Title	Cross-asset management for road infrastructure networks
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Publication date	2015-10
Publication information	Proceedings of the Institution of Civil Engineers - Transport, 168 (5): 442-456
Publisher	ICE Publishing
Item record/more information	http://hdl.handle.net/10197/10409
Publisher's statement	All rights reserved.
Publisher's version (DOI)	10.1680/tran.13.00087

Cross-Asset Management for Road Infrastructure Networks

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Abstract: Limitation of resources and variations of interest or priority of different stakeholders of road infrastructure networks often lead to multiple considerations of intervention options. It is of interest to identify the best available intervention or investment option under a multi-criteria framework. Markers of performance may be varied and the approach towards maintenance management may have different philosophies based on specific organisational structures of governance. This paper presents a methodology for cross-asset management that caters to different maintenance management systems without modification. Optimisation approaches and effective implementation methods are identified. Practical implementation guidelines of the developed framework are illustrated.

Keywords: Infrastructure management, Infrastructure network, Cross-Asset, Stakeholder, European Union, Implementation

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Notation:

a	*Asset*
BCR	*Benefit-cost ratio*
BE	*Benefit*
Bud	*Budget*
C	*Asset specific maintenance treatments*
CC	*Construction costs*
CM	*Cross-asset maintenance treatment strategies*
ExC	*External costs*
M	*Maintenance treatment strategy*
p	*Maintenance project*
PC	*Potential of coordination*
t	*Time frame, year*
T	*Target function*
TP	*Technical parameter*
X, Y	*Decision variables*

1. Introduction

A significant number of infrastructure networks maintain their assets (Znidaric et al., 2011) or sub-assets through objectives or goals that are often independent of one another at a component or a project level, when in reality significant interdependencies exist. Consequently, resources allocated for the maintenance of these networks are not utilised in an optimal manner. This inefficient use of resources can result in insufficiency to carry out necessary interventions on time. Moreover, inadequate acknowledgement of the multiple criteria guiding a project (O'Connor et al., 2012), or failure to acknowledge the requirement of multiple stakeholders may result in inadequacy related to safety and serviceability (Estes and Frangopol, 2001). Much research has been carried out to determine a life-cycle safety analysis of infrastructure assets, in order to determine likely periods of intervention. These methods include using advanced probabilistic methods (Frangopol & Bocchini, 2012; Frangopol, 2011), to using various methods of linear, non-linear, and dynamic programming (Ng et al., 2011; Medury & Madanat, 2013). Significant research has also been conducted in an effort to formalise the Markov decision process to evaluate the areas of risk to the network (Kobayashi et al., 2012; Seyedshohadaie et al., 2010). When areas of concern to the network are identified, the intervention decision can largely be subject to the criteria of conflicting stakeholders. In the example of road pavement maintenance, cost-savings were observed when moderate maintenance was conducted at higher frequencies (Gu et al., 2012), but a network based approach to resource allocation was seen to be favoured over a higher level of technical improvements by local asset managers (Sathaye & Madanat, 2012). Thus, it can be seen that an apparently successful intervention on a section of the infrastructure network in a given year can contradict a network strategy devised using a cross-asset approach, the final results of which may not address the objectives of a potential investment framework, leading to inefficiencies.

Independent of approaches of infrastructure owners, it is important to develop a generic methodology which caters to the varied requirements of multiple stakeholders (Orcesi and Frangopol, 2011) and also acknowledges the condition of each asset and sub-asset. Cross-asset management combines engineering principles with sound business practice and economic realities. The generic methodology is a best practice guideline through which a defined infrastructure network is maintained and operated in a safe and efficient fashion, with an emphasis on minimisation of tangible and intangible costs (Pakrashi et al. 2011). Cross-asset management needs to combine the different maintenance needs of the single assets and the general, strategic requirements at a network level (O'Connor et al., 2012). Impact of asset inventory, condition rating of assets and sub-assets, and the integration of such information in decision making is possible (Reale and O'Connor, 2012). The various hierarchical stages of risk ratings and rankings, ranging from expert ratings or from visual data (Akgul and Frangopol, 2004) to testing (Pakrashi et al., 2012), deterministic assessment and semi-probabilistic and probabilistic assessment (O'Brien et al., 2003) have already been investigated. It is important to synthesise such information in cross-asset management, as well as using contemporary methods to plan and minimise the effect intervention options have on the road user (Hajdin & Lindenmann, 2007).

This paper first investigates the formats in which information is collected for infrastructure networks within the European Union (EU) to recognise cross-asset interdependencies and impact of selected measures and activities related to operational experiences. Influencing factors and stakeholders' requirements have also been identified. A generic, procedural framework for cross-asset management for total road infrastructure networks is detailed, with guidelines for practical implementation of the proposed framework presented through an example of a road infrastructure network. Certain human effects, like political effects and corruption are not considered as a part of this framework.

2. Understanding of Cross-Asset Management

2.1 Involvement of Stakeholders

Detailed interviews and discussions were carried out with the stakeholders of infrastructure in a number of countries within EU (Austria, Belgium, Denmark, Finland, Germany, Ireland, Netherlands, Norway, Slovenia, Sweden, Switzerland and United Kingdom) to identify existing practices of asset management processes and understanding cross-asset interdependencies and costs or values to evaluate the impact of maintenance activities on different sub-assets. Organisational structure, methodology of road infrastructure management, source of money, intervention methodology, coordination of maintenance works, performance indicators, implementation procedures, awareness of cross-asset management and the requirement for a generic framework were discussed.

