

## **INTEGRATED TUNNEL DESIGN FROM CRADLE TO GRAVE ENHANCING STRUCTURAL PERFORMANCE AND OWNER CONFIDENCE**

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### **ABSTRACT**

This paper presents the outline of the DARTS concept (Durable and Reliable Tunnel Structures), namely the systematic basis for selection of the best alternative among competing solutions for a new tunnel structure with respect to *the total economic life cycle cost*. The application of the DARTS concept will render structures, which are optimal with respect to all the decision-makers' identified goals. It is illustrated how topics like "hazards aspects", "durability" and "environmental impact" are modelled and included in the decision process.

### **1. INTRODUCTION**

Planning of tunnel structures preferably should result in optimal solutions. Choice of the optimal tunnel structure and design solution is however not straightforward due to the high degree of complexity establishing such solutions. The design includes numberless parameters to be chosen, and each parameter may result in a number of diverse effects within the fields of financial costs, environmental effects, hazard related effects, and traffic effects.

Traditionally the different decisions to be made in the phases of planning, designing, constructing and operating a tunnel structure has not been regarded as a coherent optimising problem; rather the individual tasks are solved one by one, which inevitably leads to "sub-optimising". The purpose of DARTS (Durable and Reliable Tunnel Structures) has been to develop a decision framework transforming the traditional fragmented design approach into an integrated total economic life cycle evaluation, a so-called "*Cradle-to-Grave*" approach.

By *life cycle evaluation* is meant that costs (and benefits) arising from all life phases, that is constructing, operating, maintaining and disposing a tunnel, must be taken into account. By *total economic evaluation* is meant that not only *financial costs* in terms of construction, operation and maintenance costs should be included. Rather, all effects on the society, that is financial, environmental, hazard and traffic related costs, should be included.

In order to assess total life cycle costs the various effects must be comparable. This is done by expressing the effects in terms of monetary values. Whereas this is evident for some effects like construction costs, other effects such as environmental effects are rather difficult to assess in terms of a monetary value. Hence it is of great importance to develop a common approach for assessing and combining effects quantitatively.

Thus, the core of an integrated design is that all types of effects on the society over the entire lifetime of the tunnel project must be assessed as an integrated process. At the same time the level of detail should be adjusted to the actual phase of planning/design and the related decisions that have to be taken at each stage of the process.

Such an approach makes a demand on all the involved parties to cooperate as a team and not as contractual opponents. This will incorporate the influence of design, specifications, contracts, the organisation of the execution phase and the interfaces between owner - designer - contractor - user into an integrated design of tunnels.

## 2. DECISIONS AND PROJECT PHASES

### 2.1 Decision Structure

The common denominator between all the various problems in different types of structures and project phases is that decisions have to be made. The decisions should be made taking into account all available information and with the goal of reaching the optimal solution seen in a life-cycle perspective. With the term "utility" describing the overall benefit of a certain activity, the optimal decision is formulated as:

The decision giving the highest expected "utility" among all possible decisions

- "all possible decisions" implies the need of a complete identification of alternatives and options (including also: status quo, detailed investigations, tests programmes, etc)
- for all possible decisions the expected utility will have to be determined
- "expected" means the expectation value, in statistical sense, of all uncertain events
- all types of consequences of the decision (advantages, disadvantages) must be identified
- quantified implications must be adjusted to a common scale by means of "utility functions"
- costs are negative utilities and quantified criteria can be transformed to monetary units
- in a life-cycle consideration the present value of the utility will have to be determined

As it appears, the rational decision-making includes aspects of (objective) physical modelling of the characteristics of the options, but it also has subjective aspects especially concerning the criteria of decision and the preferences between them. It is important to clearly define, who is the decision-maker (or on whose behalf does he act) and to make the model transparent in order to illustrate, which (subjective) choices have been made.

The structure of rational decision-making can be formulated in terms of decision trees, for example formulated as prior decisions, see Figure 2.1. The prior decision supports the choice between alternatives. For each of the alternatives there is a chance of the occurrence of different states and for each state there is a utility. The qualification of the states can be considered estimation of risk - in a broad understanding of the term "risk". The decision is based on the available information. If additional information is achieved, the analysis can be formally up-dated.

