EXAMPLE FROM PRACTICAL APPLICATION OF THE INTEGRATED DESIGN APPROACH

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ABSTRACT

Traditionally the different management phases of tunnels, the design phase, the construction phase and the operation phase are not regarded as a coherent optimising complex, but rather as individual tasks, which are solved one by one leading to “sub-optimising”.
For tunnels the initial investment and the exploitation expenses are often provided by the same body. By considering costs arising in all management phases an economic optimisation can be carried out ensuring a proper balance between initial financial investments, future exploitation and maintenance costs. Furthermore the optimisation shall respect societal needs, environmental protection and sustainable development and hazard risks.
Designing a tunnel is a rather straightforward process, in which in each phase of the design process certain questions arise and the effects on design options have to assessed by the stakeholder. The aim of DARTS is to provide a tool to improve the foundation for optimal integrated economic decision making in the area of tunnel structures.

1. INTRODUCTION

The border line between wanted and unwanted events is called a limit state. When designing or assessing structures, it is generally agreed to recognise two different sets of limit states: ultimate limit states (ULS) and serviceability limit states (SLS). Suitable definitions of both types of limit states can be found in the "Background Documentation" of the Eurocode. Summarised in short, according to DARTS - Limit State Formulation Report[1]:
ULS: Crossing the limit means failure, is irreversible, usually has a distinct (crisp) border line and crossing it usually endangers humans, for examples collapse.
SLS: Crossing the limit means hindrance, is usually reversible, has a vague (wide) border line and does not endanger human beings.
When treating ULS usually a fixed upper limit is used for the design and assessment of the structure over service life. Such upper limits of failure probabilities are for example given in the EN 1990[2] or in the JCSS Probabilistic Model Code[3]. As human life is not directly at stake when crossing a SLS an economic optimisation is considered to be much more appropriate, as furthermore for tunnels the initial investment, the exploitation and the maintenance expenses are usually provided by the same body.
Durability consideration, environmental impact assessment and hazard risk analysis each provide a set of operational tools for the stakeholder in the creation and operation of a tunnel.

To integrate the aspects of durability, environment and hazard into an overall approach consequences linked to possible lay-out options have to be expressed by an overall superior assessment unit, for example in monetary values. In the presented example the optimisation procedure linked to durability consideration is outlined, as one of the three modules (durability, environment, hazard). By applying the design procedure in a similar way for hazards and environmental considerations a fully integrated design can be carried out.

2. EXAMPLE: OPTIMISATION LINKED TO THE DURABILITY ISSUE

2.1 Structure

As a heavily frequented motorway is crossing a very exclusive historical village, which is popular for sightseeing, shopping and living, it has been decided upon to build a motorway tunnel of approximately 800 meters length. Above ground the old motorway will be replaced by a pedestrian precinct. The service life of the tunnel has been chosen to be 100 years. Furthermore it has already been decided to use the cut & cover method for construction.
In Figure 1 a cross section of this tunnel is outlined, in which also environmental loading affecting the inner concrete walls is indicated.

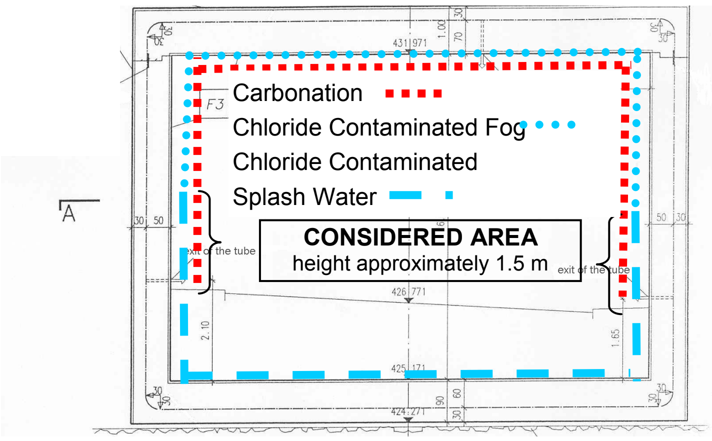

Figure 1 Environmental loading on the tunnel surfaces

2.2 Limit state

As the tunnel is to be built in a very exclusive area, the visual appearance of the tunnel is of major interest, because potential visitors or habitants are considered to feel very sensitive to this item. Beside usual dirtying, which will be cleaned on a regular basis, especially reinforcement corrosion induced delamination/spalling of the concrete cover is identified as the main contributing parameter affecting the visual appearance. Furthermore frost damage of the tunnel lining and alkali aggregate reaction can lead to an impaired visual appearance. In the considered example these causes have been excluded by choosing an appropriate concrete mix.
Therefore besides ULSs, which have always to be considered, the SLS of delamination/ spalling of the concrete cover from the tunnel walls has been identified as relevant.
Consequences of crossing the chosen SLS (having delaminted/spalled concrete surface) might be hindrance of the functionality of the tunnel structure, as the accident rate increases due to distraction of tunnel users by spalled concrete pieces laying on the road deck. Furthermore the

users of the tunnel might feel uncomfortable, which leads to a loss of image of the structure and the therewith of the village. It might be difficult to quantify these consequences into monetary values, especially the loss of image.
Since in the splash zone the environmental impact causing corrosion is very severe, this zone has been chosen as relevant for the optimisation procedure, cp. “considered area” in Figure 1.

