailed design and consequently in each phase the stakeholders need more detailed information to make the right decisions. Each phase has a specific set of stakeholders that are responsible for the decisions and their consequences.

The design model and the assignment of the most important stakeholders for the decisions dealing with environmental issues, and the level of detail that is needed are presented in this paper. This information will help to understand the decision making process and allows us to develop a tunnel design method.
Various environmental effects play a role during the realisation phase and the exploitation phase of a tunnel and must be considered during the design phases. In the DARTS project a comprehensive inventory was performed to reveal these effects. The results are presented in this paper.
The basis of the DARTS design method is the economic optimisation (or, to be more precise: a societal cost benefit optimisation which includes the direct and the indirect costs and benefits) of design options combined with a probabilistic approach of the design variables and the costs. It is therefore necessary to provide the designers with this statistical, economical and probabilistic information. This means that we also need this kind of information on the environmental impacts (the indirect costs). However, it is still not common practise to present the impact of environmental effects as an amount of money and neither is there a uniform technique or instrument to provide us with that information. A list of methods that can help to deal with this is presented in his article.
A (combination of) measure(s) may be applied to abate or to mitigate the impact of environmental effects, but what is the most optimal combination? A standard procedure and tool based on the DARTS design model were developed to select the most optimal (combination of) measure(s). This procedure and tool should be applied to each design (environmental) aspect. This paper presents this procedure and tool and gives an example of the use.

2. ENVIRONMENTAL ASPECTS OF TUNNELS

2.1 Inventory of the environmental aspects

A tunnel project has impacts on 4 types of environment as shown in figure 1. We distinguish the natural environment, the man-made environment, humans and society. In order to develop an adequate design method we can confine ourselves to impacts on the first 3 types; the impact on society and the effects on the construction people of a tunnel are not considered here. The tunnel has an impact on its environment, but vice versa the natural environment will also have an impact on the tunnel, like for instance chemical effects (salt intrusion) and physical effects (instability of soil, earthquakes). However, this is not the subject of this paper but will be presented elsewhere as it is an aspect of the technical durability of tunnel design.
Various environmental effects play a role during the realisation phase and the exploitation phase of a tunnel and must be considered during the design phases. The effects of a tunnel on the natural environment, the man-made environment and on humans are caused by either chemical or physical impacts. The chemical impacts on the environment are caused by emissions of various kinds; the seriousness of the impact is dependent of the existing environmental quality. The existing environmental quality may give risks (delay, extra costs) to realisation and maintenance of a tunnel and should therefore be analysed and pictured beforehand.

The physical impacts on the environment may affect the:

- living conditions for humans 'humans' (e.g. noise)
- habitat of fauna around the tunnels ' natural environment' (e.g. disturbance)
- cultural quality 'man made environment' (e.g. landscape and design)
- use of resources 'natural environment' (e.g. depletion of energy and materials)

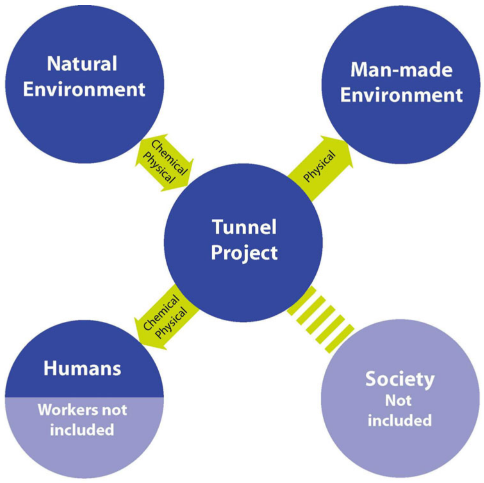

Figure 1 Four types of environment are effected by a tunnel project

A comprehensive study was performed to make an inventory of all the environmental aspects that can play a role during the realisation and exploitation phase of a tunnel. These aspects were listed and are presented in table 1. The DARTS055 report[1] gives more background information on these environmental aspects.
It is desirable to be able to calculate the impacts of all these different effects and to present the quantitative results. This is needed as input for the economic optimisation of the design.