### 2.2 Identification

The identification of the decision alternatives and the possible outcomes (states, ref. Figure 2.1) is particularly important. If only a subset of actions (structural solutions, systems etc) has been identified, there is a probability that the optimal solution is among those not identified. This may seem evident, but in reality it is very difficult to determine whether a full identification has been achieved. Also the identification of all relevant possible outcomes is necessary in order to obtain a proper comparison. Omission of a type of outcome will unrightfully favour solutions with negative features associated to this outcome.

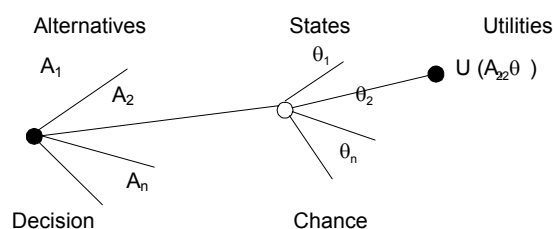


Figure 2.1 Prior decision tree

The identification process is not trivial as it is a creative process depending on the imagination, experience and professionalism of the persons involved. The process may be structured by various tools as a brainstorming activity performed in groups.

### 2.3 Uncertainty

Regarding the process of creating and operating tunnels as a chain of decisions, which all can be modelled in terms of decision trees, an important notion in the modelling is the uncertainty of the information. Uncertainty covers here not only the physical and statistical uncertainty in the classical sense but also the uncertainty in terms of the degree of belief.

The uncertainties are comprised by the decision modelling, for example in terms of:

- the probability of unwanted events / accidents
- the reliability of the structure with respect to ultimate limit states, durability criteria, etc
- uncertainty in the information about costs of design modifications, structural behaviour, geotechnical conditions or environmental impacts.

Sometimes decisions can be taken even though the uncertainties are quite large; this requires that the expected utility of the decision is much higher than the expected utility of the alternative. I.e. if the right decision is evident, there is no need for detailed studies. Vice versa the studies should be detailed, and the uncertainties thereby reduced, until sufficient information has been collected and the decision-maker can be confident about his decision. This is done practically in steps where the decision on excluding the least competitive option is made and the next step is a detailing of the studies of the remaining options. Due to the detailing variants of the remaining options may appear and the number of options may increase. At some level of detailing, further studies will not be feasible, as the complications and costs involved in reducing the uncertainty can no longer be defended by the reduction of uncertainty. At this point the decision of the design option shall be taken.

Hence, the necessary level of detailing depends on the uncertainty of the information in relation to the consequences of the decision.

### 2.4 Phases and stakeholders in the planning process

The planning of a tunnel project is a long process that consists of a number of phases. The process is not a strict procedure but is different for each new tunnel project. It is important to realise that different interests and stakeholders are at stake depending on the location and situation and the type of tunnel.

The planning process is normally divided into four phases: Feasibility study, conceptual design, outline design and detailed design phase. Very generally, the feasibility study phase can be said to deal with the question of whether to construct a tunnel or not. Conceptual design phase deals with the overall choice of tunnel type, whereas the purpose of outline and detailed design phases is to choose among actual design options.

DARTS has developed a very simple model to describe the design process of tunnel projects, which is shown in Figure 2.2. Designing a tunnel is presented as a straightforward process: one starts with an idea and adds more and more details when going from one phase to the other. In each phase of the design process certain questions are worked out and the effects of design options are assessed and the results are presented to stakeholders and decision makers. The stakeholders use this information to decide on the terms of reference for the next phase of the project. These terms of reference determine the boundary conditions and the activities in the next phase of the design process. Furthermore there are aspects in an idea that must be worked out in detail in the earlier phase of the process in order to assess effects and resolve problems that will be encountered later during the process.

