PROCROSS

Development of Procedures for Cross Asset Management Optimisation

Tentative Document - The Procedures for Cross Asset Management Optimisation

Deliverable No. 3

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Österreichisches Forschungs- & Prüfzentrum Arsenal Ges.m.b.H. (AIT)

SEP Maerschalk

Slovenian National Building and Civil Engineering Institute (ZAG)

Trinity College Dublin

PMS-Consult GmbH
Engineering Office for Traffic and Infrastructure

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Executive summary

This report presents the development and practical implementation of a robust cross-asset management procedure for infrastructure networks. The methodology can accommodate both top-down and bottom-up approaches of different road authorities, including variability in existing sub-asset management software, available information, bias towards solutions, uncertainties related to sub-asset condition quantification and vague or imprecise information.

The theoretical procedure considers a constrained optimization format in a multi-objective framework, considering the requirements of different stakeholders. Intangible costs can be easily incorporated in this approach and agreed performance functions may be constructed through agreed key performance indicators and intervention options at a sub-asset level over different time horizons.

The practical implementation of the developed methodology is first presented through a realistic network under consideration. Optimized management of sub-assets are uniquely identified for different investment patterns. The minimum technical requirement for all sub-assets within the network is maintained at all times.

The key to implementation of the method at a wider level is related to the confidence of the end-users in the proposed method and their ability to adapt to the approach. To this effect, a moderated workshop has been organised involving the end users and their ability to adopt to the format is demonstrated by a separate network level example where the end-users themselves follow the developed methodology and identify the optimised intervention and investment strategies through cross-asset management format.

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1.1 PROCROSS overview and objectives

This report provides a basis for cross-asset management methodology for implementation by the European road administration authorities. The approach recognises that the governing philosophy behind maintenance and management of road infrastructure can be significantly different from country to country and provides a common ground for top-down and bottom-up approaches to base upon. The proposed method targets the saving of monetary and non-monetary resources along with minimizing negative impacts from socio-economic, technical and environmental factors considering requirements and expectations of multiple stakeholders.

The objectives of PROCROSS, with respect to WP3 and this report,are as follows:

- Development of procedures for the generation and assessment of maintenance strategies for sub-assets and the total road asset considering LCC-analysis, appropriate performance prediction methods, representative monetary and non-monetary values of a maintenance strategy for multiple stakeholders, impacts of measures, etc.
- Development of Procedures for combination of sub-asset maintenance strategies to total asset management strategies through appropriate weighting factors and matrices, flexible assessment of sub-asset maintenance strategies and assessment of impacts of combination at different levels of operation.
- Development of a generic formulation of an optimization problem for cross-asset management.
- Development and illustration of cross-asset optimisation at a practical level, related to the developed generic formulation at a theoretical level along with the investigation of the use of the practical procedure at different levels, including data requirement, requirements for expert software systems (BMS, PMS etc.) and practical decision markers.

1.1.1 Description

This report presents a robust cross-asset management for infrastructure networks that can accommodate the existing setup of a wide range of infrastructure maintenance management methodology in place for different roads authorities. The report also presents examples of the practical implementation of such cross-asset management, including demonstration of such decision making from the end-users.

1.1.2 Expected results

The results create a theoretical framework for cross-asset management of infrastructure networks. The theoretical framework may be adapted by infrastructure stakeholders to create cross-asset management systems. Examples of practical implementation are obtained from the results that provide a guideline for practising engineers to implement the concept for decision-making on a real infrastructure network. The combined results are expected to form a general guidance for cross-asset management of infrastructure networks.

1.2 Method

The method of developing a cross-asset management format from a theoretical perspective is obtained from the consideration of constrained multi-objective optimization of cost functions based on the combined requirements of the stakeholders of infrastructure networks. The practical implementation is presented as a realistic, but synthetic network, acknowledging that interpretation of feasible solutions and the involvement of engineers as conscious decision makers in the process. The implementation barrier of the proposed methodology is addressed by presenting an example of hands-on cross-asset management implementation by the end-users in a moderated workshop.

2 Procedure framework

A significant number of infrastructure networks still maintain their assets [1] or sub-assets through an approach where the objectives or goals are often independent of one another at a component or a project level, when in reality significant interdependencies between the components or assets exist in that level.

Consequently, money allocated or used is not optimised. Such under-utilisation of resources is not sustainable and may result in insufficient funds being available to carry out necessary interventions in time due to restricted resources in the current financial climate [2]. On the other hand, inadequate acknowledgement of multiple criteria [3] guiding a project, or failure to acknowledge the requirement of multiple stakeholders may result in an inadequacy related to safety [4], serviceability [5], societal [6] or policy level [7]. So, even after an apparently successful intervention on a section of infrastructure network, the final results may not address the objectives, leading to a significantly inefficient investment methodology.

Independent of how different infrastructure owners approach this problem [8], it is important to develop a generic methodology for cross-asset management which caters to the multiple requirements of multiple stakeholders and also acknowledges the current condition of each asset or sub-asset utilizing maintenance management tools which provide performance markers for them. Thus, cross-asset management combines engineering principles with a sound business practice and economic realities.

The generic methodology should be viewed as a best practice guideline through which a defined infrastructure network may be maintained and operated in a safe and efficient fashion with an emphasis on cost minimisation. The term ‘cost’ is used in a broad sense and may cover tangible or intangible factors [9]. The optimization of investment comes through the consideration of multi-criteria objectives, requirements, expectations and information of various stakeholders.

Cross-asset management needs to combine the different maintenance needs of the single assets and the general, strategic requirements at network level [10]. Thus, it is necessary to implement and work with procedures which enable on the one hand a clear definition of technical maintenance needs of each single asset and on the other hand to assess the consequences and effects in doing maintenance in relation to the given strategic requirements (budget, availability, safety, etc.).

Finally, it should be possible to find those asset specific solutions, which show the lowest negative effects under the given requirements. PROCROSS is an ongoing road ERA.net European project focusing on cross-asset management for road infrastructure networks at a country level. The approach considers a wide number of influencing parameters including age, environment, materials, deterioration processes, loadings, maintenance policies, etc. PROCROSS attempts to identify best practice of asset management processes and understanding cross asset interdependencies and costs/values to evaluate impact of maintenance activities on the different sub-assets. In this regard, development of generic multi-objective optimization processes is extremely important.

Impact of asset inventory [11], condition rating of assets or sub-assets [12] and the integration of such information in decision making [13] is possible through this project. The various hierarchical stages of risk ratings and rankings ranging from expert ratings [14] using from visual data to [15] testing, deterministic assessment [16], semi-probabilistic [17] and probabilistic assessment [18] have already been investigated in depth and it is possible to synthesise such information in a cross-asset management procedure.

Cross asset management procedures offer a maximised transfer of benefit by addressing diverse performance measures or requirements from the stakeholders' perspective. PROCROSS initially investigated the various formats in which information is collected for diverse infrastructure networks. Such information helped recognize cross-asset interdependencies and the impact of selected measures and activities due to operational experiences.

Governing influencing factors and stakeholders requirements and expectations were also identified. The monitoring requirements for effective cross-asset management were established by identifying relevant monitoring requirements.

This report presents generic procedures for cross-asset management considered in the PROCROSS project. The approach helps analyze the impact of spatial and temporal spread versus the aggregation of measures. It also recommends prioritization strategies and optimization procedures which consider the organizational requirements of road administrations, the technical requirements of sub-asset management and cross-asset interdependencies, the availability of KPIs and monitoring requirements and the stakeholders' expectations. The approach of PROCROSS towards cross-asset management is holistic and based on the total road infrastructure. The procedures developed in this project facilitate/enable combined maintenance activities on different sub-assets and thereby reduce negative impacts and effects to road users or other affected parties. The results from this project are immediately important for road administrations and road operators. The implementation of such procedures is valuable for the identification of effective and non-effective maintenance strategies for different sub-assets as well as for a future oriented planning process.