Environmental issues (general)	Environmental effects / aspects	Parameters / Units
Emissions	Air pollution (traffic & explosives)	load in g/day and concentration of: SO_2, $NO_{2/x}$, CO, benzene, lead (Pb), fine dust particles (PM10), see also Emissions directive (EC) in µg/m^3
	Smell	number of complaints during a certain period (a day, a month)
	Wastewater (rain, drainage, groundwater, drilling)	concentration (mg/l), environmental effect in terms of: load on sewage purification plant, duration time * concentration * toxicity, costs to purify the waste water (€)
	Pollution of ground & groundwater	kg of pollutant spilled or lost, tons of polluted soil, mg pollutant/kg soil dry weight (d.w.), m^3 polluted groundwater, mg pollutant/l, costs of a risk assessment of the risk of pollution, the costs of measures that must be taken in order to prevent pollution, the costs of the clean up activities
	Pollution of surface water	the area that has been polluted (m^2), the amounts of pollutants that have been discharged on the surface water (g), the effects on wildlife (mortality, reduction of nr of species, etcetera)
	Pollution of excavated material (debris/muck/dredged material)	m^3 polluted material, concentration of pollution, type of pollution
Environmental quality	Quality of soil & groundwater	tons of polluted soil, mg pollutant/kg soil (dry weight), m^3 polluted groundwater, mg pollutant/l, Other important factors are: the content of Fe^{2+}-iron, total nitrogen, nitrate, soluble oxygen and salinity in groundwater
	Air quality	concentration and kind of pollutants
	Surface water quality	concentration and kind of pollutants
	Groundwater level	groundwater level in m, m^2 of land influenced by groundwater lowering, flow of groundwater to the tunnel in l/s or l/min/100m tunnel, other chemical parameters could be relevant to monitor changes in the composition of the groundwater as well, for instance: mg pollutant/l, m^3 polluted groundwater, chlorosity (concentration of chloride), salinity or conductivity, costs of damage repair
	Soil (in)stability	costs of damage repair , costs of risk assessment and costs of measures to prevent soil instability
Materials	Primary building materials	m^3 (tonnes) saved, improved LCA-score (Life Cycle Analysis)
	Secondary building materials	m^3 (tonnes) used in stead of primary building materials, improved LCA-score
	Renewable materials	improved LCA-score
	Reusable excavated material	m^3 of sediment or rock to be reused, size fractions
	(Chemical) Products	Quantity : cables, signalling - , lighting - & electronic equipment, ventilation, generators, pumps, pipes, batteries, chemicals (detergents, paints, glues, solvents, etc), existing lca-information
	(Dangerous) Waste material	m^3 (tonnes) of dangerous waste and m3 of non-dangerous waste (e.g. pile sheets left)
Energy	Production of building materials	tonnes of CO_2 or MegaJoules (MJ), €
	Transport of building materials	tonnes of CO_2 or MegaJoules (MJ), €
	Construction equipment	tonnes of CO_2 or MegaJoules (MJ), €
	Installations	tonnes of CO_2 or MegaJoules (MJ), € during exploitation
	Traffic	tonnes of CO_2 or MegaJoules (MJ, roller coster effect: Copenhagen-metro!) €
Living conditions	Noise	number of persons hindered, costs to mitigate the effects, decibels
	Vibrations	number of persons 'hindered', costs of damage to structures, scale of Richter
	Dust	number of persons hindered, costs to mitigate the effects
Cultural quality	Visual design & landscape values	appreciation
	Archaeological, palaeolontological and geomorphological values	number of sites effected, time (delay during realisation), costs of excavations
	Historical and cultural heritage	number of items effected, costs of precautionary measures, costs of replacements and repair, time (delay during realisation)
	Demolition of real estate & other man made structures	costs of replacement and repair, costs to buy out the owners of real estate
Habitat	Degradation of habitat	area (m^2) that is degraded (for instance caused by decrease of groundwater level or other causes: pollution, disturbance, etc) time span of degradation (reversible or irreversible), size of population (% of species of the population) that is gone
	Fragmentation of habitat	population and nr of specific species (flora/fauna) that are divided (Habitat directive, EC)
	Disturbance of fauna	number of species and/or number of animals hindered

Table 1 Overview of all the environmental aspects that play a role in tunnel design and their parameters / units

2.2 Relative importance of environmental effects

It is obvious that not all the environmental aspects are equally important in the design process. An extensive study was performed in order to reveal the most important aspects in the tunnel design process: several workshops were held with construction engineers and designers and a number of project managers were interviewed. They were also asked to indicate which actions for what environmental aspects should be performed in each specific phase. This resulted in a ranking of the environmental aspects to importance (see table 2).
The darker the boxes are in table 2, the more important the aspect is in that phase of the process. The twelve most important aspects are indicated with an arrow.