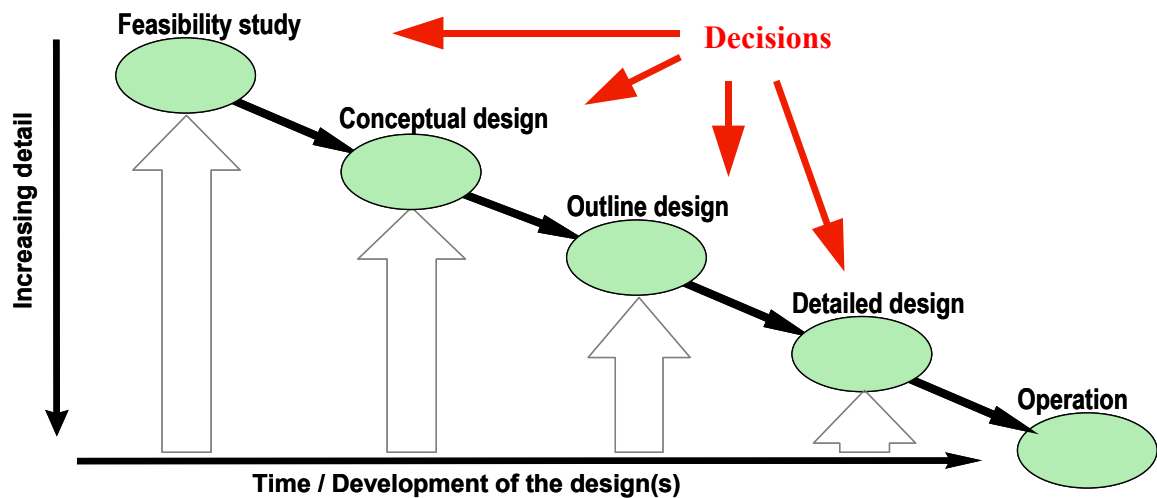


Figure 2.2 Simplified model of the design process of a tunnel

This is true for each design phase: options and possibilities must be elaborated in more detail in order to assess their effects and to provide the stakeholders of that phase with information to formulate their terms of reference for the next phase.

Stakeholders are different in each phase. For instance, authorities that decide on the initiation of the project (politicians, bankers, government) are generally not interested in the details. In the other end of the design process, the stakeholders of the detailed design phase such as the future owner/operator and the contractor are very much interested in the details of the lining type, joints, electrical installations etc: they must make decisions on this detailed level. So in the feasibility study most information is generated to decide on financial and environmental issues. In the next phases the accent is more on the technical and engineering aspects.

### 3. CRADDLE TO GRAVE APPROACH

#### 3.1 Total economic life cycle cost

The definition of the cost approach to be used for evaluation of tunnel structures must be properly clarified. The term “cost” is often considered rather limited in connection with tunnel projects to only include financial costs arising in the construction phase. For a general cost optimisation for the society or the decision-maker, this cost definition is not adequate.

Firstly, not only costs of construction should be considered, but evaluation of the economic aspects of a project should consider all costs (and benefits) arising during the entire lifetime of the tunnel – from *cradle to grave*. This is called the *life cycle costs* (LCC).

Secondly, the cost approach must be extended to include, in principle, all impacts relevant for the decision-maker or the society. This includes environmental effects, hazards and user benefits. This approach is termed total economic cost approach and is illustrated in Figure 3.1. Construction costs are the financial costs arising during the construction phase. Operation, maintenance and demolition costs are the financial costs arising in the operation phase. Environmental related costs include external effects on the environment. Hazards effects may arise in terms of increased financial costs during construction and operation phase and in terms of non-financial costs to be included in environmental related costs. Traffic related costs consider the user benefits, mainly in terms of change in travel time and distance.

It is important to highlight that the term "costs" actually is interpreted as the net costs, which is the costs minus the benefits (thus in some cases, cost may be negative).

