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NPV - Decision making model for street maintenance and rehabilitation

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NPV – Decision making model for street maintenance and rehabilitation

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ABSTRACT: The cost-efficient provision of public infrastructures, such as street networks, can only be assured if funds are optimally allocated, not just during the initial construction but also, above all, to the maintenance of existing structures. The Net Present Value model developed by the Institute for Construction Engineering and Management at SFIT Zurich for quantifying the macroeconomic impacts of various approaches to maintenance offers decision makers a means of probabilistically simulating the long-term consequences of their decisions. A street maintenance system that can map the widest range of maintenance approaches is defined on the basis of a standardized catalog of maintenance measures and empirically derived progress curves to determine the condition of the street network.

1 INTRODUCTION

In recent decades the continual expansion of the road network in Switzerland has created values worth billions. Preserving the value of these investments is enormously important nowadays. In terms of the temporal planning of maintenance works, performing repairs as early as possible and on an ongoing basis throughout the entire life cycle is currently assumed to be the most beneficial approach. There is, however, currently no evidence that clearly substantiates this assumption. Equally little is known about the precise impacts of any deviation from this maintenance strategy. As such, shifting maintenance works within an overall life cycle approach can result in higher, but also - in individual cases - in lower expenditure.

In this paper a model for quantifying the costs of different maintenance variants is presented. The model was developed within a research project conducted at the Institute for Construction Engineering and Management at the Swiss Federal Institute of Technology in Zurich together with the Swiss Association of Street and Traffic Experts.

The model allows the analysis of various issues relating to maintenance planning such as postponing a single measure, a temporary departure from a defined strategy due to financial constraints or even the axiomatic comparison of different maintenance strategies. A Net Present Value is probabilistically simulated (Fig. 1) for these decision variants.

2 RESEARCH METHODOLOGY

An interpretivist and constructivist research approach was applied to developing the simulation model, since they structure social systems based on an intended input-output effect.

The constructivist simulation model is theory based using a deductive approach based on the one hand on scientific (financial) mathematical methods, such as cost calculation and investment budgeting, and on the other hand on the process of calculation based on simulating fuzzy variables.

The results are processed using the interpretivist research approach (Weber 1922, Girmscheid 2004), whereas the actual simulation model is developed using the constructivist research approach (Piaget 1973, Glasersfeld 1998, Girmscheid 2004).

The resulting "flexible" models are capable of revealing the bandwidth of the actual financial
impacts of individual decisions at a relatively early planning stage in terms of the total costs over the life cycle and form the basis for objective decision making.

3 SYSTEM DEFINITION

The developed model is based on a street maintenance system. This system includes the road condition and its development as well as the effect of maintenance measures and the necessary constraints.

3.1 Road condition

The road condition is the basic parameter in maintenance planning. Every decision is directly or indirectly dependent on the actual road condition or its expected development.

3.1.1 Condition indices

According to Swiss standard (SN640925b 2003) the road condition is indicated in five condition indices. These indices describe the surface damage, the longitudinal and transverse evenness, the skid resistance and the bearing capacity. According to the condition determined by visual evaluation or measurement for each index a value between zero (good condition) and five (bad condition) is assessed (Fig. 2). Additionally the structural index is defined which models the differences in the temporal development of the road condition according to its structure.

For the computer-aided analysis of the different maintenance variants the curves describing the development of the road condition are indicated as mathematical functions:

\[ I_x(t)_{\text{Road,Pavement,Traffic,Climatic}} = f(S,t) \]

where \( I_x(t)_{\text{Road,Pavement,Traffic,Climatic}} \) = Road condition in condition index x under the default of the kind of road, the pavement, the volume of traffic and the climatic conditions, \( x=\{1,2,3,4,5\} \), \( S = \) Structural index, \( t = \) Time.

3.1.3 Impact of maintenance measures

Performing a maintenance measure improves specific or all condition indices and possibly also the structural index.

In a predecessor project a catalog of standardized maintenance measures was set up. This catalog contains the costs of each measure as well as its impact on the five condition indices and the structural index. Less extensive measures, e.g. surface dressing, only cause a slight improvement to individual indices, while a more extensive measure, such as pavement replacement, will reestablish new conditions in all condition indices and improve the structural index.