	Environmental issue	Environmental effects/aspect	Feasibility study	Conceptual design	Outline design	Detailed design	Realisation	Exploitation
⇨	Emissions	Air pollution (traffic during exploitation)						
⇨	Living conditions	Noise & vibrations during exploitation						
⇨	Energy	Traffic during exploitation						
⇨	Cultural quality	Visual design and landscape values						
⇨	Environmental quality	Groundwater level during realisation						
⇨	Environmental quality	Soil stability during realisation						
⇨	Habitat	Fragmentation of habitats						
⇨	Habitat	Degradation of habitat						
⇨	Habitat	Disturbance of fauna						
⇨	Cultural quality	Historical and cultural heritage						
⇨	Energy	Installations						
⇨	Living conditions	Noise, vibrations & dust during realisation						
	Emissions	Waste water						
	Emissions	Pollution of ground and groundwater						
	Materials	Primary building materials						
	Materials	Secondary building materials						
	Materials	Reusable excavated material						
	Materials	Chemical products						
	Materials	(Dangerous) waste material						
	Environmental quality	Quality of soil and groundwater						
	Emissions	Pollution of excavated material						
	Cultural quality	Archaeological values etc.						
	Materials	Renewable materials						
	Emissions	Pollution of surface water						
	Cultural quality	Demolition of real estate etc.						
	Energy	Production of building materials						
	Energy	Transport of building materials						
	Energy	Construction equipment						
	Environmental quality	Air quality						
	Environmental quality	Surface water quality						
	Emissions	Air pollution (explosives/rock tunnel)						

Table 2 Environmental aspects ranked to importance.

3. THE DESIGN PROCESS AND THE ENVIRONMENTAL ASPECTS

3.1 The DARTS model of the design process

A standard procedure based on the DARTS design model was developed (see figures 2 and 3). This procedure should be elaborated for each (environmental) effect or design aspect. The procedure includes directions for each phase of the design process: effects must be modelled, quantified and monetarised; mitigating and anticipating measures should be proposed and assessed and, as a result, the effectiveness and costs of each measure should be calculated and presented. The procedure also provides in the application of a uniform economical analysis.
The result of this analysis is the information that is used to take the decisions for the next step in the design process.