2.3 Lay-Out Options

To demonstrate the workability of the decision tool beside a reference option three further options have been defined. The considered options 1-4 with their main characteristic are given below:

1. reference: black steel as reinforcement
   conventional concrete
2. stainless steel: reference option extended with stainless steel as a preventive measure
   (only the reinforcement next to the concrete surface exposed to air will be replaced by stainless steel, the rest of the reinforcement is made of black steel)
   conventional concrete
3. repair: reference option extended with repair action as an intervention measure
   black steel as reinforcement
   conventional concrete
   intervention method: replacing of chloride contaminated concrete
   time of intervention: t_{repair} = 50 years
4. cladding: reference option extended by the application of lining elements to the concrete surface as an intervention measure
   black steel as reinforcement
   conventional concrete
   cladding applied after 50 years of exposure

2.4 Estimation of spalled concrete surface over service life

In the considered case the degree of spalled concrete surface at the tunnel walls, expressed in percent, is called damage ratio. As spalling is considered to be the main cause affecting the visual appearance the process of the damage ratio over service has to be analysed for each lay-out option. A model for a first approximate calculation of the damage ratio has been applied based on the DARTS - Modelling Report[4] and the DARTS - Data Report[5]. To calculate the damage ratio it has been assumed that the event of spalling occurs as soon as a critical corrosion depth at the reinforcement is reached. Figure 2 gives an overview of the qualitative progress of calculated damage ratios over service life for each lay-out option.

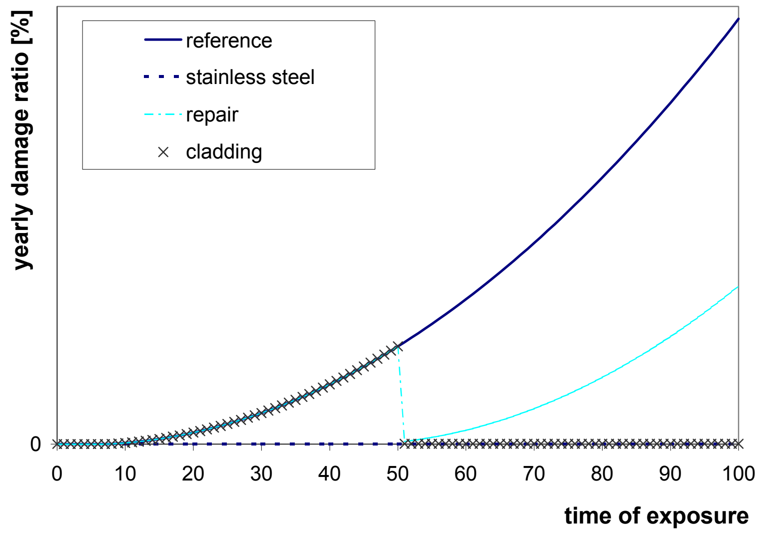

Figure 2 Damage ratio over service life for all lay-out option linked to SLS of spalling of concrete cover caused by reinforcement corrosion

2.5 Costs

In a next step the costs for each option have to be determined. Within the given example the costs as given in Figure 3 have been considered.

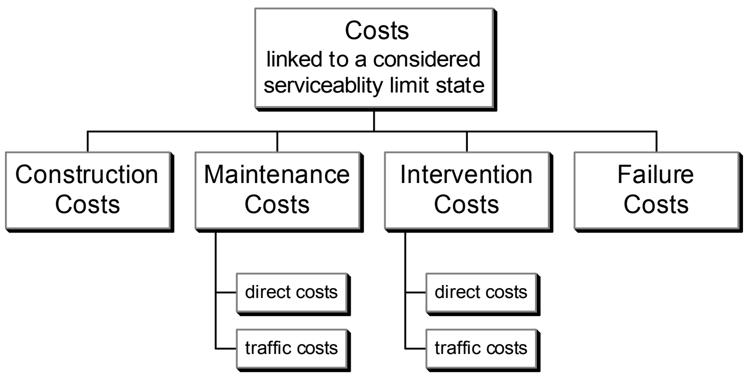

Figure 3 Costs to be considered for each lay-out option

As the cost difference among the lay-out option is decisive to find the optimum, costs occurring for all options with the similar quantity have in general not been considered. In correspondence to the defined side conditions of the lay-out options (time for setting up the cladding or carrying out repair action) the distribution of costs over service is given in Figure 4.