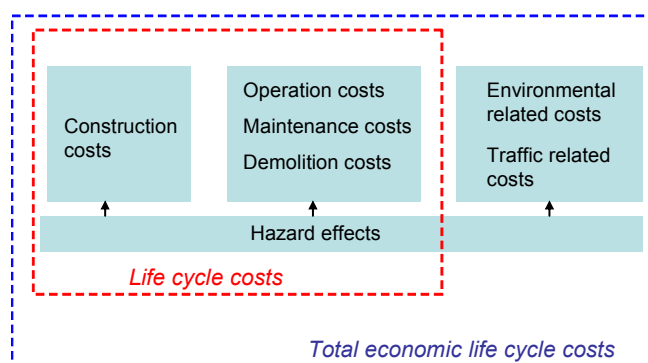


Figure 3.1 Assessment approaches: Life cycle costs and total economic life cycle costs

### 3.2 Mapping of impacts

The actual input to be assessed consists of numerous aspects within the areas of construction costs, operation, maintenance and repair costs, environment, hazards and traffic effects. The assessment includes a number of steps to be followed within each area.

Initially, considerations are to be made regarding what impacts to be included at what stage of the process and how to assess them. This will be done under the headline "Overview tables for actions". The starting point is an overview table including all aspects to be evaluated along with the parameters to assess them. For each aspect and parameter it should be considered at what stage of the planning process it is to be included. This will result in a table like the one illustrated in Table 4.1 for the durability aspects. Similar tables are established for other aspects concerned with environment, hazard etc. Each aspect may be assessed by one or more parameters. The set of parameters to be used, depend on the phase of the project.

Subsequently, each aspect and parameter in the table is considered in more detail in terms of how they are assessed. These issues will be presented in tables like Table 4.2, which illustrate the example of durability / corrosion. Such a table can be established for each parameter within each aspect. The following issues are considered:

- *Degree of accuracy:* Impacts may be assessed qualitatively, quantitatively or preferably monetarily. The unit of measurement should be stated.

- *Degree of detailing:* Considerations of how to estimate the actual parameter. There are various ways resulting in different degree of detailing, e.g. rough estimate based on overall average figures, estimates based on some key figures or detailed modelling.
- *Input:* What input is needed to perform the assessment of the parameter? This should include the conditions affecting the parameter.
- *Output:* Each analysed parameter results in some specified measure to assess the aspect.

## 4. MODELLING

### 4.1 Durability

It is often required for large projects that the structural lifetime shall be at least 80, 100 or 120 years. However, until few years ago it was not possible to determine exactly which measures should be undertaken to achieve the required lifetime. Also the definition of the "life" or "death" of a structure is weak. After the completion of the EU Brite EuRam III research project "DuraCrete" this has drastically changed. Now models are available for describing the deterioration processes and determining the probability of exceeding the specified limit states. DARTS models have been further developed and extended for tunnel structures. In particular, the tunnel specific conditions (environment, chloride and CO<sub>2</sub>-loading, moisture, temperature) have been quantified.