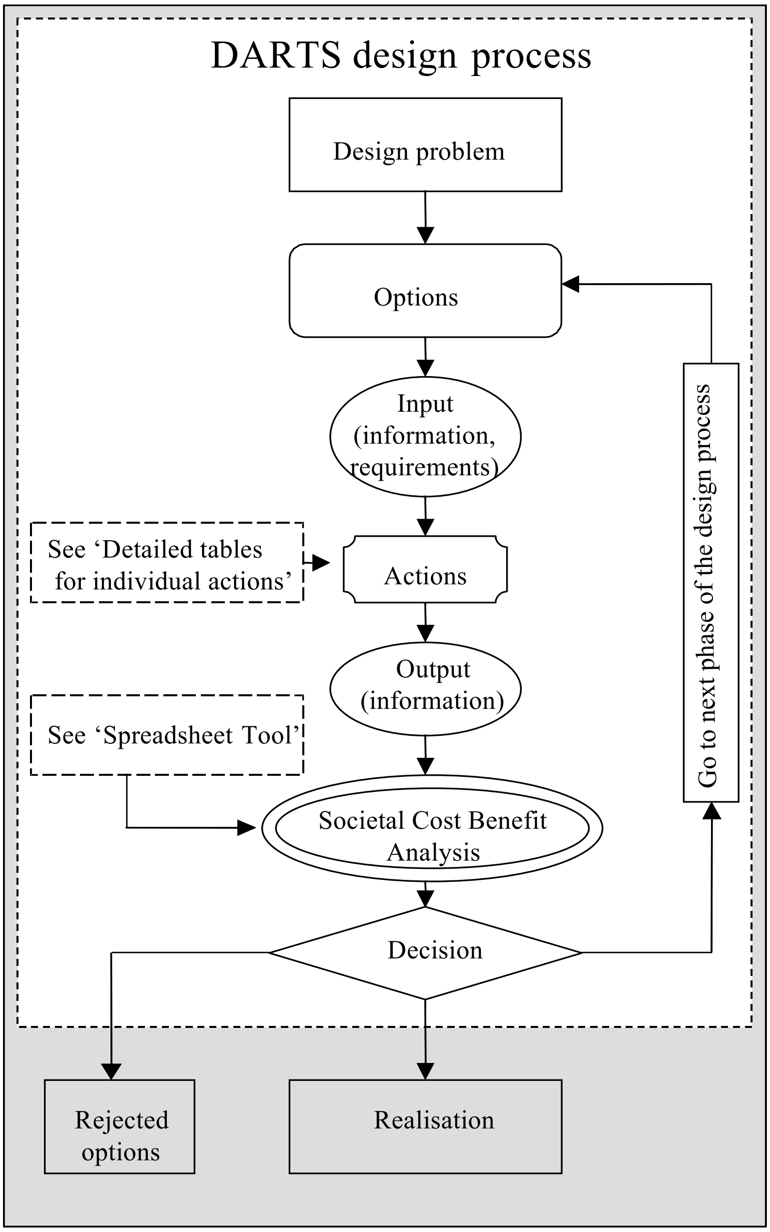

Figure 2 The simplified model for the design process according to DARTS

3.2 Decisions and stakeholders

The solution for an infrastructure problem develops gradually during the design process from a general idea into a set of very detailed instructions to the contractor. The DARTS approach distinguishes 4 phases in an iterative design process. These are: 1) the feasibility study; 2) the conceptual design; 3) the outline design and 4) the detailed design. In principle each phase passes through the same set of activities and shows the same characteristics, only the details increase and the decision makers (stakeholders) of each phase differ. It is very important that the designers realise for whom they produce the information: e.g. the commissioner and the financers are not interested in the details of the design and the realisation, while neighbouring citizens are not interested in the costs, but worry about the inconveniences during realisation or the noise during exploitation. An overview of the stakeholders and the phases in which they play a role is given in table 3.

Stakeholder		Feasibility study	Conceptual design	Outline design	Detailed design	Realisation	Exploitation
Commissioner		X	X	-	-	X	X
Financers		X	-	-	-	-	
Owner (road tunnel)	-Government -Province -Municipality	X	X	-	-	-	X
Owner (rail tunnel)		X	X	-	-	-	X
Government (if not-owner)		X	X	-	-	-	-
Province (if not-owner)		X	X	-	-	-	-
Municipality (if not-owner)		X	X	-	-	X	-
Users		X	X	-	-	X	X
Interested parties		X	X	-	-	X	X
Contractor		-	-	X*	X*	X	X

*: depends on the type of contract

Table 3 Stakeholders and the phases in which they play a role (marked with an X)

3.3 Design phases and information retrieval

As was stated before, the societal cost benefit optimisation of the tunnel characteristics is the very essence of the DARTS design method. In order to perform such an optimisation, information has to be produced about the costs associated with the environmental effect; the cost of measures to reduce the associated costs; and the (expected or probable) effectiveness of the measures. This requires a thorough understanding of the nature and the causes of the environmental effect, their sub-causes, the consequences and impact, the mitigating and anticipating measures and the probable effectiveness of these measures. Note: the term mitigating measures is used for those measures that reduce the impact of an effect, and the term anticipating measures is used for measures that reduce the cause of an effect.

So indeed, models must mostly be developed to bring into view the processes and parameters involved in the origin (or cause) and impacts of environmental effects. The accuracy of these models depends on the phase of the design process for which they are produced (see figure 3).

Figure 3 shows a simplified model of this iterative design process and the actions that have to be performed in the consecutive phases. As can be seen from the figure each phase starts with the information from the preceding phase and the terms of reference from the decision makers (stakeholders).