2.2 Key Definitions

Terminologies related to cross-asset management used in this paper (italicised) are based on existing literature (COST354, 2008; PIARC, 2011) and interactions with stakeholders. The *Total Road Infrastructure Asset* is a comprehensive term combining all single *assets* of the road infrastructure, which are necessary to operate a road under given requirements and pre-conditions (safety, comfort, environment etc.). *Assets* are elements and/or components of the *Total Road Infrastructure Asset*. A group of single *assets* from a more general point of view (bridges, tunnels, culverts, etc.) are termed *Engineering Structures*. Road signs, guard rails, lighting are grouped as *Road Furniture*. *Stakeholders* are defined as a specific or general group of people who are directly or indirectly affected by the planning, construction, operation and maintenance of the *Total Road Infrastructure Asset*. The *Stakeholders* can be categorized into *Users*, *Owners*, *Operators*, *Neighbours*, *Financing body* and *Society*. *Asset Management* is a comprehensive term to describe all management activities on one or more *Assets* of the *Total Road Infrastructure Asset*. *Cross-asset Management* is the combination of management tasks and activities over different *Assets* of the *Total Road Infrastructure Asset* within a pre-defined management process. These tasks and activities can have technical, economic, strategic and environmental objectives. *Performance Indicator* is a comprehensive term indicating the condition (often non-dimensional) of the *Total Road Infrastructure Asset*. A *Combined Performance Indicator* is a dimensional or dimensionless number related to two or more different characteristics of *an Asset*, *Sub-asset* or *the Total Road Infrastructure Asset.* A *General/Global Performance Indicator* is a mathematical combination of *Single and/or Combined Indicators* which describes *a Single Asset* or *the total Road Infrastructure Asset* condition.

2.3 Requirements of Stakeholders

Cross-asset optimisation attracts *owners* where the impacts are assessed in terms of direct investment. The *users*' requirement may encompass intangible costs (pollution, comfort). The *neighbours* are usually concerned with safety and environment aspects. The *societal* expectation is often based on the perceived level of safety or service. The *financing body*'s expectation is generally based on a long term cost minimised solution with the cost prioritisation aligned with available cash flow.

2.4 Value, Cost, Environmental Impact and Benefits

The *value* of an *asset* network is comprised of a number of tangible and intangible factors and their combination without an agreed definition. The perceived level of safety and service, the real cost of the network, the life-cycle-cost, the environmental cost, the impact on the *society* and the economy are the major influencing factors. The use of life-cycle costs and the cost to the road user and society (indirect costs) have gained significant acceptance nowadays. The environmental impact is mostly guided through legislation and implemented through contractual conditions. The overall *benefit* is rarely expressed as a unique value of investment required or saved. *Benefit*, in terms of financial savings can be translated contextually and related to the expectations of *stakeholders*. It is strongly dependant on the type and number of maintenance activities, the number of affected *assets*, the coordination of maintenance activities and the relationship between different *assets* and objectives to be achieved. For instance, the replacement of the surface layer of a pavement has a different benefit (improvement of the road safety) in comparison to the replacement of an old, inefficient noise barrier, which improves the environmental situation alone. Usually, the effects of maintenance treatments are defined in the form of relative values in comparison to the “do-nothing” or “routine maintenance only” solutions. The sum of all maintenance effects define the overall *benefit* of a maintenance strategy and enable to assess pre-defined targets stipulated in form of service level agreements.

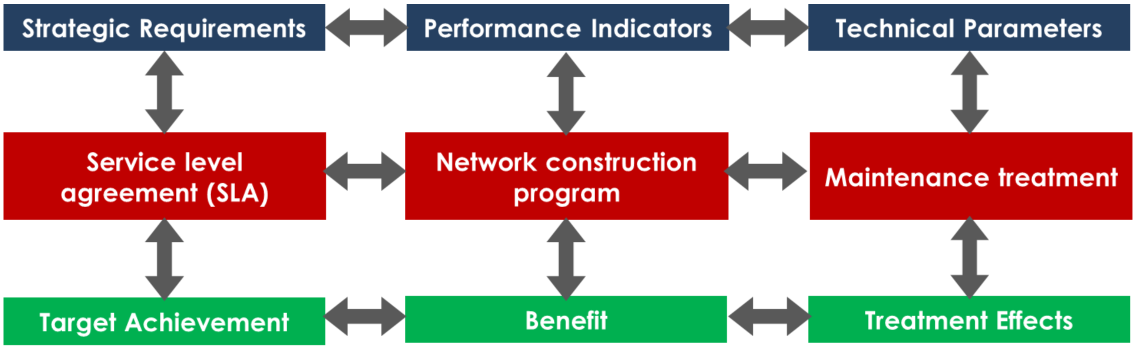


Figure 1 Fundamental framework of modern asset management

2.5 Organisational Structure

Based on the collected information from European road authorities, a general grouping was carried out according to the responsibilities in asset or objective related management structure. The *asset* related management structure is characterised by different administration units which cover the management responsibilities for a single *asset* or a group of *assets*. An objective related structure is characterised by units which fulfil a single management task or function, like planning, financing, operation or maintenance. In many organisations, a mixture of both can be found. A second grouping of *asset* management is based on the geographical or topographical consideration. This is strongly dependent on the size of the road network and on the number of activities within the management processes. For example, if the operational activities are outsourced, it is not necessary to have a high number of employees at regional branches. Also, organisations may be centralised or decentralised. In case of a mix of the two, strategic decisions are usually taken at centralised headquarters. The type and extent of cross-asset management is dependent on the organisational structure of each authority, funding allocation and *stakeholder* expectations. The governing factors with maximum impact within cross-*asset* management from the organisational point of view were noted as minimising cost of maintenance operation, optimal use of taxpayers' money and other funds, optimal maintenance investments, avoidance of unnecessary repetition of maintenance activities, reducing negative effects on neighbours, avoiding multiple road interventions, increase availability and reducing user costs.