The procedure is flexible and thus can be adapted to different road administrations which comprise different technical and organizational structures. From the PROCROSS project point of view it is essential to blend the specific technical maintenance needs of single assets or sub-assets (Bottom-up approach), with the general strategic targets of the whole network (Top-down approach). The spatial and chronological combination of maintenance treatments with follow- up assessments seems to be an adequate solution.

Figure 1 depicts this approach schematically.

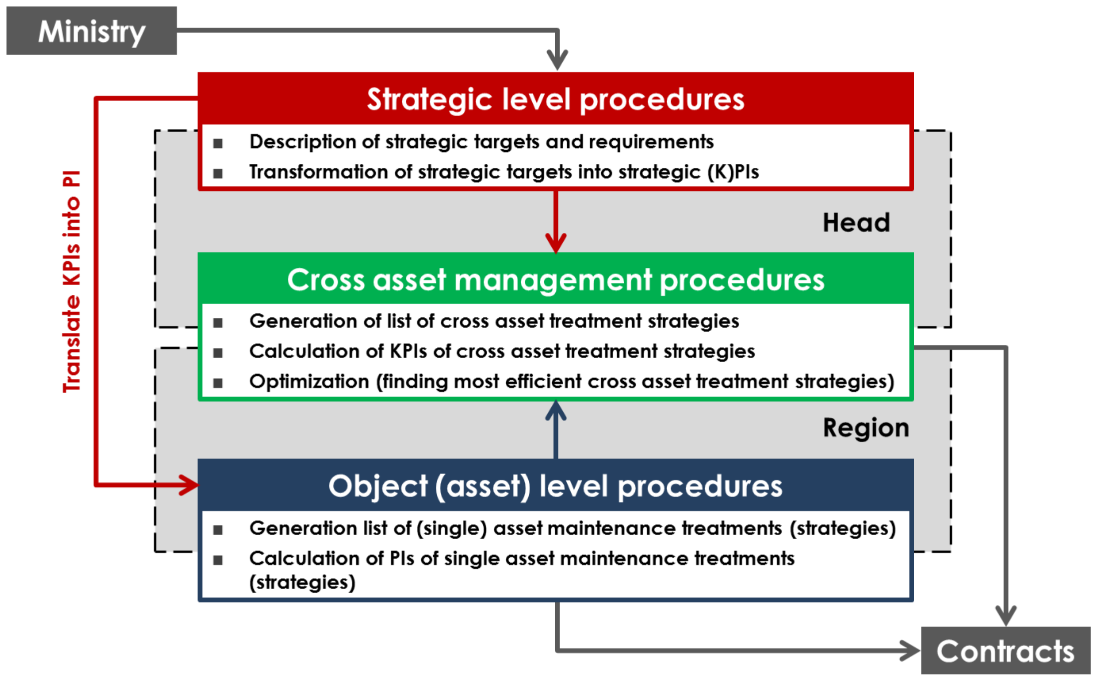

Figure 1: Combination of bottom-up and top-down approach within cross-asset management.

The strategic level procedures and the object level procedures are both addressed through the cross-asset management procedures, which is - a middleware in the asset management process. Only, the integration of the cross asset management procedures between the strategic and object level enables true combination of both levels thereby creating the opportunity to adopt a range of cross asset management optimization tools.

Considering the fact that the former approach is top-down and the latter bottom-up, the developed procedure can be considered to incorporate both fundamental approaches of asset-management.

The impact of various indicators, interventions andstrategic level requirements are all considered in the developed methodology. The cross-asset strategies investigate a number of important scenarios. Intangible costs are proposed as possible factors in the management process. Engineering judgment can be used to significantly limit the number of feasible intervention options for specific networks. Consequently, the expertise of consulting engineers is not undermined, but enhanced through this approach.

Furthermore, Figure 1 shows schematically the combination of asset management procedures with the organizational structure of a NRA, where the strategic targets are usually strongly influenced by the ministry (policy makers) and the technical assessment of assets will be carried out by local branches or asset specific departments. The location of cross asset management could therefore be seen as a combination of head and region in the form of a connecting string between the strategic and the technical level.

An important factor for the developed procedures is the translation or transformation of strategic targets and objectives into technical performance indicators. Only the technical understanding of strategic goals enables integration into the technical level and thereby into asset specific management systems such as PMS, BMS, TMS, etc. Without this connection it would be difficult to bring the results from the asset specific assessment process in line with the owner/manager/end user strategic targets and objectives.

2.1 Strategic targets and technical requirements

A key factor for the development of a holistic Asset Management approach is the requirements of the different stakeholders, which define the technical and strategic performance indicators (PIs). In general, these road- or asset-specific requirements can be summarized into the following main targets:

- Maximization of traffic safety
- Maximization of riding comfort
- Maximization of availability
- Minimization of negative environmental impacts and effects
- Compliance of maintenance budget restrictions
- Other strategic or political requirements and targets

The translation of strategic targets and objectives into technical indicators is a key issue in the whole process. For the integration of the strategic goals into a technical process, the performance indicators (PIs) have to be described in the form of one or more (technical) performance indicators. For example, the safety and comfort requirements on the road pavement can be described by thresholds of rutting, skid resistance, roughness, etc. These parameters are usually based on national and international standards in comparison to other requirements (e.g. available maintenance budget, the availability, the environmental impact, etc.), which are strongly influenced by the economic, the environmental and finally the political situation.

2.2 Strategic and technical performance indicators

2.2.1 General indicators

An essential precondition for the practical application of cross-asset management is the definition of adequate performance indicators, which can be used for the tasks as follows:

- Indicators for the description of the effects of treatments on single assets or of the effects caused by coordinated maintenance treatments:
    - Costs
    - Benefit (effect of a treatment in relation to a referencing value or situation)
    - Combination of costs and benefit (e.g. cost-benefit ratio)
- Indicators for the description of requirements on the strategic and the object (technical) level:
    - Budgetary restrictions
    - Strategic restrictions
    - Technical restrictions and minimum requirements
    - Others

Both types of indicators can be based on different input parameters or can be calculated from single indicators into combined performance indicators. For the practical application of cross-asset management procedures, the indicators need to be specified. Within PROCROSS the following indicators were defined as a first assumption:

- External costs (*ExC*)
- Benefit (*BE*)
- Construction costs (*CC*)
- Minimum technical requirements of an asset *a*, expressed by a technical parameter or an index (*minTPa*)

On the basis of this list, it is possible to define the following indicators (effects) for a maintenance treatment strategy *M* of an asset *a* for a given time frame *t*:

- Present value construction costs of maintenance treatment strategy *M* ($CC_{M,a}$)
- Present value external costs (Sum of costs due to condition of asset *a* and due to maintenance treatments on asset *a*) of maintenance treatment strategy *M* ($ExC_{M,a}$)

In addition to the indicators listed above, it is necessary to include a decision variable *X*, which guarantees the compliance of the minimum (technical) requirements of a maintenance treatment strategy *M:*

$$X(M_a) = 1 \text{ for } TP_a \geq \mathrm{minTP_a}$$

$$X(M_a) = 0 \text{ for } TP_a < \mathrm{minTP_a}$$

2.2.2 Additional indicators (alternatives)

In addition to the indicators considered in the sections above, the following costs [22] can also be taken into consideration for cross asset management.