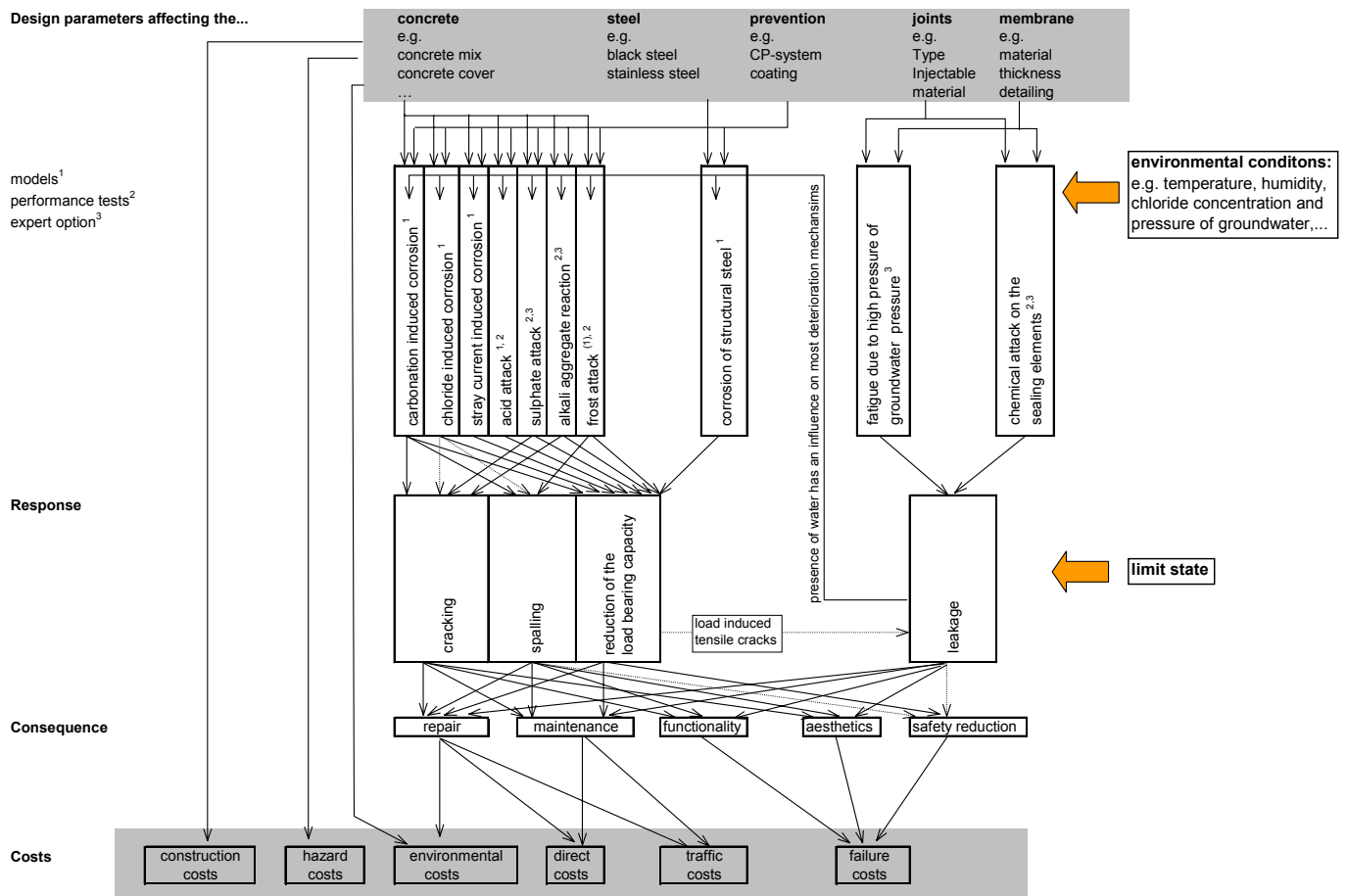


Figure 4.1 Costs linked to durability considerations

In Figure 4.1 the design parameters (materials/and elements) affecting the durability aspect are outlined. The term of durability is mainly linked to the extent of deterioration and its effects over service life. Therefore the prediction of deterioration progresses over service life plays a key role, when optimising a structure with regard to durability. Based on Figure 4.1 a list of deterioration mechanisms to be considered is given (e.g. carbonation and chloride induced corrosion, acid attack, frost attack).

For the durability aspect of concrete deterioration Table 4.1 illustrates what kind of information will enter into the different management phases.

One of the major objectives of the reliability based service life design are the prevention of reinforcement corrosion, with focus on corrosion due to chloride ingress and carbonation, and the design for watertightness (avoidance of leakage) of the cracked and uncracked concrete. The probabilistic calculations have been extended to include the effects of different maintenance and repair measures. In Table 4.2 details are given concerning the evaluation of corrosion including degree of accuracy, detailing, input and output for different phases. For the quantitative evaluation the "DARTS" durability models are used.

The risks of accumulation of chlorides by evaporative effects on the air-exposed face of tunnels - which are exposed to salt containing water (seawater, brackish water, and groundwater) - have been investigated. The model of chloride accumulation was always controversial and discussed by leading concrete and durability experts. The clarification of this issue is one important achievement of DARTS.