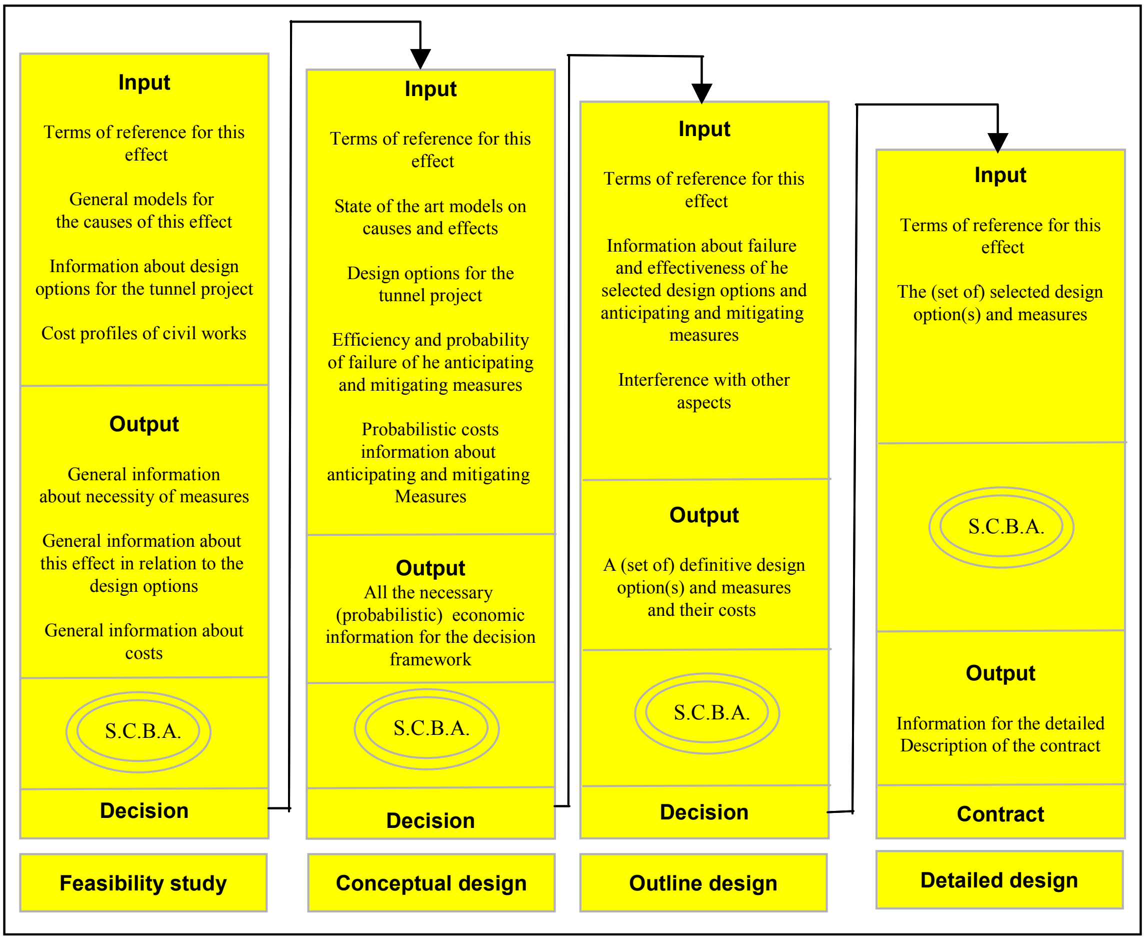

Figure 3 Detailed table for individual actions, activities within the DARTS design process. S.C.B.A.: Societal Cost Benefit Analysis, see figure 4.

3.4 Monetarisation of environmental effects

The impact of an environmental effect is not directly measurable in terms of money as are the costs of a piece of hardware. This is a setback when one wants to take the environmental aspects into consideration in the societal cost benefit optimisation of a tunnel design. Yet economists have developed methods to monetarise the impacts of all kinds of environmental effects and have come up with tools to express these impacts in terms of money.