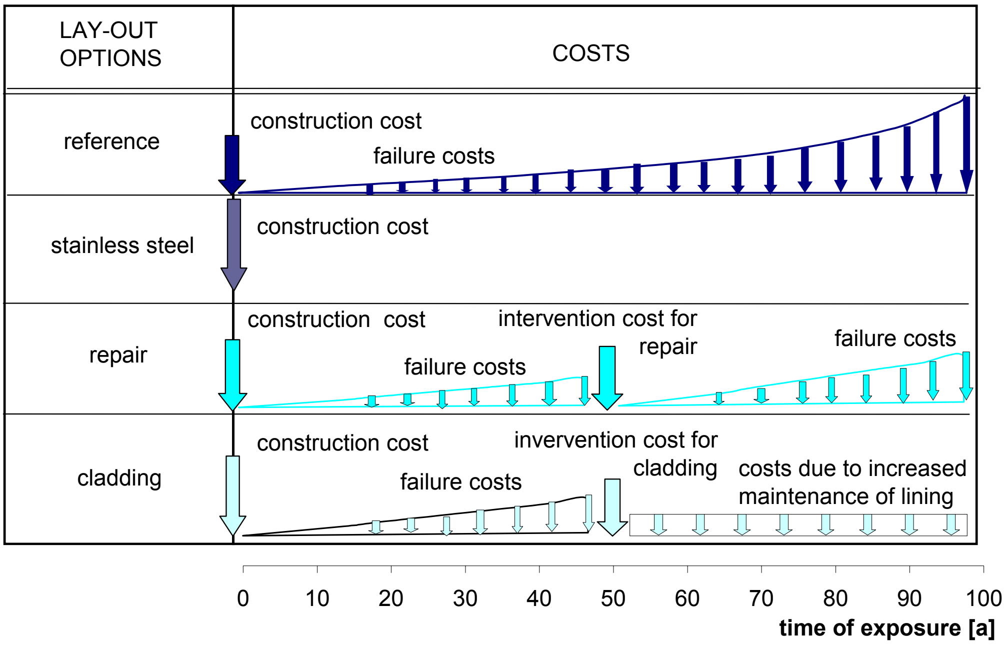

Figure 4 Costs over service life for the considered lay-out options

More background information of the considered costs is given in Table 1.

Lay-out option	Construction Costs	Maintenance Costs (due to extra maintenance compared with reference option)	Intervention Costs	Failure Costs
reference	Costs for building a reinforced tunnel wall with ordinary black reinforcement.	-	-	The consequences of spalling have to be translated into costs. By considering these costs and the predicted damage ratio of each lay-out option (cp.Figure 2) the failure costs can be calculated.
stainless steel	Costs for building a reinforced tunnel wall with stainless steel as the outer reinforcement layer (for the rest ordinary black reinforcement is used).	-	-	
repair	Costs for building a reinforced tunnel wall with ordinary black reinforcement.	-	Costs for conventional repair (removal and replacement of concrete). Here direct costs as well as travel costs should be included, as during repair the traffic flow might be considerably hindered.	
cladding	Costs for building a reinforced tunnel wall with ordinary black reinforcement	As soon as the cladding is installed extra maintenance costs for the concrete wall arise, as the cladding is covering the concrete surface and therewith maintenance action becomes more complex (removing panels). On the other hand the cleaning of the tunnel lining to maintain aesthetic demands might be easier and therewith less costly. In this example it has been assumed, that the positive effect of the cladding is outrun by the extra maintenance action for the tunnel wall.	Costs for installing the cladding at the tunnel wall. Here direct costs as well as travel costs should be included, as during installation the traffic flow might be considerably hindered.	

Table 1 Considered costs over service life for each lay-out option

To enable a comparison of costs for each lay-out option as given in Table 1 a discount rate has to be considered, as the outlined costs occur at different points in time, cp. Figure 4.
With the discount rate the present value can be calculated.

By calculating the present value the cost refer to a defined point in time. In the considered case t = 0 year has been chosen as the reference time. Therefore all costs occurring over service life have to be calculated back to this point in time. The discount rate in the presented example has been chosen to 2 %, as for example the German KVR-guideline[6] gives an upper limit of 2 % for comparing different options linked to public installations.
As mentioned in Table 1 the failure costs depend on consequences due to limit state based failure (here: spalling), which have to be translated into a monetary value and on the damage ratio. In the Figure 5 the result of the failure cost calculation is outlined, considering a discount rate of 2 %.