Delay Cost

$$C_{TC} = \mathrm{D_0} \sum_{\mathrm{l}} \mathrm{np_l T_l u_l} \left(\frac{\mathrm{L_d}}{\mathrm{v_r}} - \frac{\mathrm{L_d}}{\mathrm{v_n}}\right) \frac{1}{(1+R)^{T-t}}$$

where C_{TC} is the delay cost from intervention activities, D_0 is the number of days of intervention, np_l is the number of l^{th} vehicle *u*, *l* is an index of vehicle type, *t* is the intervention period, T_l is the average daily traffic volume of l^{th} vehicle, v_r and v_n are the average vehicle speed under normal conditions and maintenance activities respectively, L_d is the route affected by intervention activities, u_l is the time price of l^{th} vehicle users, *R* is the discount rate and *T* is the service life of the sub(asset).

Loss of Comfort and Convenience Cost

$$C_{SC} = \mathrm{Sc_{pt} M} \frac{1}{(1+R)^{T-t}}$$

where C_{SC} is the loss of comfort and convenient cost, *S* is the comfort index under a certain intervention, c_{pt} is the per capita income within the region of intervention activities and *M* is the total population within the region of maintenance activities.

Social Costs due to Security Incidents

$$C_{PC} = D_0 \sum_{l} V_l T_l (p_{ul} - p_{nl})(H_l R_1 + L_l R_2) \frac{1}{(1+R)^{T-t}}$$

Where C_{PC} is the social cost due to security incidents during intervention activities, V_l is the average losses of a single vehicle (l^{th} vehicle), p_{nl} and p_{ul} are probabilities of traffic of l^{th} vehicle under normal conditions and intervention operations respectively, H_l and L_l are the probabilities of personal injury and death respectively related to accidents and R_1 and R_2 are the average losses due to personal injury and death respectively.

Societal Costs Related to the effects on neighbouring industries

$$C_{IC} = D_0 \sum_{m=1}^{l} (1-\alpha)\beta_l E[B_m]$$

where C_{IC} are the societal costs related to the effects on neighbouring industries, α is the coefficient of intervention activity on the (sub) asset and assuming continuous values between 0 and 1, β_l is the correlation coefficient of m^{th} industry on related to the (sub) asset and also assuming continuous values between 0 and 1 and $E[B_m]$ is the expectations of day's earnings of m^{th} industry.

2.3 Cross asset maintenance treatment strategies

2.3.1 Asset specific maintenance treatment strategies (object level)

In the context of life cycle cost analysis (LCCA), the planned maintenance treatments for a specific road asset (pavement, bridge element, etc.) need to be assessed according to their positive and negative effects over a certain time-period (Kong, J.S. et al. (2003)). Within this approach, the prediction of the performance (condition) is a decisive factor.

If the condition reaches a certain level (trigger), different maintenance options can be applied where the short- and long-term effects are usually different. Because of the future-oriented approach of LC(C)A, it can happen that the trigger is reached a second or a third time during the assessment period. Thus, it will be necessary to speak about maintenance treatment sequences or asset-specific maintenance treatment strategies, which can consist of a single activity or of more than one activity within the assessment period. Figure 2 shows the deterioration of two single road assets and the different options to improve the condition by applying maintenance treatments.

Each single maintenance option, which can be defined as an object- or element-specific treatment sequence, can be described by different values or indicators, which enable the engineer or decision-maker to select the “best” solution that needs to coincide with the strategic targets and requirements but also with the (minimum) technical demands.

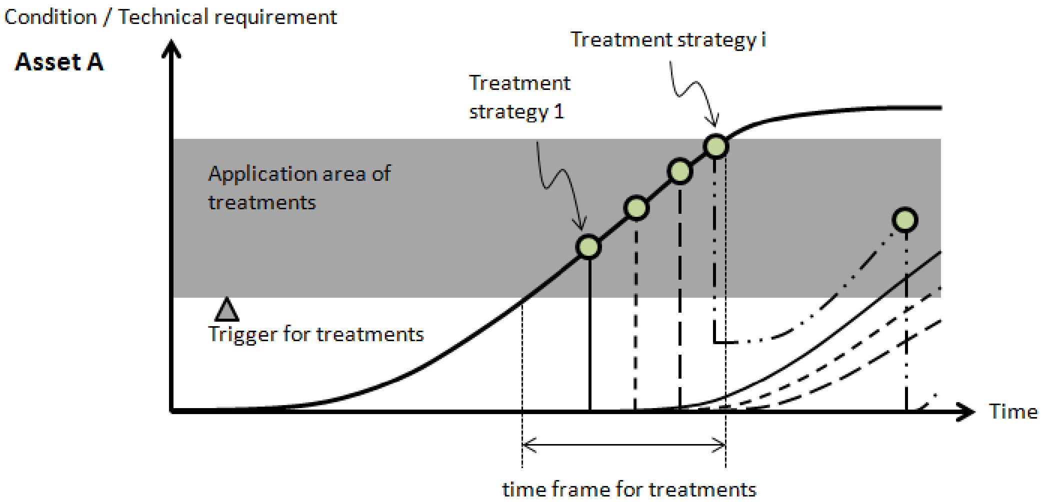

Figure 2: Deterioration and maintenance treatment strategy of asset A

2.3.2 Maintenance projects

In many cases the coordination of asset-specific maintenance treatments is related to a larger maintenance project or scheme. It includes a certain number of assets, which are limited by a specific area and a certain time frame. The coordination of asset-specific maintenance treatments will usually be carried out by the projects individually, but needs to be brought together over the whole network for the optimization.

Based on the available information and the maintenance needs of the different single assets, it is possible to define such projects over the whole network for a given time frame. In many countries, the time frame for projects or schemes is between 1 and 6 years. For the definition of the projects or schemes the following parameters need to be taken into consideration:

- Year of construction of road
- Year of construction of assets along the road
- Condition and difference of condition between the different assets
- Performance prediction and maintenance intervals of assets
- Minimum and maximum length of construction sites
- Sequence and extent of assets
- Asset value
- Cross section of road
- Critical phase of assets
- Traffic routing
- Spatial situation
- Others

2.3.3 Generation of cross asset maintenance treatment strategies

To reduce the negative effects of maintenance treatments, it is necessary to combine them to a wide extent into the same maintenance project. Thus, the main objective of cross-asset management is to fulfill the given strategic, economic and of course technical requirements with the lowest negative effects to the different stakeholders over the whole network and over all projects or schemes.

The combination procedures can be quite complex and are strongly related to the number of assets or sub-assets to be taken into consideration, but also to the spatial distribution of maintenance needs on the different assets. In many countries the combination of maintenance treatments from different assets is based on engineering judgement, where the asset managers and engineers try to assess the consequences manually. The primary aim of cross-asset management is not to replace the engineering judgement, but to provide better information and indicators, which enable the asset managers and engineers to assess different *Cross Asset Maintenance Treatment Strategies*. These indicators will be described below. Furthermore, it is beneficial to use these indicators for finding solutions which best fulfill the different requirements. For this purpose, an optimization routine can be used. This will also be described below.

Figure 3 shows schematically the combination of asset-specific maintenance treatment sequences or strategies (Asset A+B). The different *Cross Asset Maintenance Treatment Strategies* are based on the deterioration of the single assets. Figure 3 shows, that a possible *Cross Asset Maintenance Treatment Strategy* (e.g. Cross Asset Maintenance Treatment Strategy 2) is only the sequence of individual single treatments of asset A and B. They do not offer a combined treatment potential. Cross Asset Maintenance Treatment Strategies 1 is a real combination of maintenance activities on asset A and B.