3. Development of a Framework of Cross-Asset Management

3.1 Cross-Asset Management Approaches

Based on the discussions with *Stakeholders*, a *Bottom-up* approach, a *Top-down* approach and most commonly, a combination of the two have been identified. The difference is in the way the optimum solution is identified and the way strategic targets are translated to technical parameters (object level). The *Bottom-up* approach is influenced by the technical assessment of individual groups of object level *assets* through pre-defined technical requirements or thresholds and target-values set by *Stakeholders*. A *Bottom-up* process can be well established and strongly supported by sophisticated management tools. The results of the individual asset assessments are the basis for the definition of maintenance projects across different types of road assets, where technical and economic *Performance Indicators* (*PI*) describe the effects of the measures. Optimal maintenance solutions of the single groups of assets often change during coordination and may not correspond to the network optimised solution. The advantage of the *Bottom-up* approach lies in a comprehensible technical assessment of single assets, while the disadvantage is in the lack of foresighted adjustment with global optimisation from the beginning.

A *Top-down* resource allocation is based on a central decision at a network level and requires a comprehensive understanding of the overall state of the network. This allocation aims at maintaining or improving an overall standard of infrastructure that corresponds to a desired or feasible target. The implementation is highly dependent on how the road agencies themselves function. Each group of *assets* may be managed by different departments competing for resources. Some countries manage infrastructure on a regional basis, where *assets* within the same area are treated collectively, whereas others have a central administration, which facilitates fund allocation with respect to achieving a uniform objective or strategy across a country. Irrespective of structure, the essence of a centralised fund designation is that decisions are made ideally to a strategic target at network-level with an optimal maintenance focus on the life cycle, rather than dealing with individual *assets* (Mild and Salo, 2009). These are in agreement with factors contributing to the *global performance indicator* defined in COST354 (Litzka et al., 2008). The maintenance strategy arising from a central resource allocation is the result of subjectively defined guidelines or minimum requirements. These targets are subject to certain boundary conditions (e.g. restricted funding) and are usually a multivariate function where each variable has an arbitrarily assigned weighting factor that depends on whether the problem is approached from the point of view of the road operator or other *stakeholders*.

Where a combination of *Bottom-up* and *Top-down* is applied, the strategic targets and requirements are defined by the ministry or the head of the organisation and are compared with the results from the technical assessment of single *assets* at object level. This level defines the maintenance activities in so-called *projects*, *scheme* or *planning*, which are essentially an aggregation of the technical maintenance needs of different *assets*. In most cases, this is where strategic preconditions are recognised. However, these projects or schemes can also cause conflicts between the strategic department and technical branches.

Authorities organised strongly in terms of its *assets* tend to administer more *Bottom-up* approach. A strong strategy oriented approach shows a risk that *asset* specific requirements on technical or object level will be omitted or not taken into consideration to the necessary extent although providing clear and comprehensible preconditions for the technical level. To address this, a clear understanding of the relationships between the different strategic targets is required. The number of strategic objectives and targets are crucial for this. If this number is low, the processes within the approaches are much simpler and offer usually a clear understanding of *asset* management. Many authorities use a high number of different performance indicators dependent on technical parameters and indices at a technical level, which are needed for the selection of adequate maintenance treatments, but not to be used for the assessment of strategic targets and requirements and thus not defined in service level agreements. *Bottom-up* oriented approaches tend to consider a higher number of technical parameters. The compatibility of the elements of the *asset* management framework is crucial, which are more *Top-down* oriented and hold a high number of strategic targets.

The combination of *Bottom-up* and *Top-down* fulfils most of the requirements for the practical application of cross-asset management optimisation. The right balance has to be found for specific *asset* management framework. The optimisation procedures are quite different and strongly dependent on the decision. Thus, a summation or aggregation of the needs from the strategic level and the object level is essential. Figure 2 presents the generic schematic of cross-asset management.

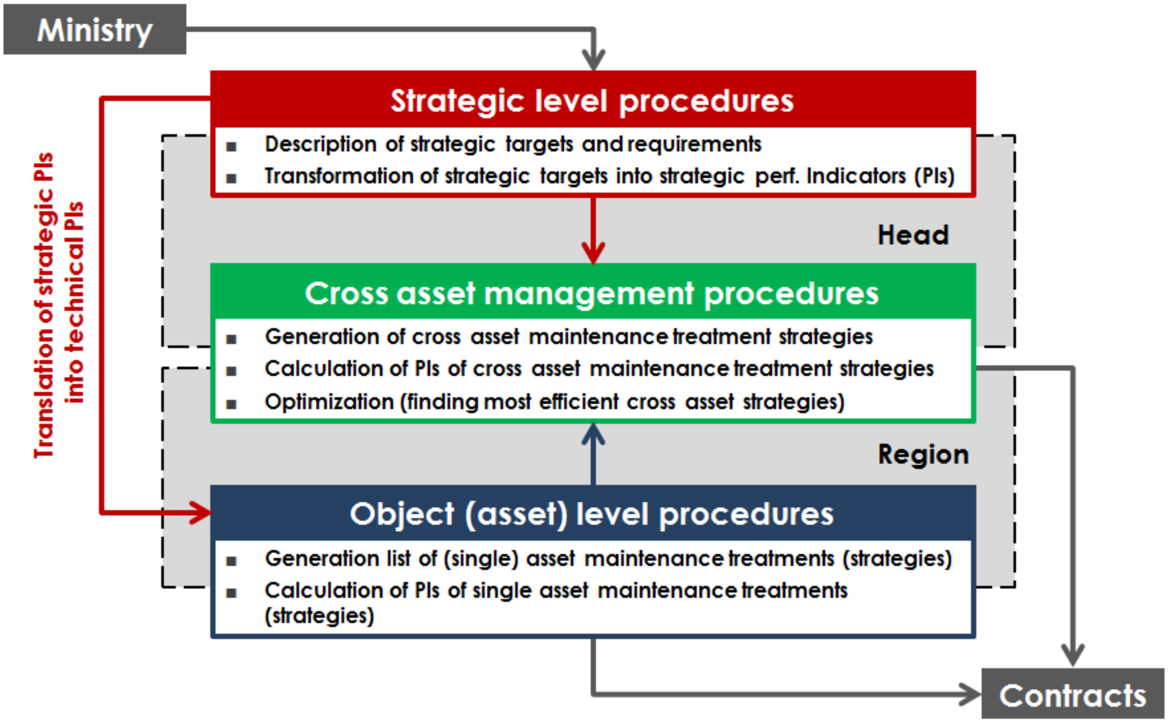
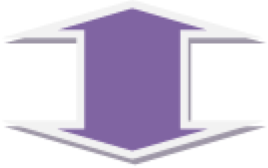