There are many techniques to monetarise environmental effects. E.g. : measures to abate or to mitigate the impact of environmental effects are mostly straightforward civil or mechanical constructions that cost money. If one presumes that the decrease of the impact is directly related to the investment costs of those civil constructions, then it enables us to express environmental impact as a monetary quantity. But there are more techniques to monetarise the consequences of environmental impacts.

Table 4 lists the three categories of techniques and the commonly practised techniques together with a description of their characteristics. This list is derived from the report 'Internalisation of environmental costs in tunnel projects'[2]. More information on monetary valuation can be found for instance in Turner and Batterman[3].

Category of technique	Data used	Market situation	Name of Technique	Description
Market value approaches (these techniques derive value from comparisons of costs and revenues)	Prices or cost of environ-mental resource	Observable market data for prices	Change in productivity	Change in availability, quality or quantity of an output
			Change in income	Change in availability, quality or quantity or an input
			Replacement cost	Individuals, groups or society replace and entire asset, part of an asset, or quality of an asset
			Preventative expenditure	Individuals, groups or society spend money to defend their environment
			Relocation cost	Individuals, groups or society relocate an activity
Surrogate market approaches (these techniques derive value from costs and revenues in related markets)	Prices or costs of surrogate goods or services		Travel cost	Cost travel is a proxy for price to paid use the environmental resource
			Market price of good with an environmental characteristic	Change in price of good is value of change in the characteristic
			Wages to labour	Change in wage is value of change in environment
			Value of a close substitute	Value of a close substitute is value of effect of interest
Simulated market approaches (these techniques derive value from hypothetical questions)	No observable market data for prices or costs	Responses to questions in a survey which simulates a market	Contingent valuation	Purchase of environmental good, service or asset (direct questions about willingness to pay/accept)
			Trade-off game	Choice between alternatives each with a different level of the environmental effect
			Contingent ranking and contingent rating	Rank or rate environmental and other goods and services (direct questions about preferences)
			Priority evaluator	Choice of quantities to purchase in market setting (direct questions about preferences)

Table 4 Categories of techniques for monetarisation and their most practised techniques together with a description of the characteristics

3.5 Societal Cost Benefit Analysis

Once all information on the process is obtained, a bow tie graph can be assembled in order to perform the optimising procedure. DARTS has developed a tool to facilitate this optimising procedure that is presented in figure 3 as the double (S.C.B.A.) ovals in each column. Figure 4 is an enlarged presentation of a double (S.C.B.A.) oval.

This societal cost benefit analysis should be performed in each phase of the design process, the accuracy and detail depend on the phase. As can be seen in this figure, the tool needs the following input: 1) the causes and sub causes and the contribution (in %) of each (sub) cause to the effects (in %); 2) the costs of the measures and their effectiveness (in %); 3) the associated costs of the impact; and 4) the probabilistic information on the preceding parameters. The economic optimum for the (set of) measures to reduce the impact of an environmental effect can then be found by combining the options for measures and assessment of the results of the costs and the benefits of these combinations.