Figure 4 shows the changes to the condition indices and the structural index caused by two measures of differing magnitude. The development of condition between the measures is currently still based on assumptions (q.v. 3.1.2).

It also becomes clear that the measure selection is usually affected by a decisive index. It is not likely that all indices lie within the recommended application range for one measure.
3.2 System boundary

Clear system boundary conditions must be defined for the applied model as the basis for a reliable economic comparison of different maintenance variants. Therefore it is necessary to assure comparable boundary conditions for each variant analyzed. Boundary conditions have to be defined in terms of content and time.

The economic comparison is carried out using the economic minimum principle, which means that a defined benefit shall be achieved with a minimum of costs (Wöhe 2005, Newnan, Eschenbach & Lavelle 2004). For street maintenance the aspired benefit is the provision of all maintenance measures which are necessary to ensure safe use and the conservation of value.

3.2.1 Content boundary conditions

The different maintenance variants are compared by calculating the Net Present Value of each variant as the balance of expenditure and income in the regarded period. As street maintenance generates no income the Net Present Value is reduced to the sum of expenditure. The expenditure is discounted to a reference point using dynamic calculation methods.

The analysis includes expenditure of the street operator, user costs and third party costs (Fig. 5). Together these three cost types present the entire economical costs of a maintenance variant. In some cases, e.g. for the budget planning of the street operator, the analyses can be reduced to one of these cost types.

<table>
<thead>
<tr>
<th>Expenditure Street Operator</th>
<th>Costs Users</th>
<th>Costs Third Party</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Expenditure for construction measures</td>
<td>- Time costs Users</td>
<td>- Environmental costs Accidents</td>
</tr>
<tr>
<td>- Fixed expenditure</td>
<td>- Car operating costs</td>
<td>- Accident costs</td>
</tr>
<tr>
<td>- Variable expenditure</td>
<td>- Accident costs</td>
<td></td>
</tr>
<tr>
<td>- Increased expenditure for maintenance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The expenditure for construction measures depends on the measures conducted in the regarded period. All other cost types are directly dependent on the road condition (Fig. 6). Maintenance expenditure increases if a street is operated in bad condition. In this case larger numbers of small measures are necessary to ensure safe use. The user costs continuously rise with the impairment of the road condition due to rising time costs through speed limits, increased vehicle operating costs through increased abrasion and higher accident costs.

Since the goal of the analysis is to compare different variants in street maintenance, it is sufficient to regard the relative changes to the user costs and third party costs. The calculation of the Net Present Value only includes the increase in these costs compared to an optimal road condition. Therefore the total values of these costs do not have to be calculated.
3.2.2 Temporal boundary conditions
A uniform time frame must be defined for the different maintenance variants, within which the Net Present Values of the maintenance variants is compared. Thus a start point \( t=0 \) and an end point \( t=t_e \) is defined. For the comparability it is important that conditions are comparable at both start and end point for all maintenance variants simulated.

At the start point this requirement is fulfilled in any case, because the road condition at the point \( t=0 \) is equal for each variant. Different maintenance strategies however cause the road condition and the asset value of the roads to develop differently during the regarded period. Thus the comparability at the end point is not given, since different variants of road maintenance produce different residual values of the road. To compensate this effect the fall in value, i.e. the difference \( \Delta V^i \) between the original value and the residual value, is regarded as additional expenditure at the end point (Fig. 7). The fall in value is equal to the expenditure which is necessary to restore the original road condition. It is calculated as the difference of the asset values at the start point and the end point.

\[
\Delta V^i = V_0^i - V_{t_e}^i
\]

where \( \Delta V^i \) = Fall in value with variant \( i \), \( V_0^i \) = asset value with variant \( i \) at the point \( t=0 \), \( V_{t_e}^i \) = asset value with variant \( i \) at the point \( t=t_e \).

![Figure 7. System boundary for different maintenance variants.](image)

3.3 Additional Constraints
In addition to the system boundaries defined in chapter 3.2, the following constraints are relevant for road maintenance and must be considered within the different maintenance variants:

- Application range of each measure
- Minimum requirement for road condition
- Annual budget of the street operator

The widest range of maintenance variants can be analyzed and compared on the basis of these constraints.