Figure 2 A generic schematic of cross-asset management

3.2 Strategic and Technical Performance Indicators

In order to avoid a situation where strategic objectives are inferred from technical parameters which are not easily understood by all *stakeholders* or simplified performance indicators, a clear translation from strategic targets to performance and measurement is required. Table 1 demonstrates the relations between strategic targets, performance indicators and technical parameters.

Table 1 Connection of strategic requirements, performance indicators and technical parameters

Strategic requirements	**Performance Indicators**	**Technical Parameters**
Safety	Accident rate Fatalities	Rutting Skid resistance Texture
Costs	Costs	Costs Structural condition
Availability	Vehicle lost hours	
Customer satisfaction	Customer satisfaction	Evenness, Texture
Environment	CO2, Particle emissions, Noise	Rolling resistance, Rolling noise emissions, Texture
Target achievement	**Benefit**	**Effect**
		
Service Level Agreement (SLA)	**Network Construction Programme**	**Maintenance Measures**

Indicators for the effects of treatments on single *assets* or of effects caused by coordinated maintenance planning are chosen as *costs*, *benefit* (defined as the effect of maintenance on achieving the strategic targets) and a combination of the two *costs* (e.g. cost-benefit ratio). Indicators for the description of requirements on the strategic and the object level are *budgetary restrictions*, *strategic restrictions*, *technical restrictions*, *minimum requirements* and *others*. For the application of cross-asset management procedures the indicators need to be specified. These are *external costs* (*ExC*), *benefit* (*BE*), *construction costs* (*CC*) and *minimum technical requirements* of an *asset* (*a*), expressed by a *technical parameter* (*TP*), $minTP_a$. A number of indicators for the effects of a maintenance treatment strategy (*M*) of an *asset* for a given time frame (*t*) is defined as the present value *construction costs* of *maintenance treatment strategy* (*M*), $CC_{M,a}$, and the *present value external costs* defined as the sum of costs due to the condition of the *asset* and to the *maintenance treatment strategy*, $ExC_{M,a}$. Additionally, a decision variable

X is defined to guarantee the compliance of the minimum technical requirements of a *maintenance treatment strategy* as

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

$$X(M_a) = 0 \quad \text{for } TP_a < \mathrm{minTP_a} \qquad (2)$$

In the context of *Life Cycle Cost Analysis* (*LCCA*), the planned maintenance treatments for a specific road *asset* need to be assessed according to their positive and negative effects over a certain time or assessment period respectively (Kong, J.S. et al., 2003). To enable an assessment of treatment sequences it is necessary to extend this period as long as possible, taking into consideration the statistical spread of the predicted values. In many authorities the engineering structures show the longest assessment period (e.g. 70 years), followed by pavements (e.g. 30 years) and road furniture (e.g. 10 years). The prediction of the performance (condition) is a decisive factor for finding the best year or interval for a maintenance treatment. 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 *LCCA*, it can happen that the effect of a maintenance treatment is short-term and the performance prediction after the treatment reaches again a condition level, where a second maintenance treatment can be applied. **Error! Reference source not found.** shows the deterioration of a single road *asset* and the different options to improve the condition by applying maintenance treatments. The first timeframe for treatments starts when the performance curve enters the application area of the treatments (trigger) and ends theoretically when the *do-nothing* curve exceeds the worst possible condition. In practice, the treatment strategy *i* is the solution, which fulfils the minimum requirements. A second timeframe for treatments

(Figure 3) starts by entering the performance curve into the application area of treatment strategy. The number of time frames for treatments depends on the starting point of the performance curves, on the deterioration rate, on the effects of the single maintenance treatments and finally on the length of the assessment period, which are different for different type of *assets*. Each single maintenance option is defined as an object or element specific treatment sequence described by different values or indicators.