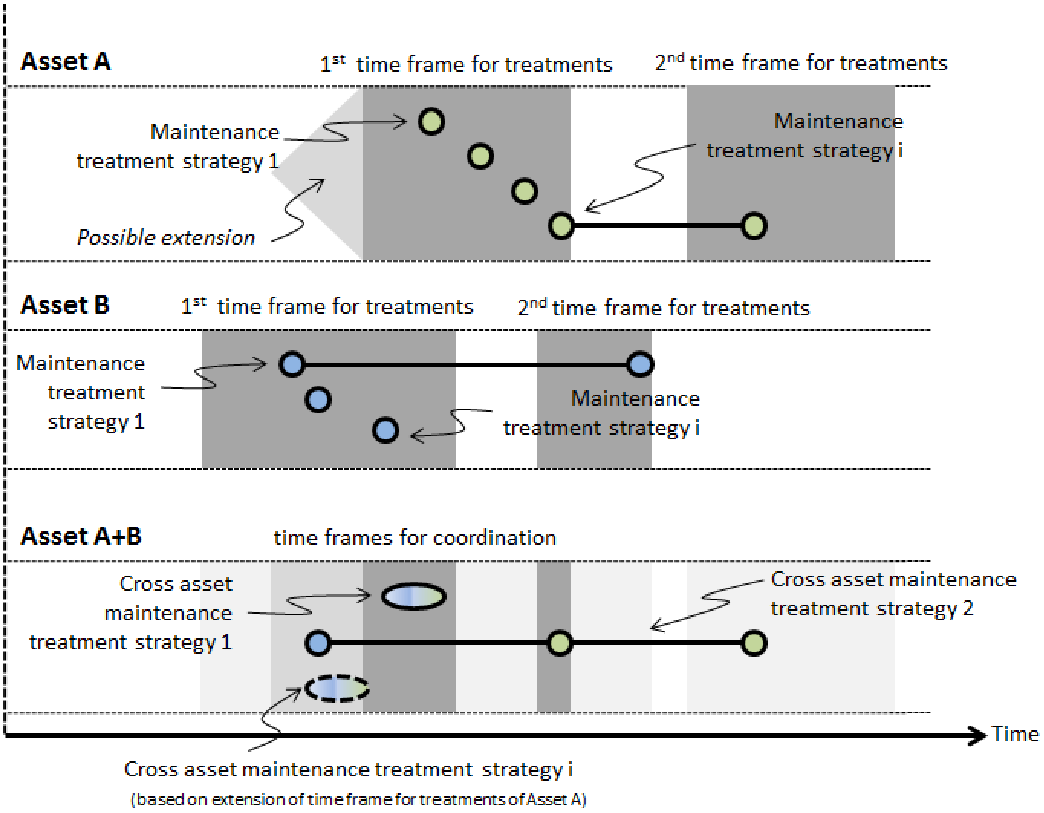

Figure 3: Combination of asset-specific treatment strategies to cross-asset maintenance treatment strategies

Independently from the main target to combine the asset-specific treatments as far as possible, it will be necessary to keep the “uncombined” solutions in the procedure. Otherwise it will be not possible to fulfill all given requirements. Sometimes, it makes sense to extend the time frame for finding more combination possibilities.

As a result of this discussion the following main groups of *Cross Asset Maintenance Treatment Strategies* can be defined:

- *Cross Asset Maintenance Treatment Strategies*, which are based on a real combination of single asset specific maintenance treatments (e.g. Cross Asset Maintenance Treatment Strategy 1)
- *Cross Asset Maintenance Treatment Strategies*, which are based on a sequence of single uncombined maintenance treatments of single assets (e.g. Cross Asset Maintenance Treatment Strategy 2)
- *Cross Asset Maintenance Treatment Strategies*, which are based on an extension of the application area to combine asset specific maintenance treatments (e.g. Cross Asset Maintenance Treatment Strategy i)
- Combination of the previous *Cross Asset Treatment Strategies*

Within cross-asset management, it is necessary to distinguish between the different groups because the calculation of the indicators to be used for the description of the *Cross Asset Maintenance Treatment Strategies* can be different.

It has to be stated that cross-asset maintenance treatment strategies CM_p of a project p, which do not fulfill the minimum (technical) requirements $X(M_a) = 0$ have to be excluded from the combination process.

2.3.4 Indicators of cross asset maintenance treatment strategies

The indicators to describe *Cross Asset Maintenance Treatment Strategies* can be grouped in the same way as the indicators of asset-specific maintenance treatment sequences or strategies on object level. *Cross Asset Maintenance Treatment Strategy* can be described by the following indicators [23]:

- **Present value construction costs** of coordinated cross-asset maintenance treatment strategy CM_p of a maintenance project p in year t, taking into account different assets a ($CC_{CM,p,t}$)
  - for combined maintenance treatments

$$CC_{CM,p,t} = \bigcup_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1$$

  - for maintenance treatment sequences (uncombined)

$$CC_{CM,p,t} = \sum_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1$$

- **Present value construction costs** of coordinated cross-asset maintenance treatment strategy CM_p of a maintenance project p over the whole assessment period, taking into account different assets a ($CC_{CM,p}$)
  - for combined maintenance treatments

$$CC_{CM,p} = \sum_{t} \bigcup_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1$$

- for maintenance treatment sequences (uncombined)

$$CC_{CM,p} = \sum_{t}\sum_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1$$

- **Present value external costs** of coordinated cross-asset maintenance treatment strategy CM_p of a maintenance project *p* over the whole assessment period, taking into account different assets *a* ($ExC_{CM,p}$)
  - for combined maintenance treatments

$$ExC_{CM,p} = \bigcup_{A} ExC_{M,a,p} \quad \text{for all } X(M_a) = 1$$

  - for maintenance treatment sequences (uncombined)

$$ExC_{CM,p} = \sum_{A} ExC_{M,a,p} \quad \text{for all } X(M_a) = 1$$

- **Potential of coordination**

  An additional criterion of a coordinated cross-asset maintenance treatment strategy CM_p could be the potential of coordination. The more maintenance treatments of different assets which can be combined at the same time, the better the coordination overall. Although the external costs indicate the effect indirectly, the calculated values do not show the positive effect with the required extent for all situations. In particular the effect of coordination of maintenance treatments with a very low benefit on external costs (e.g. bridge maintenance treatment, which does not affect the road users) needs to be ranked higher using this potential of coordination ($PC_{CM,p}$).

  The potential of coordination $PC_{CM,p}$ of a coordinated cross asset maintenance treatment strategy CM_p of a maintenance project *p,* over the whole assessment period, taking into account different assets *a,* can be defined over the number of coordinated asset specific maintenance treatments *C* as follows:

$$PC_{CM,p} = \sum_{C} CM_{a,p}$$

- **Benefit**

  Beside costs, the benefit is the second essential indicator for the assessment of coordinated cross-asset maintenance treatment strategies. The benefit can be defined as the positive impact of maintenance treatments on the condition of the respective asset. Usually the benefit will be calculated as a relative value in the form of a comparison between the “do-nothing” and the maintenance activities, which have to be carried out to fulfill the minimum requirements.