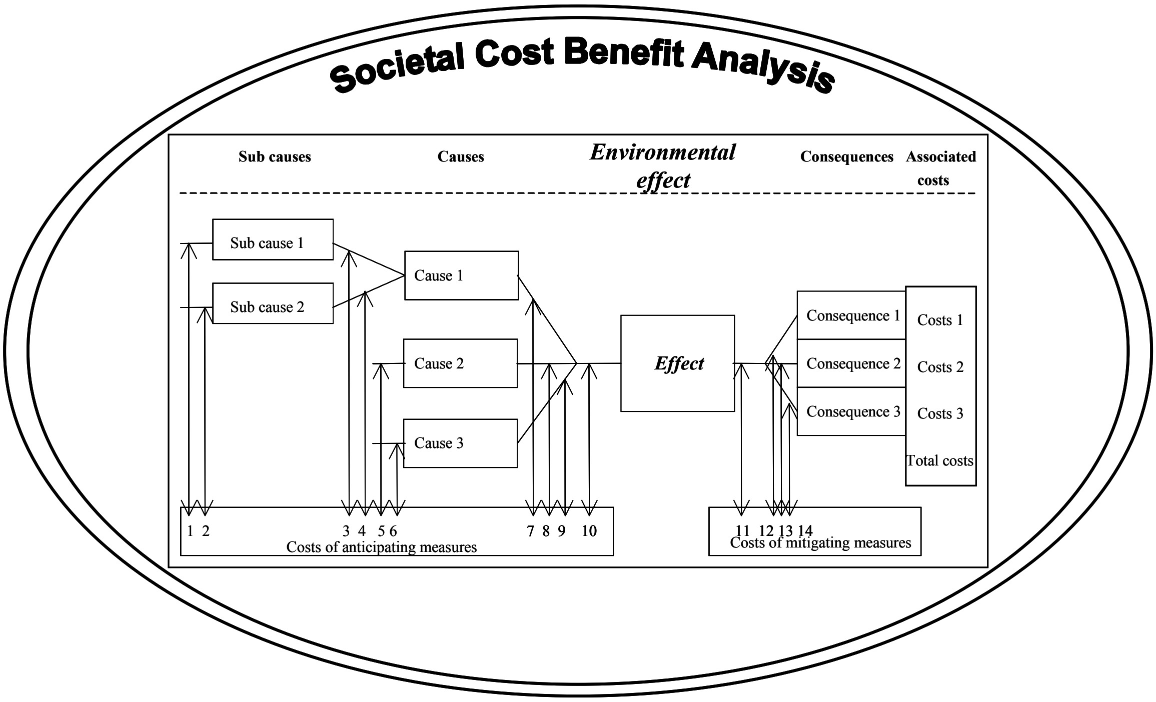

Figure 4 Bow tie graph representing the societal cost benefit analysis of options for measures that reduce the costs of environmental effects.

4. EXAMPLE

Loud noise coming from a tunnel portal is a common problem for all tunnel types. Several measures or combinations of measures may abate noise. It was therefore selected to illustrate the method to optimise the selection of measures. Note that this is a hypothetical case and that the data are not based on an existing tunnel project. The assumption for this hypothetical case is that the process to design the tunnel is in the Outline Phase. This means that the concept for the tunnel is known and only additional improvements can be proposed. The following steps are to be performed:

1. The identification of the causes (and sub causes) of noise and their (relative) contribution to the effect (in %). This requires a well-developed model for the origin of noise and the propagation of noise.
2. The identification of the consequences and the calculation of the costs associated with those consequences. This requires information from extensive fieldwork and also the application of monetarisation techniques and tools.

3. The measures and options are proposed and their effectiveness in reducing the effect (in case of *anticipating* measures) or the consequences (in case of *mitigating* measures) must be assessed.
4. The investment costs of these measures must be calculated as well as the maintenance and operation cost for the life time of the tunnel (using discounted cash flow values)
5. The tool that is developed by DARTS can now be used to produce the costs and benefits of the (combinations of) measures, provided that all the information gathered in steps 1 to 4 is presented.
6. The optimisation is assessed by calculating the benefits and costs of all possible options of combinations of anticipating and mitigating
7. A proposal is made for the stakeholders and the measures are elaborated in the next (the detailed) design phase.
8. The data on probability distributions of the information gathered in step 1 to 4 should be added, but this was not elaborated here further

Figure 5 shows the information that is assembled in steps 1 to 4. This study must be performed with great care and knowledge. It has revealed the consecutive order of causes and sub causes and their contribution to the effect, the effectiveness of each measure and its costs, the probability of failure of each measure and the (monetarised) consequences. Note that measure 4 (Improvement of car engines) is in fact an autonomous development that can't be influence by the designer and is therefore not a measure *as such*. Nevertheless, it will haven a huge impact on the design characteristics and is therefore here presented as a measure.