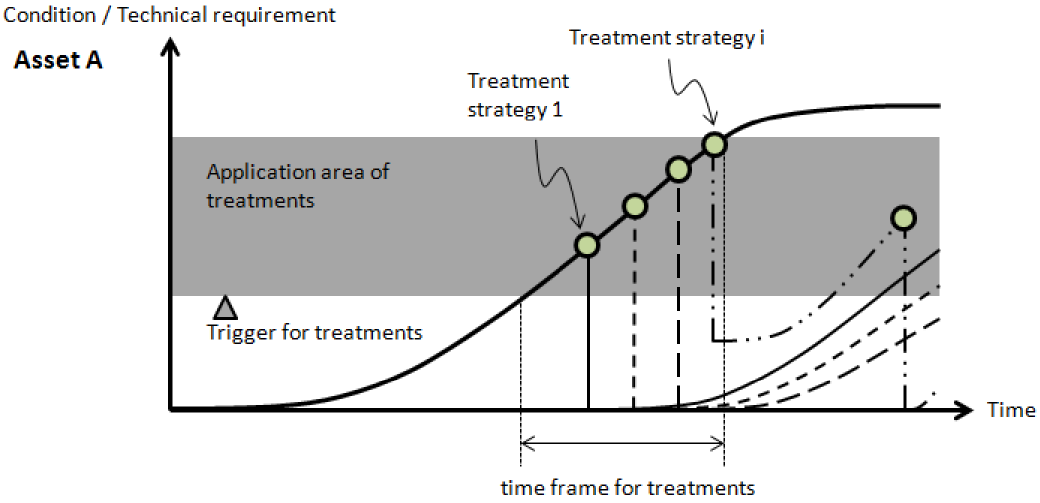


Figure 3 Deterioration and maintenance treatment strategy of asset A

The coordination of asset-specific maintenance treatments can be related to a larger maintenance project or scheme by including a number of *assets* limited by a specific area and a certain time frame within its life cycle. 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 optimisation. In many countries, the period for projects or schemes is between 1 and 6 years, which is different to the much longer assessment or analysis period generally considered. Consequently, to reduce the negative effects of maintenance treatments, it is preferable to combine activities into larger projects. The spatial distribution of maintenance needs on different *assets* is a decisive factor and can be based on engineering insight or expertise. Figure 4 shows that a possible *Cross-asset Maintenance Treatment Strategy* (e.g. Strategy 2) is only a sequence of individual single treatments of *asset* A and B do not necessarily offer a combined treatment potential. Cross-asset Maintenance Treatment Strategies 1 is a real combination of maintenance activities on *asset* A and B. It is necessary to keep the uncombined solutions in the procedure and it may sometimes be helpful to extend the time frame for finding more combination possibilities.

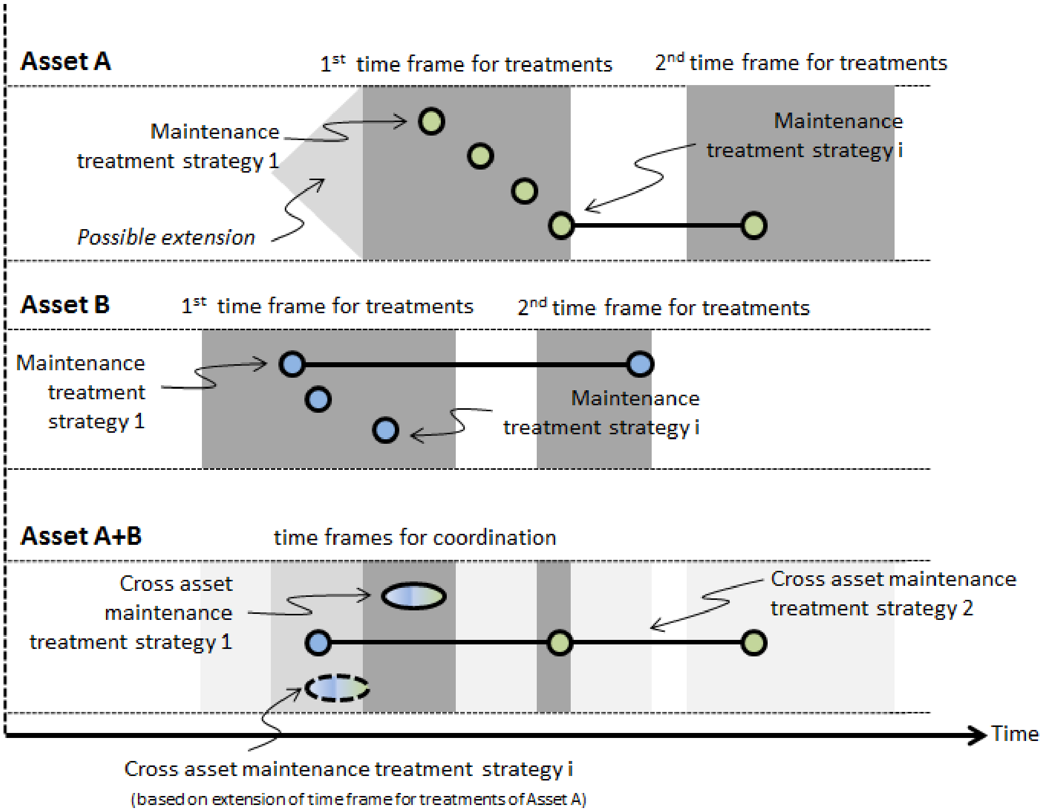


Figure 4 Combination of asset-specific treatment strategies to cross-asset maintenance treatment strategies

Groups of *Cross-asset Maintenance Treatment Strategies* can be based on a real combination of single *asset specific maintenance treatments* (*C*) (e.g. Cross Strategy 1), on a sequence of single uncombined maintenance treatments of single *assets* (e.g. Strategy 2), on an extension of the application area to combine *asset* specific maintenance treatments (e.g. Strategy i) or a combination thereof. It is necessary to distinguish between these groups because the calculation of *PI* can be different. Cross-asset maintenance treatment strategies, CM_p, of a *project* (p) not fulfilling the minimum technical requirements $X(M_a) = 0$ have to be excluded from the combination process.

Present value construction costs, CC, of CM_p of a maintenance *project* in a given year for combined maintenance treatments, taking different *assets a* ($CC_{CM,p,t}$) into account is

$$CC_{CM,p,t} = \bigcup_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1 \tag{3}$$

and for maintenance treatment sequences (uncombined)

$$CC_{CM,p,t} = \sum_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1 \tag{4}$$

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

$$CC_{CM,p} = \sum_{t} \bigcup_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1 \tag{5}$$

and for maintenance treatment sequences (uncombined) is

$$CC_{CM,p} = \sum_{t} \sum_{A} CC_{M,a,p,t} \quad \text{for all } X(M_a) = 1 \tag{6}$$

Present value external costs of 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 is

$$ExC_{CM,p} = \bigcup_{A} ExC_{M,a,p} \quad \text{for all } X(M_a) = 1 \tag{7}$$

and for maintenance treatment sequences (uncombined) is

$$ExC_{CM,p} = \sum_{A} ExC_{M,a,p} \quad \text{for all } X(M_a) = 1 \tag{8}$$

These external costs enable a back-translation of technical effects of maintenance treatments into monetary terms and an easy summation or aggregation over all *assets* for the definition of benefit. Theoretically, the external costs can be replaced by non-monetary indicators, where *asset*-specific effects have to be weighted according to the extent of target achievement before summation or aggregation. This could be quite complex and requires a clear understanding of the specific importance or meaning of different objectives and targets. The union operator, ⋃, is used when considering costs not absorbed by construction costs for combined maintenance activities, and the summation operator, ∑, is used when considering uncombined maintenance activities, in order to model the cumulative costs of not coordinating maintenance.