  The benefit $BE_{CM,p}$ of a coordinated cross-asset maintenance treatment strategy CM_p of a maintenance project *p,* over the whole assessment period, taking into account different assets *a,* in relation to the maintenance treatment strategy, which fulfills the minimum (technical) requirements ($minCM_p$), can be defined by using the external costs (*ExC*) as follows:

$$BE_{CM,p} = ExC_{\min CM,p} - ExC_{CM,p}$$

- **Efficiency and benefit-cost ratio**

  To include only those solutions in the optimization process which offer a good economic solution, it is necessary to asses each coordinated cross-asset maintenance treatment strategy according to its efficiency. The most effective way of assessment is the comparison of costs and benefits in the form of a benefit-cost ratio. In order to include the strategy which fulfills the minimum (technical) requirements (which could be an uneconomic solution), it is necessary to calculate the benefit-cost ratio in relation to this strategy.

  The benefit-cost ratio $BCR_{CM,p}$ of a coordinated cross-asset maintenance treatment strategy CM_p of a maintenance project *p* in relation to the maintenance treatment strategy, which fulfills the minimum (technical) requirements ($minCM_p$), can be defined by using the construction costs (*CC*) and the benefit (*BE*) as follows:

$$BCR_{CM,p} = \frac{BE_{CM,p} - BE_{\mathrm{min}CM,p}}{CC_{CM,p} - CC_{\mathrm{min}CM,p}}$$

  For strategies, which show a negative difference to the benefit and/or costs BCR should be set to zero.

2.3.5 Optimization approach

As already mentioned, it is important to find out which combination of *Cross Asset Maintenance Treatment Strategy* CM_p over the whole network (sum of projects *p*) fulfills the requirements best. For this purpose, different optimization targets can be defined, taking into account all, or only the most important indicators.

The following general definition of the optimization target is based on maximizing the benefit of all *Cross Asset Maintenance Treatment Strategies* over the whole network, taking into account only those strategies which fulfill the economic and technical requirements as well as budgetary and other constraints [23].

Mathematically, the optimization objective can be described by a target function T, which is equal to the total benefit BE_{total} of all projects *p*:

$$T = BE_{total} = \sum_{CM}\sum_{P} ExC_{CM,p} \cdot PC_{CM,p} \cdot Y_{CM,p} \Rightarrow \mathrm{max!}$$

The following constraints have to be met:

- Compliance that two or more maintenance treatment strategies of a project *p* will not be selected at the same time by using the decision variable *Y*:

$$\sum_{CM} Y_{CM,p} \leq 1 \quad \text{for} \quad p = 1,\ldots,n$$

- Compliance that the yearly available maintenance Budget Bud_t will not be exceeded by the construction costs of the maintenance treatments in a certain year:

$$\sum_{P} CC_{CM,p,t} \cdot Y_{CM,p} \leq Bud_t \quad \text{for} \quad t = 1,\ldots,n$$

- Compliance that the yearly available budget Bud_t is greater than the minimum budget minBud_t to fulfill the minimum (technical) requirements:

$$Bud_t \geq \min Bud_t \quad \text{for} \quad t = 1,\ldots,n$$

- Compliance that the efficiency of the maintenance treatment strategy is higher than the minimum efficiency $minBCR_{CM,p}$:

$$BCR_{CM,p} \geq \min BCR_{CM,p} \quad \text{for} \quad p = 1,\ldots,n \quad \text{for} \quad CM = 1,\ldots,n$$

3 Practical approach of procedures

3.1 Background

The procedure framework establishes an appropriately robust methodology for cross-asset management. However, not all combinations of sub-assets and intervention options permuted over a range of time zones are practical for consideration. This is fundamentally due to the fact that feasible interventions require expert interpretation through an appropriately qualified and trained consultant. Even if pre-existing management systems (e.g. Bridge Management System (BMS), Pavement Management System (PMS)) are used to obtain possible intervention strategies as automatic outputs, the cross-asset strategies will not necessarily be combinations of these interventions, nor will all combinations form a comprehensive set of the number of interventions that may be possible. Consequently, in practice, the objectives and the broad methodology presented in section 2 of this report would have to be achieved by reasonably considering a wide number of feasible interventions. Establishing these interventions directly draws from the expertise of the engineer and enhances the importance of training, information and knowledge of engineers in the field of infrastructure maintenance management. This section presents scenarios that may work as a guiding example of how a cross-asset management approach can be incorporated to existing systems (top-down or bottom-up), from a practical point of view, following the fundamental principles presented in section 2.

3.2 Analysis of network-level hierarchical scenarios for cross asset management

The practical implementation of cross-asset management is carried out through an iterative approach. The methodology for this practical implementation is presented below. The analyses of example scenario are presented next to illustrate this approach.

The network is required to be defined in the beginning and the components appropriately established. Information on the existing conditions of the sub-assets, including network level information, testing information, information of previous assessments, outputs of management system software, available finance and resources, performance conditions from stakeholders and feasible interventions should also be identified based on best available information. Tangible and intangible costs and benefits are to be computed next, with the definition of costs and benefits previously agreed on. At all levels, it is assumed that there is enough investment to ensure that all sub-assets conform to the minimum technical requirements related to safety and usability. The following strategy is an example of using the cost-benefit ratio as an appropriate indicator to establish an appropriate cross-asset management:

1. The list of intervention is sorted according to the cost-benefit-ratio, where the highest ratio is at the top.
2. A do-minimum approach is considered for all projects forming a part of the network and a distribution of cost is arrived upon.
3. The best cost-benefit analysis is compared against the do-minimum condition. If the required budget for the best cost-benefit option is available, this option is chosen for the respective project and the available budget is reduced to the replaced, required budget.
4. The option related to a cost-benefit ratio immediately lower than the best available is considered next. If this strategy corresponds to a project that is different from the already chosen strategy, a change is carried out from do-nothing to this strategy, again comparing the needed with the actual available budget. A reduction of the actual available budget with the needed one takes place if this strategy is adopted.
5. A search is carried out next along the sorted list to establish if there is a strategy that has a higher benefit than the selected strategy for the project and is still within the originally available budget.
6. The search is resumed until a strategy is encountered, where the benefit is lower than the selected strategy for the project, to that point. All strategies with a lower benefit than the chosen one can then be disregarded independent of the cost.
7. The search is still resumed to identify strategies that correspond to a higher benefit than the chosen strategy, but where the budget exceeds what is available for the time period under consideration.
8. Once the entire search is complete, the process is started again from step 2 of this schema till convergence, since a change of strategy in a previous iteration may change the required budget.

This approach is a reasonable way to realise the methodology presented in section 2, but is not necessarily the only way. Other equivalent methods from different road authorities can also be accommodated within the framework. However, for any approach – an example of the implementation is recommended through scenario analysis.

3.3 Example of cross-asset management optimization

The following generic, fictive examples should give an overview of the solution described above and help the reader of this report to understand the basic ideas of PROCROSS. The full example can be taken from an MS Excel spreadsheet, which was explained during the 3rd Workshop.

As shown in Figure 4, the network consists of a limited number of roads (Road A to G), which are subdivided into 3 projects (A, B and C). Each project (scheme) includes different assets (pavement P, bridge B, tunnel T, noise barrier N).