Aspect	Parameter	Feasibility Study	Conceptual Design	Outline Design	Detailed Design	Realisation, Update	Operation, Update
<b>Durability</b> (Visual Appearance, Structural Integrity, Structural Functionality Load Bearing Capacity)	<b>Concrete/Reinf. Concrete</b>						
	- carbonation induced corrosion						
	- chloride induced corrosion						
	- acid attack						
	- alkali aggregate reaction						
	- sulphate attack						
	- frost attack						
	- abrasion						
	<b>Steel</b>						
	- corrosion						
	<b>Joints, Gaskets, Inserts</b>						
	- deterioration						
<b>Watertightness</b>	<b>Membrane</b>						
	- deterioration						
	<b>Concrete/Reinf. Concrete</b>						
	- water ingress through uncracked concrete						
	- water ingress through cracked concrete						
	<b>Joints, Gaskets</b>						
	- water flow beside joints, gaskets						
	<b>Membrane</b>						
	- water flow through membranes						

Table 4.1 Overview of aspects (impacts) and parameters

Aspect	Parameter	Phase	Feasibility Study	Conceptual Design	Outline Design	Detailed Design
			(1)	(2)	(3)	(4)
durability	reinforcement (and structural steel) corrosion	degree of accuracy	estimation based on experience	general assessment to identify critical boundary conditions and possible technical solutions	calculation taking different basic layout options into account	detailed calculation of the most promising layout options identified in the outline design
		degree of detailing	qualitative assessment	qualitative assessment	quantitative assessment	monetary assessment
		Input	general experience taking - service life - environmental conditions - global material properties	limit state report standards/guidelines - service life - environmental conditions - global material properties - requirement according to the standards	modelling report stray current report repair report - service life - environmental variables - material variable based on standards or common experience	modelling report data report stray current report repair report - service life - environmental variables - material variable based experience and if necessary (most likely) quantification based on performance tests
		Output	possible/not possible	- formulation of requirements - Identification of critical circumstances with regard to durability (e.g. chloride contaminated excavation has to be considered, when using aggregate for the concrete)	identification of promising layout options, with regard to the considered limit state: - type of reinforcement - prevention methods - repair	set of economic layout options, defined by: - type of reinforcement - concrete resistance against carbonation and/or chloride ingress - concrete cover - maintenance /repair strategy