An additional indicator is the potential cost-savings through coordinated maintenance activities. Although the external costs indicate the effect indirectly, the calculated values do not always show the complete effect. In particular, the effect of coordinated maintenance treatments with low savings on external costs needs to be valued higher by referring through coordination. The *potential of coordination* (*PC*) of a coordinated cross-*asset maintenance treatment strategy* of a maintenance *project,* over the whole assessment period, taking into account different *assets,* can be defined over the number of coordinated *asset* specific maintenance treatments as

$$PC_{CM,p} = \sum_{C} CM_{a,p} \tag{9}$$

Theoretically, the cross-*asset* maintenance treatment *benefit* is the sum or aggregation of all effects caused by single, *asset*-specific maintenance activities defined within the cross-*asset* maintenance treatment strategies and usually calculated as a relative value as compared to the *do-nothing* solution or the maintenance activities to be carried out to fulfil the minimum requirements. External costs are an applicable solution for the summation or aggregation. The *benefit* (*BE*) of this approach, in relation to the maintenance treatment strategy, which fulfils the minimum technical requirements, can be defined by using the external costs as

$$BE_{CM,p} = ExC_{\min CM,p} - ExC_{CM,p} \tag{10}$$

To include only those solutions in the optimisation process which offer a good economic solution, it is necessary to asses each coordinated cross-*asset* maintenance treatment strategy according to its efficiency, typically considered using benefit-cost ratio. The *benefit-cost ratio* (*BCR*) of *CM* of a maintenance project in relation to the maintenance treatment strategy, which fulfils the minimum technical requirements, can be defined by using *construction costs* and *benefit* as

$$BCR_{CM,p} = \frac{BE_{CM,p} - BE_{\min CM,p}}{CC_{CM,p} - CC_{\min CM,p}} \tag{11}$$

Strategies with a negative difference to the benefit and/or costs *BCR*, should be set to zero. An optimal solution identifies the combination of *CM* over the whole network best contributing to fulfilling the strategic targets. Theoretically, a multi-criteria optimisation should exist but it can be mathematically or computationally difficult to be included in practice. Commercial *asset* management tools usually do not offer such mathematical suites and a practical solution should be simplified as much as possible without compromising with the cross-*asset* management philosophy. The optimisation objective can be theoretically described by a target function (*T*) as the total benefit BE_{total} of all projects *p* as

$$T = BE_{total} = \sum_{p} \sum_{CM} ExC_{CM,p} \cdot PC_{CM,p} \cdot Y_{CM,p} \Rightarrow \max! \tag{12}$$

The compliance that two or more maintenance treatment strategies of a project *p* will not be selected at the same time, is achieved by using the decision variable *Y* as

$$\sum_{CM} Y_{CM,p} \leq 1 \quad \text{for} \quad p = 1, \ldots, n \tag{13}$$

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 is represented by

$$\sum_{p} CC_{CM,p,t} \cdot Y_{CM,p} \leq Bud_t \quad \text{for} \quad t = 1, \ldots, n \tag{14}$$

The compliance with the fact that the yearly available budget is greater than the minimum budget to fulfil the minimum technical requirements is presented as

$$Bud_t \geq \min Bud_t \quad \text{for} \quad t = 1, \ldots, n \tag{15}$$

Compliance towards the fact that the efficiency of the maintenance treatment strategy is higher than the minimum efficiency is expressed as

$$BCR_{CM,p} \geq \min BCR_{CM,p} \quad \text{for} \quad p = 1, \ldots, n \quad \text{for} \quad CM = 1, \ldots, n \tag{16}$$

4. Practical Implementation of Cross-Asset Management

An infrastructure network (Figure 5) is considered to illustrate cross-*asset* management for road networks in practice, based on the needs of and feedback from large infrastructure managers. The *Total Road Infrastructure Asset* consists of a limited number of roads (Roads A to G), subdivided into 3 projects/schemes (A, B and C) and including different *assets*, from *Engineering Structures* (pavement P, bridge B, tunnel T), to *Road Furniture* (noise barrier N).