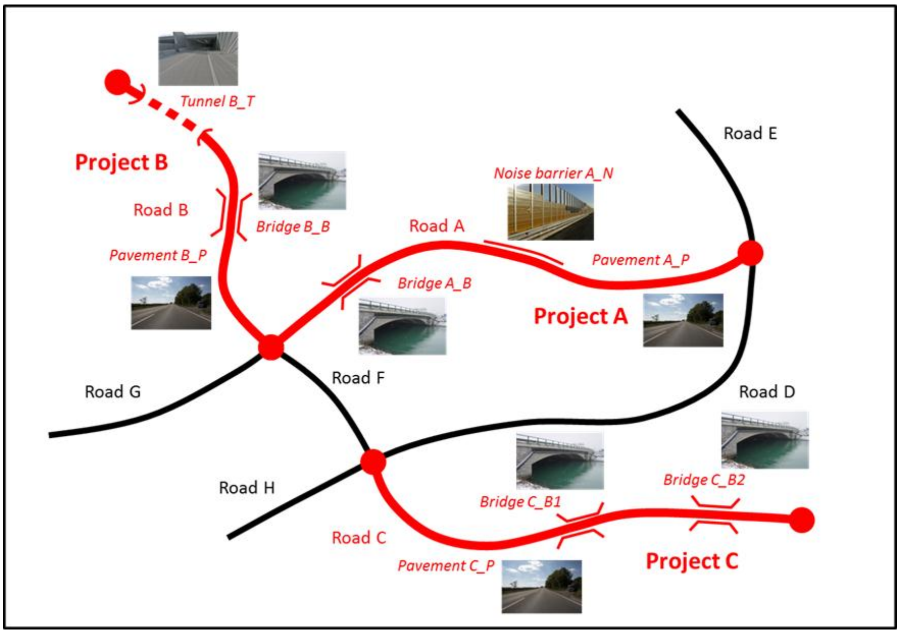

Figure 4: Example – network, projects and assets

The main objective of the cross-asset optimization is to find a solution of maintenance activities, which maximizes the benefit under given requirements (technical and strategic ones). The following list shows these requirements and targets in detail:

- Compliance with minimum technical requirements
- Maintenance activities should cause the lowest possible user disturbance
- Application of high efficient and sustainable maintenance treatment strategies
- In the year 2016, on parallel Road D extension works from 2 to 4 lanes (fixed measure!)
- Maintenance activities within budgetary constraints
- Cross asset optimization period: 2013 to 2017

The yearly budgetary constraints can be taken from Figure 5, which shows two possible budget scenarios for the whole optimization period.

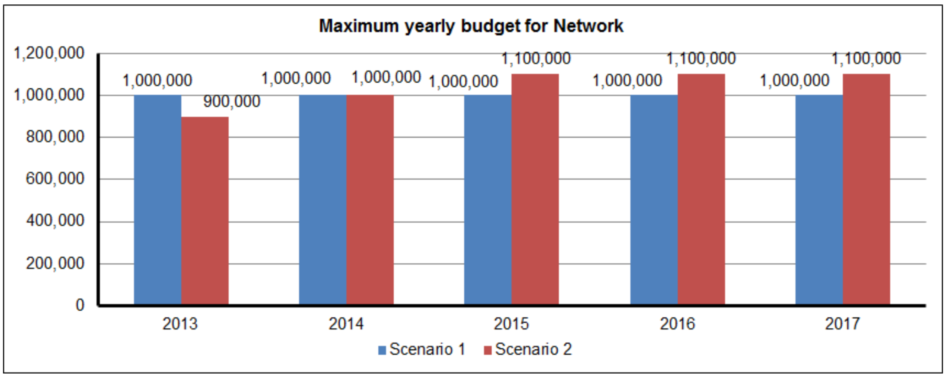

Figure 5: Example – yearly budgetary constraints

The first step of the approach is to define and assess the maintenance needs of each single asset for the 3 different projects. The assessment is based either on a sophisticated management system (PMS) or on simple engineering judgement. Regardless of the method, a list of possible asset-specific maintenance treatments is the output. Figure 6 below shows outputs of the asset-specific analysis (maintenance treatment strategy list) for the pavements of project A. The calculation of costs, disturbance and savings (= performance indicators) are based on local models and will not be explained in detail here.

Technical assessment of pavement

Output of PMS-analysis

Treatment Strategy	Treatment	Year	Cost	Disturbance	Savings	Do Minimum?
A_P1	PATCH	2015	6,000	2,500	300	
	PATCH	2017	6,000	2,500	200	
			12,000	**5,000**	**500**	Yes
A_P2	OVL	2015	800,000	20,000	64,000	
			800,000	**20,000**	**64,000**	No
A_P3	PATCH	2015	6,000	2,500	300	
	OVL	2016	800,000	20,000	59,000	
			806,000	**22,500**	**59,300**	No
A_P4	PATCH	2015	6,000	2,500	300	
	OVL	2017	800,000	20,000	64,000	
			806,000	**22,500**	**64,300**	No
A_P5	PATCH	2015	6,000	2,500	300	
	PATCH	2017	6,000	2,500	200	
	OVL	2017	800,000	20,000	64,000	
			812,000	**25,000**	**64,500**	No
A_P6	PATCH	2015	6,000	2,500	300	
	REINF	2017	2,100,000	120,000	211,400	
			2,106,000	**122,500**	**211,700**	No

Figure 6: Example – output of asset-specific analysis (maintenance treatment strategy list) for the pavements of project A

If an asset-specific maintenance treatment strategy does not fulfill the minimum technical requirements or is in conflict with other preconditions (e.g. 2016 on parallel road D extension works), the solution will be excluded (e.g. A_P3, A_P5, red light on the right). Furthermore, the strategy, which fulfills the minimum requirements with the lowest effort is defined in the "Do-Minimum?" column.

The same procedure can be carried out with all the other assets in the projects. Figure 7 shows the output of this process for the tunnel B_T of project B.

Technical assessment of tunnel

Asessment in the context of tunnel-safety program

Treatment Strategy	Treatment	Year	Cost	Disturbance	Savings	Do Minimum?
B_T1	IMPR E+M	2013	890,000	17,400	61,000	
			890,000	**17,400**	**61,000**	No
B_T2	IMPR E+M	2014	890,000	17,900	59,000	
			890,000	**17,900**	**59,000**	Yes

Figure 7: Example – output of asset-specific analysis (maintenance treatment strategy list) for the tunnel of project B

The next step in the procedure is the generation of cross-asset maintenance treatment strategies in the form of a combination of possible asset-specific solutions. This was carried out manually and yielded a high number of solutions for each single project. Figure 8 shows the list of cross-asset maintenance treatment strategies of project B, which consists just of the tunnel B_T and the bridge B_B. The pavement of project B is in good condition. The last strategy B_C6 (T1+B"New") was defined by an extension of the maintenance application area of the bridge, where the BMS does not offer this asset-specific solution

Cross asset treatment strategies

Combination of asset specific treatment strategies or sequences

Treatment Strategy	Treatment	Year	Cost	Disturbance	Savings	Do Minimum?
B_C1	IMPR E+M	2014	890,000	17,900	59,000	
T2			**890,000**	**17,900**	**59,000**	Yes
B_C2	IMPR E+M	2013	890,000	17,400	61,000	
T1			**890,000**	**17,400**	**61,000**	No
B_C3	IMPR E+M	2013	890,000	17,400	61,000	
T1+B1	MAINT SUPSTR	2017	22,000	600	4,000	
			912,000	**18,000**	**65,000**	No
B_C4	IMPR E+M	2014	890,000	17,900	59,000	
T2+B1	MAINT SUPSTR	2017	22,000	600	4,000	
			912,000	**18,500**	**63,000**	No
B_C5	IMPR E+M	2014	890,000	17,900	59,000	
T2+B"New"	MAINT SUPSTR	2014	18,000	0	4,000	
			908,000	**17,900**	**63,000**	No
B_C6	IMPR E+M	2013	890,000	17,400	61,000	
T1+B"New"	MAINT SUPSTR	2013	17,000	0	4,000	
			907,000	**17,400**	**65,000**	No

Figure 8: Example – generation of cross-asset maintenance treatment strategies of project B

Based on this list, the cross-asset maintenance treatment strategies can be compared to each other (in relation to Do-Minimum-strategy) and ranked according to their benefit-cost ratio as shown in Figure 9. The green light on the right shows that all the strategies could be used for the network optimization.