4 VARIANT COMPARISON
The different variants are compared on the basis of a Net Present Value analysis. In a first step the variants for the comparison have to be defined according to the constraints. This leads directly to the function of the road condition. Together with the maintenance measures planned during the regarded period this leads to the calculation of the Net Present Value of each variant.

4.1 Definition of maintenance variants
A maintenance variant can either be a temporary departure from a defined strategy or a new maintenance strategy. Accordingly, either the modified variant is compared with the original strategy or different strategies are compared.

The maintenance variants have to be defined considering the constraints given in chapter 3.3. If different strategies are to be developed, then additionally the principles for the measure selection have to be specified. This means specifying at which level of road condition a measure should be accomplished and the magnitude of the measure.

The condition developments shown in Figure 4 clearly reveal that the choice of measure is usually influenced by one decisive index; it is unlikely that the road condition for all indices will be within the recommended application range. The condition index may be below but may not be above the application range as in the latter case the measure would not produce the desired result.

4.2 Calculating the Net Present Value
The net present value (NPV) is calculated for each variant in order to assess and compare the various approaches to maintenance (Ross, Westerfield & Jaffe 1993). Since only costs are incurred in this system, and no income generated, the NPV is defined as the aggregate discounted expenditure in the individual years.

The costs incurred by the users and third parties that do not directly impact cash flow are nevertheless included in the calculation, since they ultimately produce indirect cash flow. In further studies the question whether these costs should be discounted or not has to be discussed. At this stage of the project they are discounted equally to the expenditure of the street operator. The issue that arises in that context is that discounting the costs aims to produce the benefit that actually occurs by if costs are incurred later rather than earlier. Money spent at an early stage generates longer interest payments or cannot be earned over the corresponding time period. This effect does not necessarily occur in the case of user and third party costs. For example, it might not be reasonable to place less value on the time lost in a
traffic jam five years down the road than on the same time loss today.

4.2.1 Deterministic calculation
The analysis can be conducted on a deterministic basis, i.e. with fixed initial parameters, for purposes of simplified analysis or when the spreads and distribution functions of the individual parameters are not available. Since the resultant value is, however, fixed and does not provide any information about the certainty of the expected result, a sensitivity analysis should definitely be performed subsequently.

The Net Present Value of a maintenance variant is the product of the operator’s expenditure together with any annual lump sum for increased individual maintenance measures over any year where performed subsequently.

\[ NPV^i = \sum_{t=0}^{\infty} \frac{A_{t,\text{Operator}}^i + \Delta A_{t,\text{User}}^i + \Delta A_{t,\text{ThirdParty}}^i}{(1+q)^t} - \Delta S^i \]

where \( NPV^i = \) Net Present Value of variant i,
\( A_{t,\text{Operator}}^i = \) Operator’s expenditure,
\( \Delta A_{t,\text{User}}^i = \) Increased user costs,
\( \Delta A_{t,\text{ThirdParty}}^i = \) Increased third party costs,
\( \Delta S^i = \) Depreciation, \( q = \) Discount factor.

The operator’s expenditure consists of the costs of individual maintenance measures over any year together with any annual lump sum for increased maintenance expenditure.

\[ A_{t,\text{Operator}}^i = \sum A_{t,\text{Operator, Measures}}^i + \Delta A_{t,\text{Operator, Maintenance}}^i \]

where: \( A_{t,\text{Operator, Measures}}^i = \) Operator’s expenditure,
\( A_{t,\text{Operator, Maintenance}}^i = \) Expenditure on maintenance measures,
\( \Delta A_{t,\text{Operator, Maintenance}}^i = \) Increased maintenance expenditure.

Increased maintenance expenditure is calculated per square meter of the road network in line with the relevant road condition, pursuant to condition index 11 (Surface damage).

\[ \Delta A_{t,\text{Operator, Maintenance}}^i = \sum_{n=3}^{5} \Delta u_n^{11} \cdot F_{11}^{t} \]

where: \( \Delta A_{t,\text{Operator, Maintenance}}^i = \) Increased maintenance expenditure, \( \Delta u_n^{11} = \) Increased maintenance expenditure per m\(^2\) of road network depending on condition index 11, \( F_{11}^{t} = \) Surface of the road network depending on condition index 11.