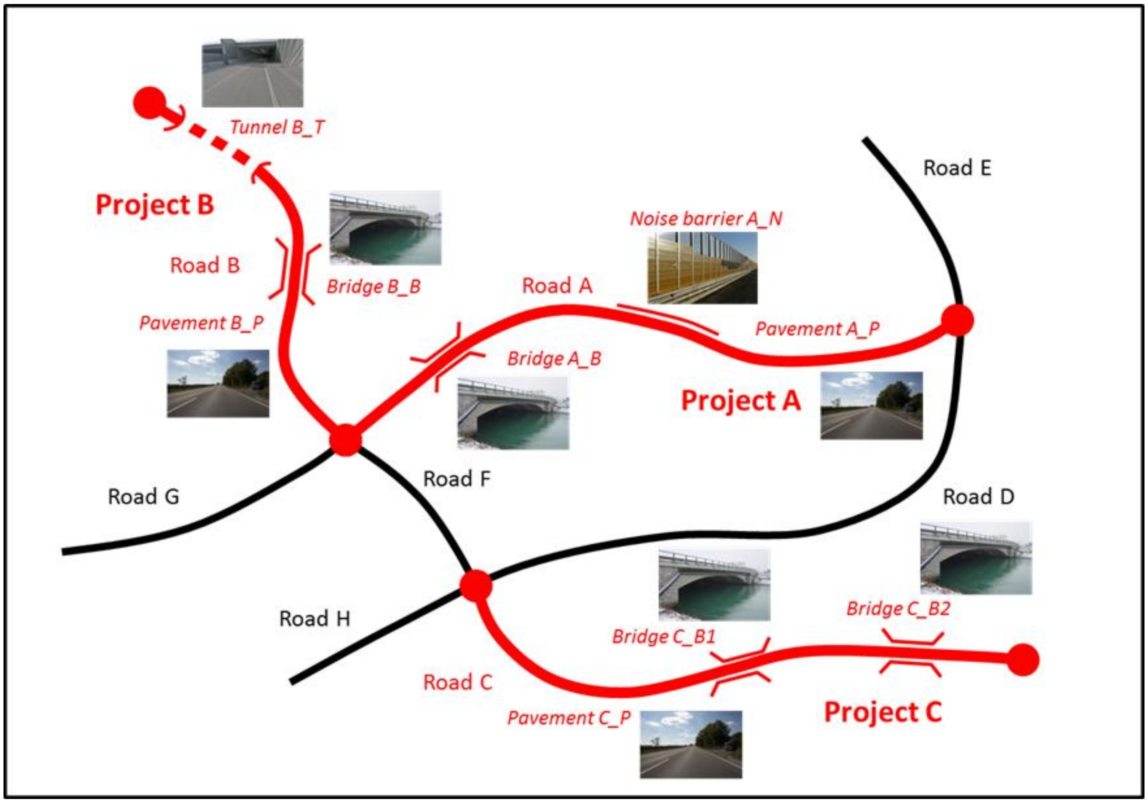


Figure 5 Example network comprising of projects and assets

A cross-*asset* optimisation should find a solution of maintenance activities maximizing the *benefit* under given technical and strategic requirements. These include, compliance with minimum technical requirements, maintenance activities causing lowest possible *user* disturbance, application of efficient and sustainable maintenance treatment strategies and maintenance activities within budgetary constraints. All associated costs have been determined using local models drawn from existing infrastructure networks and experienced by asset managers, and are analogous to the methods described in the introduction to this paper. Variations and uncertainties in costs associated with human and political influences must be accounted for on a regional basis, and are thus omitted from this paper on this basis. The cross-optimisation period is between the years 2013 to 2017. In 2016, on parallel Road D, extension will change the 2 lanes to 4 lanes. Two different yearly budgetary constraints can be taken from Figure 6.

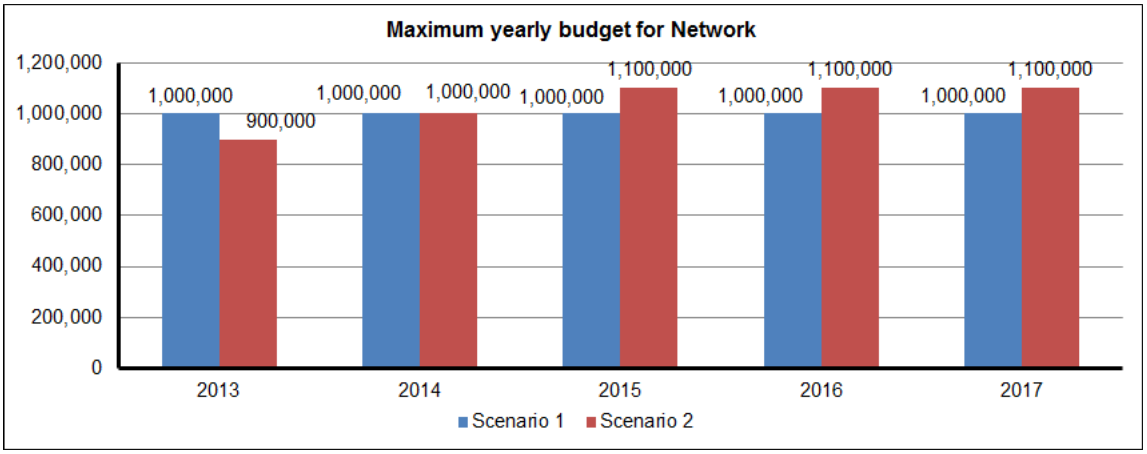
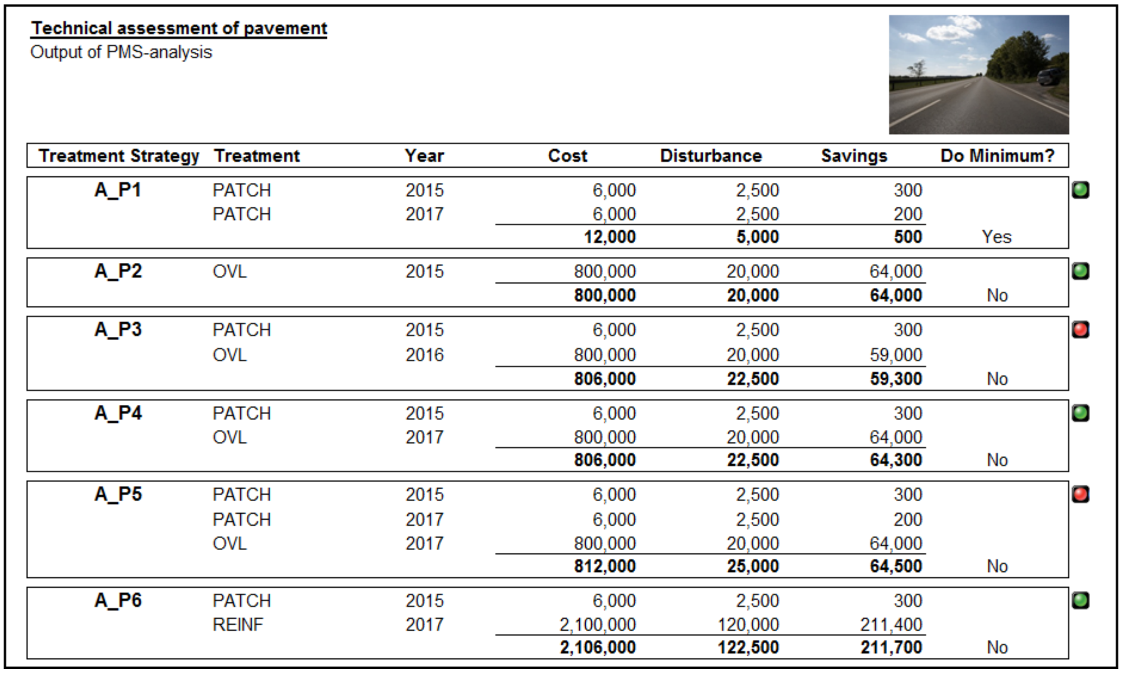