Comparison of cross asset treatment strategies

Comparison based on cost-benefit-ratio calculation (in relation to Do-Minimum-strategy = starting point)

Treatment Strategy	Costs	Benefit	Do Minimum?	ΔCost to Min.	ΔBenefit to Min.	BC-ratio
B_C1	890,000	41,100	Yes	0	0	0.000
B_C2	890,000	43,600		0	2,500	1.000
B_C3	912,000	47,000		22,000	5,900	0.268
B_C4	912,000	44,500		22,000	3,400	0.155
B_C5	908,000	45,100		18,000	4,000	0.222
B_C6	907,000	47,600		17,000	6,500	0.382

Figure 9: Example – comparison of cross-asset treatment strategies of project B

A similar list is shown in Figure 10 for project A, where some of the cross-asset maintenance treatment strategies have to be excluded because of a negative benefit-cost ratio (A_C2 and A_C3) or because of an exceedance of the yearly available budget (A_C13 to A_C16).

Comparison of cross asset treatment strategies

Comparison based on cost-benefit-ratio calculation (in relation to Do-Minimum-strategy = starting point)

Treatment Strategy	Costs	Benefit	Do Minimum?	ΔCost to Min.	ΔBenefit to Min.	BC-ratio
A_C1	57,000	-23,600	Yes	0	0	0.000
A_C2	57,000	-25,500		0	-1,900	0.000
A_C3	57,000	-25,700		0	-2,100	0.000
A_C4	225,000	-19,800		168,000	3,800	0.023
A_C5	844,900	23,000		787,900	46,600	0.059
A_C6	792,900	42,800		735,900	66,400	0.090
A_C7	844,900	22,400		787,900	46,000	0.058
A_C8	1,012,900	26,200		955,900	49,800	0.052
A_C9	850,900	20,800		793,900	44,400	0.056
A_C10	851,000	23,100		794,000	46,700	0.059
A_C11	799,000	42,700		742,000	66,300	0.089
A_C12	962,000	46,500		905,000	70,100	0.077
A_C13	2,151,000	68,200		2,094,000	91,800	0.044
A_C14	2,151,000	68,000		2,094,000	91,600	0.044
A_C15	2,049,000	92,600		1,992,000	116,200	0.058
A_C16	2,212,000	96,400		2,155,000	120,000	0.056
A_C17	792,900	45,000		735,900	68,600	0.093

Figure 10: Example – comparison of cross-asset treatment strategies of project A

In the next step, the remaining cross-asset maintenance treatment strategies have to be brought together and optimized under the given restrictions. The benefit-cost ratio is the decisive factor for the selection of the most adequate solution in this example (see Figure 11). To include the importance of the road, a weighting factor was implemented and used to weight the benefit-cost ratio.

Based on this list, the selection of the most adequate (optimized) solution was done by an iterative process, where the highest benefit-cost ratio should be achieved under the budgetary constraints.

Cross asset optimization over whole network

Comparison based on cost-benefit-ratio and benefit calculation

Treatment Strategy	ΔCost to Min.	ΔBenefit to Min.	Do Minimum?	BC-ratio	Weight	BC-ratio
C_C2	0	3,500		1.000	1.2	1.200
B_C2	0	2,500		1.000	1.1	1.100
B_C6	17,000	6,500		0.382	1.1	0.421
C_C7	316,000	101,250		0.320	1.2	0.384
C_C8	316,000	97,750		0.309	1.2	0.371
B_C3	22,000	5,900		0.268	1.1	0.295
C_C5	274,000	62,250		0.227	1.2	0.273
C_C6	274,000	58,750		0.214	1.2	0.257
B_C5	18,000	4,000		0.222	1.1	0.244
B_C4	22,000	3,400		0.155	1.1	0.170
A_C17	735,900	68,600		0.093	1.0	0.093
A_C6	735,900	66,400		0.090	1.0	0.090
A_C11	742,000	66,300		0.089	1.0	0.089
C_C3	54,000	3,750		0.069	1.2	0.083
A_C12	905,000	70,100		0.077	1.0	0.077
A_C5	787,900	46,600		0.059	1.0	0.059
A_C10	794,000	46,700		0.059	1.0	0.059
A_C7	787,900	46,000		0.058	1.0	0.058
A_C9	793,900	44,400		0.056	1.0	0.056
A_C8	955,900	49,800		0.052	1.0	0.052
A_C4	168,000	3,800		0.023	1.0	0.023
A_C1	0	0	Yes	0.000	1.0	0.000
B_C1	0	0	Yes	0.000	1.1	0.000
C_C1	0	0	Yes	0.000	1.2	0.000

Figure 11: Example – total list of cross-asset treatment strategies of all projects

The first output of the analysis is the solution which fulfils the minimum requirements, as can be seen in Figure 12.

Budget to reach minimum requirements

Treatment Strategy	Treatment	Year	Cost	Disturbance	Savings	Do Minimum?
A_C1	PATCH	2015	6,000	2,500	300	
P1+B4+N1	PATCH	2017	6,000	0	200	
	EXPJOINT	2017	40,000	25,000	3,400	
	MAINT	2015	5,000	0	0	
			57,000	**27,500**	**3,900**	Yes
B_C1	IMPR E+M	2014	890,000	17,900	59,000	
T2			**890,000**	**17,900**	**59,000**	Yes
C_C1	PATCH	2016	13,000	3,200	400	
P1+B2	PATCH	2017	14,000	3,250	500	
	REPLBEARING 1	2014	90,000	19,500	38,000	
			117,000	**25,950**	**38,900**	Yes

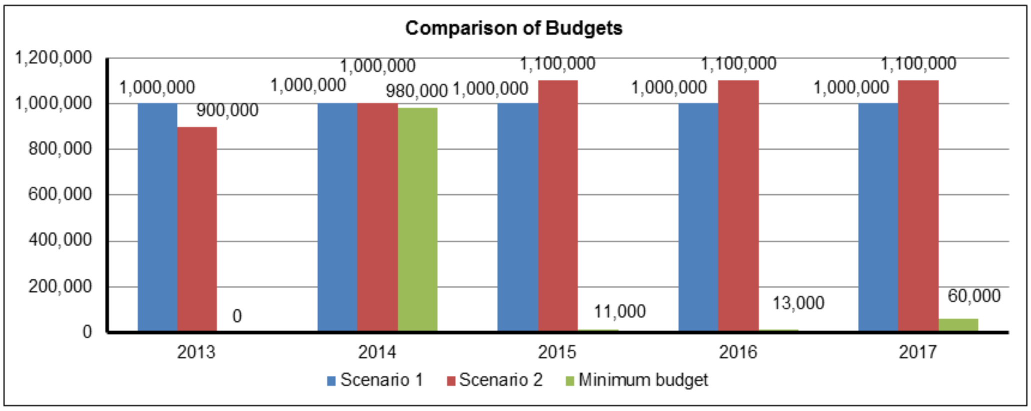

Figure 12: Example – solution which fulfils the minimum requirements

For the application of the asset-specific treatments, a minimum budget of 980 000 units in 2014, 11 000 units in 2015, 13 000 units in 2016 and 60 000 units in 2017 is needed. From an economic point of view, this solution offers the lowest benefit-cost ratio.

Because of the higher available budget, it is necessary to find solutions with a higher efficiency as can be seen in Figure 13 for scenario 1.