The road users’ costs are calculated as follows:

\[ \Delta A_{t,\text{User}}^i = \Delta A_{t,\text{User, TC}}^i + \Delta A_{t,\text{User, VC}}^i + \Delta A_{t,\text{User, AC}}^i \]

where: \( \Delta A_{t,\text{User}}^i = \) Increased user costs, \( \Delta A_{t,\text{User, TC}}^i = \) Increased time costs, \( \Delta A_{t,\text{User, VC}}^i = \) Increased vehicle operating costs, \( \Delta A_{t,\text{User, AC}}^i = \) Increased user accident costs.

The third party costs are calculated as follows:

\[ \Delta A_{t,\text{ThirdParty}}^i = \Delta A_{t,\text{ThirdParty, EC}}^i + \Delta A_{t,\text{ThirdParty, AC}}^i \]

where: \( \Delta A_{t,\text{ThirdParty}}^i = \) Increased third party costs, \( \Delta A_{t,\text{ThirdParty, EC}}^i = \) Increased environmental costs, \( \Delta A_{t,\text{ThirdParty, AC}}^i = \) Increased third party accident costs.

Increased accident costs affect both users, e.g. from damages to their vehicles, and uninvolved third parties, e.g. in the shape of follow-on costs such as disability pensions that have to be paid by the general public.

4.2.2 Probabilistic calculation
The underlying factors of the Net Present Value calculation, such as expenditure, development of road condition, traffic jam times, etc., and the discount rate fluctuate within a certain range with a usually clearly defined anticipated value as the result of natural or man-made influences. A deterministic approach only provides an anticipated value, but does not supply any information about the bandwidth within which the results can vary.

Monte Carlo Sampling or Latin Hypercube Sampling can be used to probabilistically calculate the difference between Net Present Values. With both of these methods the initial parameters of the NPV calculation are randomly varied using density function defined on the basis of a minimum, maximum and expected value of the individual parameters (Curran 1989). A BetaPERT distribution or a triangular function can, for example, be used as the density function.

The following equation then applies to the initial parameters:

\[ f(P) = \begin{cases} \text{Triangle} & (P_{min}, P_{av}, P_{max}) \text{ resp.} \\ \text{BetaPERT} & (P_{min}, P_{av}, P_{max}) \end{cases} \]

where: \( P = \) Initial parameter, \( P_{min} = \) Minimum value of the initial parameter, \( P_{av} = \) Anticipated value of the initial parameter, \( P_{max} = \) Maximum value of the initial parameter.

The calculation is performed using a large number of simulations with one possible NPV value being determined in each simulation. The aggregate results of the simulations produce a density and distribution function that can be used to derive the bandwidth of the possible results (Girmscheid & Busch 2003). Figure 8 shows a result of a simulation with anticipated, minimum and maximum values and the 5% and 95% fractile values for the NPV.

Figure 8. Result of a probabilistic simulation.
The probabilistic simulation changes not only the expenditure ratios of a variant but also the variants themselves by varying the underlying factors of the variant. For example, the time distribution or the absolute number of maintenance measures changes when the condition development varies.

4.3 NPV comparison

By incorporating the three components - operator's expenditure, user costs and third party costs - the calculated Net Present Value maps the macroeconomic impacts of the individual variants in full. A simple comparison of Net Present Value can be used to decide which variant is the most beneficial given the specified constraints. The variant with the lowest Net Present Value can be seen as the most beneficial. The optimal variant \( i_{\text{opt}} \) would be:

\[ \text{NPV}_{i_{\text{opt}}} \leq \text{NPV}_i, \text{ for all } i = 1, 2, ..., n \]

5 CONCLUSIONS AND OUTLOOK

The model presented here makes it possible to place a monetary value on the impacts of street maintenance decisions. The analysis is based on the life cycle of the network and on probabilistic parameters. This offers decision makers a means of checking the consequences of their decisions at an early planning stage and thus finding the optimal solution with regard to providing the best possible infrastructure at the lowest possible cost.

In individual cases, a definitive statement with regard to the impacts of various maintenance strategies can only be made on the basis of the specific constraints. But since comprehensive analysis is not possible or even economically defensible in all cases, continuing research will simulate a large number of different variants and scenarios to enable a definition of certain basic principles for optimized street maintenance.

REFERENCES