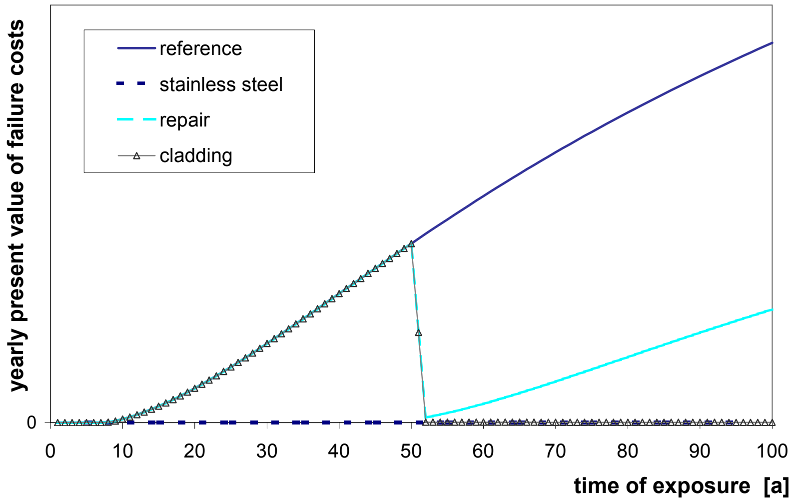

Figure 5 Yearly present value of failure costs over service life, considering a discount rate of 2 %

It can be observed, that the progress of yearly failure costs over service life looks similar to the respective damage ratio, cp. Figure 2 with Figure 5.
To determine the failure cost over service life the integrals of the curves representing the progress of the yearly present value (cp. Figure 5) have to be taken, thereby summing up the yearly costs. The result represents the failure cost over service life, which is obviously the highest for the reference option as the area beneath the curve is the biggest and the lowest for the stainless steel option, cp. Figure 5 and Figure 6. To calculate the cost over service life according to Figure 3 also the other cost categories have to be converted into present values and summed up. By doing so, the costs linked to the event of spalling for each option can be given as outlined in Figure 6.

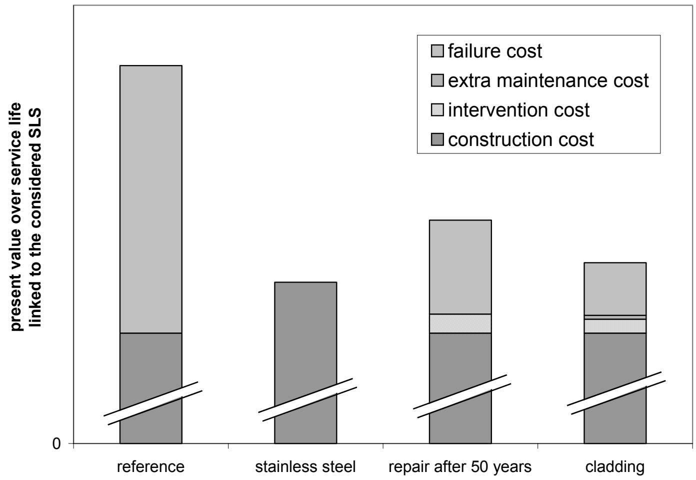

Figure 6 Costs over service life for all lay-out options, considering a discount rate of 2 %

Under consideration of the outlined boundary conditions it can be observed, that building the tunnel walls with partly stainless steel is here identified as the most economic lay-out option linked to the unwanted event of spalling and its consequences. Although at first view this option seems to be most expensive, as the initial investment, which is mainly governed by the construction costs, is the highest. The reference option on the other hand has been identified to be the less optimal lay-out solution among the considered options.
With the considered boundary conditions (in particular the translated cost linked to the consequence of spalling and the discount rate) the failure costs have a decisive influence on the optimisation result. Neglecting this cost category within the given example would lead to an opposite result. In such a case the reference option would be most economic and the stainless steel option the less economic solution among the four options.
By furthermore expressing the consequences into monetary values for hazard and environmental items the optimisation procedure can also be applied for these modules. By considering all of these costs a fully integrated design can be carried out. The challenge of the optimisation liked to all these objectives is a sound relation of the monetary values for the different consequences (e.g. due to fire, noise, reinforcement corrosion etc.).

3. CONCLUSIONS

In the presented example it has been shown how an optimisation procedure linked to durability consideration of tunnel walls has been carried out. Different lay-out options have been analysed with regard to construction, maintenance, intervention and failure costs, thereby considering direct and traffic costs. The result of such an optimisation procedure can be used as the foundation for an optimal decision making process within the design phase. By furthermore using similar modules design procedures for hazards and environmental considerations a fully integrated design can be carried out.

4. REFERENCES

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