Optimal Solution Scenario 1

Treatment Strategy	Treatment	Year	Cost	Disturbance	Savings	Do Minimum?
A_C17	OVL	2014	750,000	0	66,000	
P"New"+B1+N"New"	EXPJOINT	2014	38,000	25,000	4,000	
	MAINT	2014	4,900	0	0	
			792,900	**25,000**	**70,000**	No
B_C6	IMPR E+M	2013	890,000	17,400	61,000	
T1+B"New"	MAINT SUPSTR	2013	17,000	0	4,000	
			907,000	**17,400**	**65,000**	No
C_C7	PATCH	2016	13,000	3,200	400	
P2+B3	SURFDRESS	2017	280,000	48,000	104,000	
	REPLBEARING 1	2013	90,000	19,000	41,000	
	EXPJOINT 2	2017	50,000	0	39,000	
			433,000	**70,200**	**184,400**	No

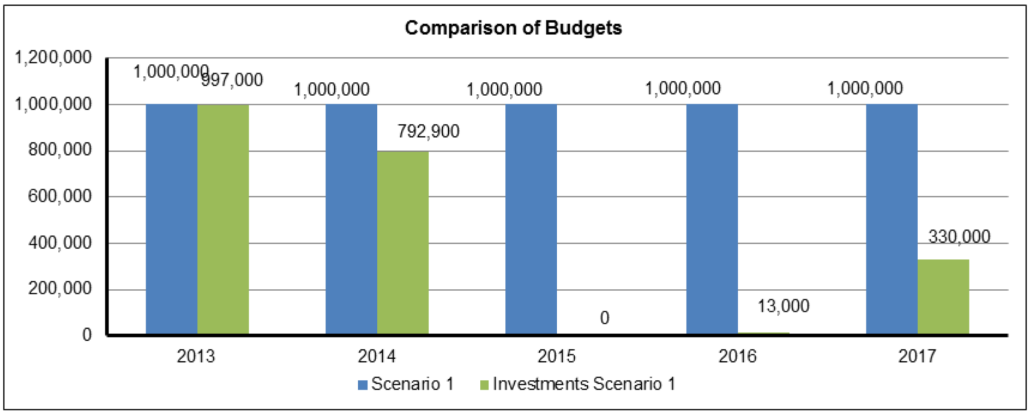

Figure 13: Example – solution scenario 1

Of course, the yearly investments of this scenario are much higher because of the higher intensity of the asset-specific maintenance treatments. The total investments are more than €2.1mil in comparison to the previous solution, which uses €1.064mil (sum of green columns in Figure 12) to fulfil the maintenance needs. The benefit-cost ratio for all selected treatment strategies of scenario 1 is greater than 0 (see Figure 11).

Figure 14 shows the results for scenario 2. Because of the lower budget in the first year, the asset-specific maintenance activities will be postponed mainly to 2014 and 2015 in comparison to scenario 1, where a high number of maintenance treatments will be applied earlierin 2013.

Optimal Solution Scenario 2

Treatment Strategy	Treatment	Year	Cost	Disturbance	Savings	Do Minimum?
A_C6 P2+B2+N1	OVL	2015	750,000	0	64,000	
	EXPJOINT	2015	38,000	25,000	3,800	
	MAINT	2015	4,900	0	0	
			792,900	**25,000**	**67,800**	No
B_C5 T2+B"New"	IMPR E+M	2014	890,000	17,900	59,000	
	MAINT SUPSTR	2014	18,000	0	4,000	
			908,000	**17,900**	**63,000**	No
C_C7 P2+B3	PATCH	2016	13,000	3,200	400	
	SURFDRESS	2017	280,000	48,000	104,000	
	REPLBEARING 1	2013	90,000	19,000	41,000	
	EXPJOINT 2	2017	50,000	0	39,000	
			433,000	**70,200**	**184,400**	No

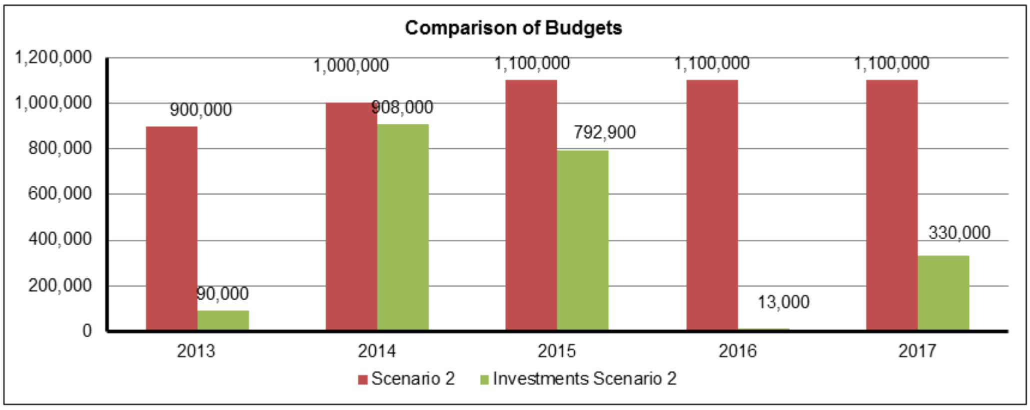

Figure 14: Example – solution scenario 2

3.4 Main-output of TAB Workshop 3

The 3rd PROCROSS TAB workshop entitled “Procedures for Cross Asset Management Optimization” was organized on 4th September 2012 in the context of the 4th European Asset and Pavement Management Conference EPAM 4 in Malmö, Sweden. The aim of this workshop was to elaborate answers to the questions based on the presentation of the developed and recommended cross asset management optimization approach:

- Do you have the same understanding of cross asset management as shown in the recommended approach?
- Is the recommended approach a practicable way for cross asset management of the road infrastructure?
- Does this approach fit into your organizational structure and how would you implement this solution?

The questions were discussed in detail with the participants. It is observed that the proposed cross-asset management format is extremely beneficial, but certain barriers remain for a full-scale implementation of this approach. These are:

- Although the theoretical basis of cross-asset management is robust and accommodates complexities at a large scale, it may not be practicable to consider and assess all options available. Consequently, the practical implementation requires some amount of engineering judgement.

- The time horizon and the size of the network needs to be realistic in terms of the optimized solution to be of relevance. There may be options available that may be specific to the network under consideration which are not automatically identified by independent maintenance management software of sub-assets. The training and expertise of the consulting engineer is important to a certain extent in this regard in order to obtain the maximum benefit from this approach.
- The confidence of the user is key to the understanding and implementation of the method. It is important for the end-users to be able to use decisions from a cross-asset management framework for this approach to be successful. Training sessions and workshops may be of great benefit in this regard.
- An agreement regarding the objectives of the network and high-quality data about the condition of the sub-assets of the network remain key to good cross-asset management. In this regard, clear ideas from the stakeholders regarding their expectations, even at a qualitative level, is necessary. Similarly, the importance of maintaining independent maintenance management systems for sub-assets and sharing of data between different authorities is also encouraged.
- A cross-asset management approach provides a systematic method to arrive at the best possible solution in the light of existing information. However, the method is reflective of the available information and related bias. Consequently, for large bias (technical or socio-political), the approach will not necessarily lead to an appropriate intervention strategy and would simply reflect the effects of the bias.
- The time frame for the practical application of such procedures is a key task for the implementation. The procedures should not be used for long-term planning processes. They are applicable for the definition of short-term projects and schemes which combine the maintenance-needs of different assets.

Even after considering barriers such as those mentioned above, it can said that the cross-asset management format proposed here is perhaps the closest methodology which can accommodate the wide variety of maintenance management systems that exist under different roads authorities and also allow for the fundamentally different top-down and bottom-up approaches to be assimilated.

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