Table 4.2 Detailed table for each parameter, here shown: durability/corrosion

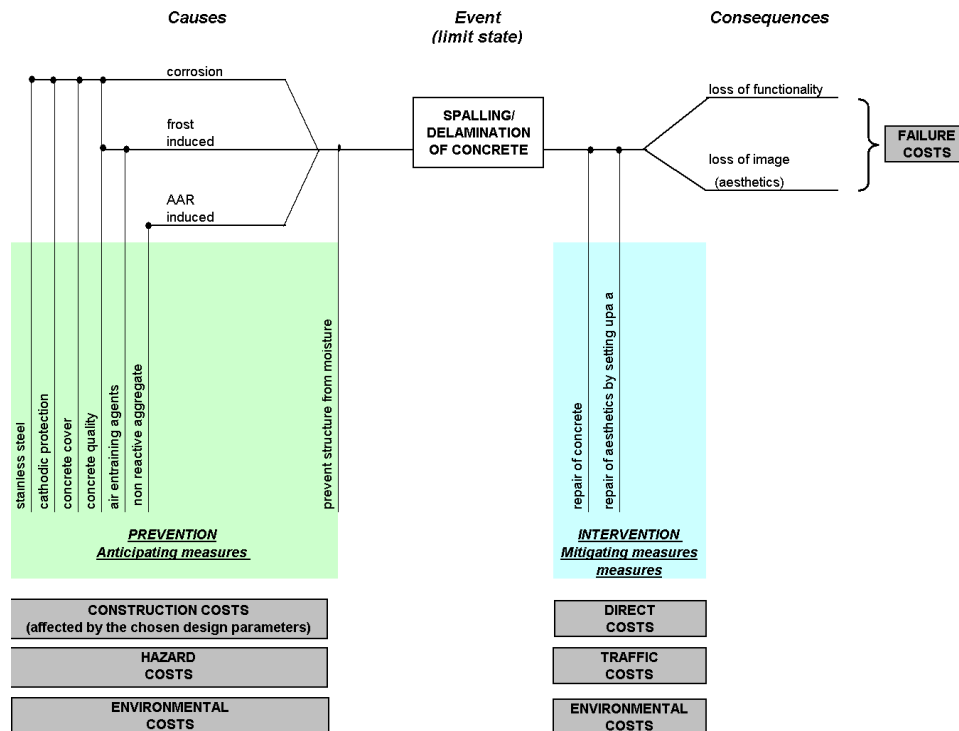


Figure 4.2 Prevention and intervention methods to steer the event "spalling of concrete surface"



This process of finding the optimal set of measures requires that the undesired event must be expressed in monetary units. There are different types of undesired events, which are denoted as limit states. The aim is to find an economic optimum linked to the relevant limit state taking investment, prevention and intervention measures into account. For example the event of spalling at the tunnel inside is unwanted, since it affects the safety, the aesthetics and the general functionality of the tunnel structure. In Figure 4.2 measures are summarised how to influence this event in a structure similar to a fault/event tree. To set up such a diagram possible causes have to be identified leading to the chosen limit state. By referring to the limit state of spalling/delamination of concrete surface, in general all concrete deterioration mechanisms have to be considered. In Figure 4.2 it is pronounced that (beside construction costs) further cost types have to be determined to evaluate economic costs over service life and to be part of the integrated design.

#### *4.2 Environmental impact*

An evaluation of the environmental impact has not only become common for large projects, it is in most cases legally required. In order to assess the environmental effects of different types of tunnel structures and to optimise designs, it is necessary to compare the different types of tunnels at different levels and aspects. Environmental aspects of tunnels, related to the impact on nature and health, are numerous. Hence, the first step has been to compile, validate and compare available data, such as:

- pollution of air, soil, ground- and surface water
- ecotoxicological effects
- noise and vibrations
- consumption of resources (land, energy, water, materials etc)
- psychical impacts
- health impacts

These impacts will have a range of effects on the environment. Some are reversible and some are irreversible. Some are local and some are regional or global. Furthermore, they will occur at different stages of the tunnel's life such as during production of building materials, tunnel construction, exploitation, maintenance, repair and demolition, etc.

Traditionally, environmental studies have tended to be very much descriptive. However, in order to become an integral part of the process the different impacts and effects will have to be quantified, prioritised and weighed in a lifetime perspective. A similar approach to the one presented for durability above is applied. For some environmental impacts (e.g. air pollution, CO<sub>2</sub> emissions and ground pollution) models are available for quantification and weighting, for other impacts models will have to be developed or a more simplified weighting procedure will have to be applied. Finally, the environmental effects will be transformed to total lifetime costs and integrated together with the other consequences of the option.

#### *4.3 Hazard aspects*

The studies of risks have become common practice in connection with tunnels. It is normal, at least for larger tunnel projects, to estimate the risk of fires and other large accidental events during construction and operation. However, in case of conflicting requirements the best decision is not always evident. If for example a structural measure can reduce the risk of fire, should it then be undertaken if it has side-effects in terms of inferior durability?

The aim of the studies of hazard aspects should be to develop a rational method for optimising measures by minimising the effect of hazards on the primary functions of the tunnel.

All types of hazards should be considered: fire, explosion, leakage of aggressive materials, toxic releases, water inundation, and earthquakes. The methods are developed with the aim of integrating design methods for the hazards in the tunnel design. The relevant aspects are identified and described in project stages as for durability.

One hazard which is creating much attention and which has significant impact on tunnel safety is fire in tunnels and a study of causes and consequences of fire is highly relevant in order to evaluate various designs and safety measures. In practice this is done by structuring the events leading to the fire in a fault tree, and in an event tree the possible consequences of the fire event. The outcome is the expected consequences, i.e. an integration of all possible consequences and their individual probability of occurrence.

Risk reducing measures are included in the model in terms of reduction factors for reducing the likelihood of the unwanted events or their consequences.