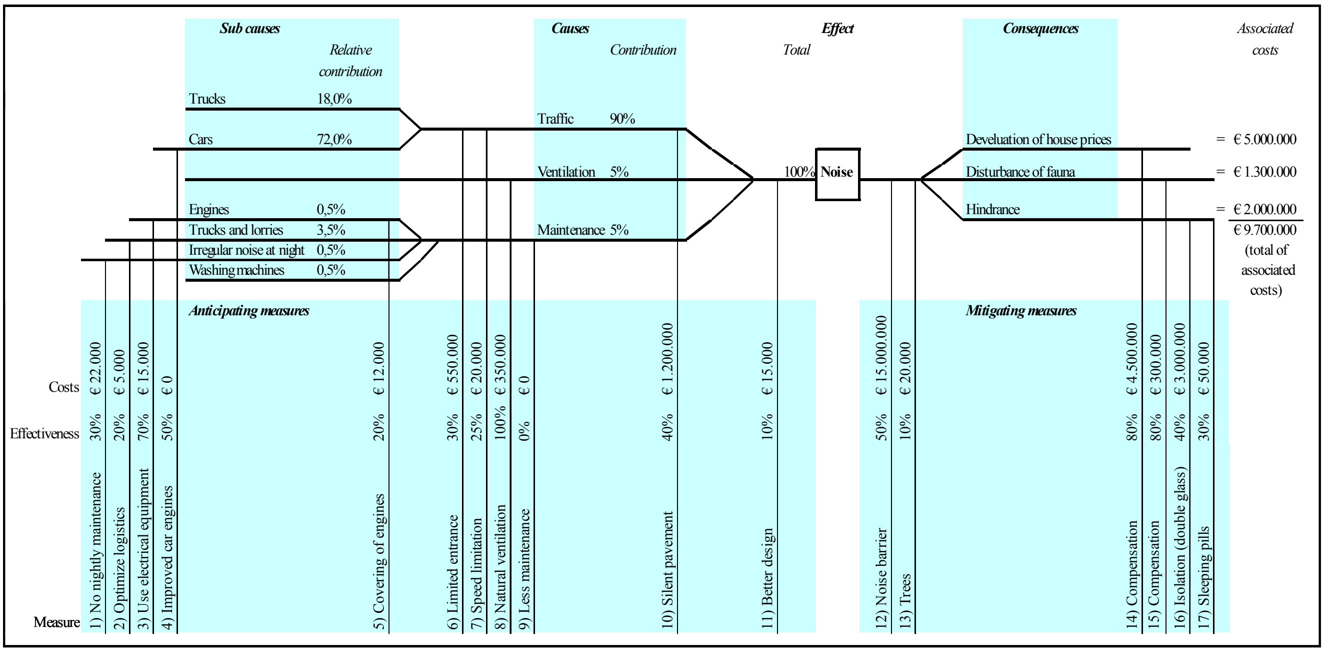

Figure 5 Scheme with the information for the optimisation of measures to reduce the consequences of noise

The tool that is developed in the DARTS study can now be applied for the assessment of costs and the benefits of the measures.

The tool presents the results as shown in table 5. It follows from this assessment that the combination of measures (Improved engines + Traffic measures + measures <100.000 + Silent pavement) with the lowest sum of Associated costs and Investment costs is the most optimal one.

Nr	Measures and combinations of measures	Associated Costs when no measures are applied (k€)	Associated Cost minus Benefits of measures (k€)	Investment Costs of measures (k€)	Associated Costs plus Investment Costs (k€)
12	Improved engines + All other measures	9,700	180	25,070	25,250
11	Improved engines + Silent pavement + Noise barrier	9,700	1,940	16,220	18,160
10	Only mitigating measures	9,700	1,400	7,850	9,250
9	Better design	9,700	8,730	15	8,750
8	Improved engines	9,700	6,210	0	6,210
7	Improved engines + All level 4 measures	9,700	6,090	50	6,140
6	Improved engines + Natural ventilation	9,700	5,720	350	6,070
5	Improved engines + Better design	9,700	5,590	15	5,600
4	Improved engines + Silent pavement + Trees	9,700	3,590	1,200	4,790
3	Improved engines + measures < E 100.000	9,700	3,730	170	3,900
2	Improved engines + measures < E 500.000	9,700	3,070	810	3,880
1	Improved engines + Traffic measures + measures <100.000 + Silent pavement	9,700	1,750	1,890	3,630

the costs have been rounded off upwards

Table 5 Results of the economical analysis of several options to reduce the impact of noise as presented in the scheme in figure 5. If one assumes that measure 8 in this list (Improved engines) is an autonomous development that will always happen, then measures 10 and 9 should not be considered. The table shows that combination nr 1 (Improved engines + Traffic measures + [measures <k€ 100] + Silent pavement) is the most optimal one.

5. REFERENCES

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