Also other hazards are modelled in terms of fault trees and event trees. These logical trees can be more or less detailed depending on the available information and the decision problem at hand. Attention has been given to the required degree of detailing in the various design stages "necessity discussion, feasibility study, conceptual design, outline design, and detailed design" of the project.

## 5. INTEGRATED DESIGN

The basic formula for integrated design takes into account all costs and benefits. Costs may be related to hazards, repair and maintenance and environmental damage. For each design option all relevant aspects are accounted for. A total value is determined as illustrated in Figure 5.1.

For determining the optimum the minimum over all design alternatives is sought. In the one-dimensional case we may have a situation as depicted in Figure 5.3.

The total value for each identified option is compared with each other. The optimum design option is found by means of the total economic life cycle cost. Only aspects, which deviate between the options, need to be included in the comparison.

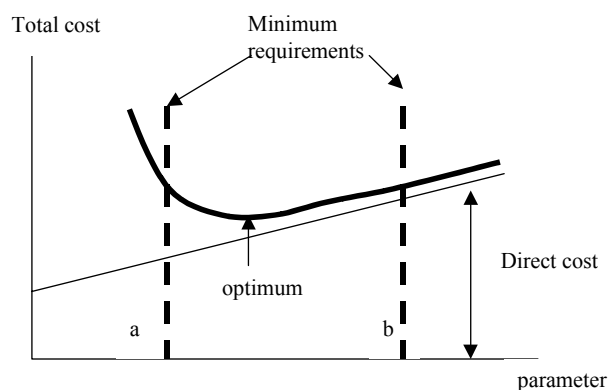
Choice of minimum total cost taking the effect of all aspects will give the best of identified options. This will represent a discrete optimisation.

Service life aspects	Expected consequences	PV2,1
	Associated costs	PV2,2
Environmental aspects	Expected consequences	PV3,1
	Associated costs	PV3,2
Hazard aspects	Expected consequences	PV4,1
	Associated costs	PV4,2
Socio-economic aspects	Expected consequences	PV5,1
	Associated costs	PV5,2
Other aspects	Associated costs	PVX
Total		$\Sigma PV i$

Figure 5.1 Principal illustration of all cost contributions for one design option

			Service life aspects	Expected consequences	PV2,1
				Associated costs	PV2,2
		Service aspects	Environmental aspects	Expected consequences	PV3,1
				Associated costs	PV3,2
	Service aspects	Environ aspects	Hazard aspects	Expected consequences	PV4,1
				Associated costs	PV4,2
Environ aspects	Hazard aspects	Socio-econom aspects		Expected consequences	PV5,1
				Associated costs	PV5,2
Hazard aspects	Socio-econom aspects	Other aspects	Total		$\Sigma PV i$
Socio-econom aspects	Other as	Total			$\Sigma PV i$
Other as	Total				$\Sigma PV i$
Total					$\Sigma PV i$

Figure 5.2 Principal illustration of all cost contributions for a (discrete) set of design options



*Figure 5.3 Cost optimisation and constraints The design parameter may not always be in terms of a continuous variable but may be identified as a discrete set of design options.*

A number of options may be chosen for further investigation. The number of options to be selected for the next stage depends on the uncertainty of the estimation of total costs. A method for this selection has been developed as part of the DARTS project. In the increasing detail in progressing stages of the project, variants and subdivisions of the decision options will be identified and the uncertainty of the estimation of the total costs will be decreased. During this process the discrete optimisation is approaching the "real" optimum.

## 6. CONCLUSION

In order to achieve the best possible solutions in the creation and operation of tunnels all relevant information will have to be utilized. The decisions shall be based on a well-structured and transparent methodology. The circumstances representing the interaction between the structure and the environment, the durability of the tunnel, the consequences of fire, and the possible consequences for the life of human beings, must be modelled. With the results of the DARTS project the tools are now available for optimisation of the process. A consequent use of such methods will result in tunnels, which are well balanced with respect to costs, environmental impact, safety, durability and other specified aims.