Figure 6 Example of yearly budgetary constraints

The maintenance needs of each *asset* for the 3 different projects are defined based either on a sophisticated management system or on engineering judgement. Regardless of the method (e.g. LCCA) and the assessment period for the different *assets*, usually much longer than the cross-asset management period, a list of possible *asset*-specific maintenance treatments is the output. Figure 7 shows outputs of the asset-specific analysis for the pavements of project A.



Technical assessment of pavement

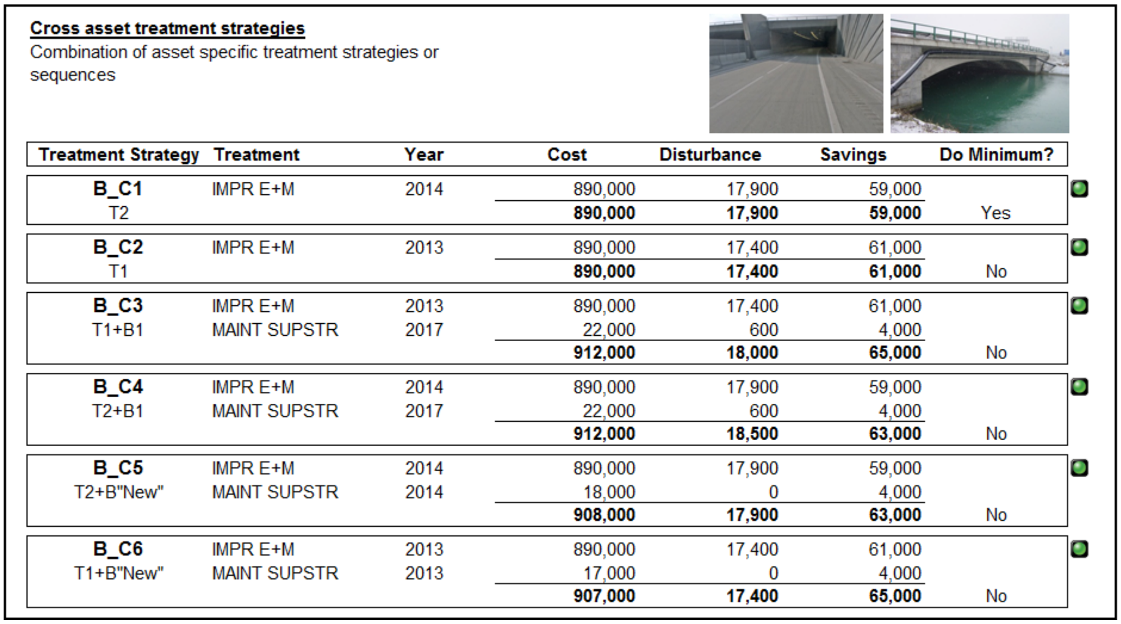
Output of PMS-analysis

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 7 A typical output of asset-specific analysis for the pavements of project A

If an *asset*-specific maintenance treatment strategy does not fulfil the minimum technical requirements or is in conflict with other preconditions (e.g. 2016 on parallel road D extension works), the solution will not be considered (e.g. A_P3, A_P5, red light on the right). The strategy, which fulfils 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 (e.g. tunnel)

A combination of possible *asset*-specific solutions was carried out and this yielded a high number of solutions for each single project. Figure 8 shows the cross-*asset* maintenance treatment strategies of project B, which consists 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.



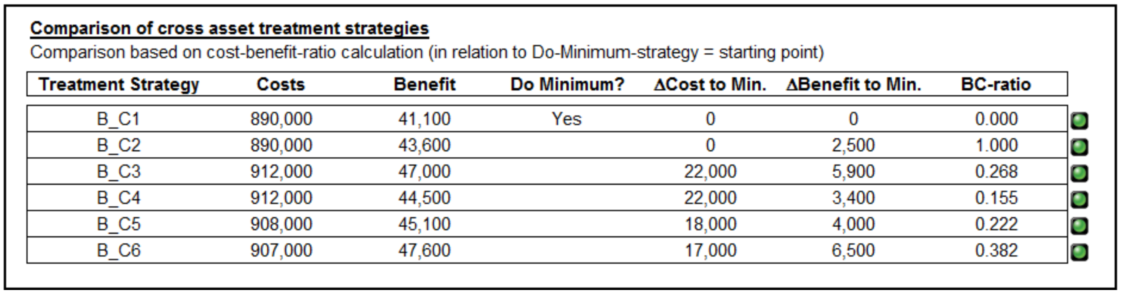
Cross asset treatment strategies

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 of the 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 (and to *Do-Minimum* strategy) and ranked according to their *benefit-cos*t ratio as shown in Figure 9, with the green light on the right indicating that all these strategies are feasible.



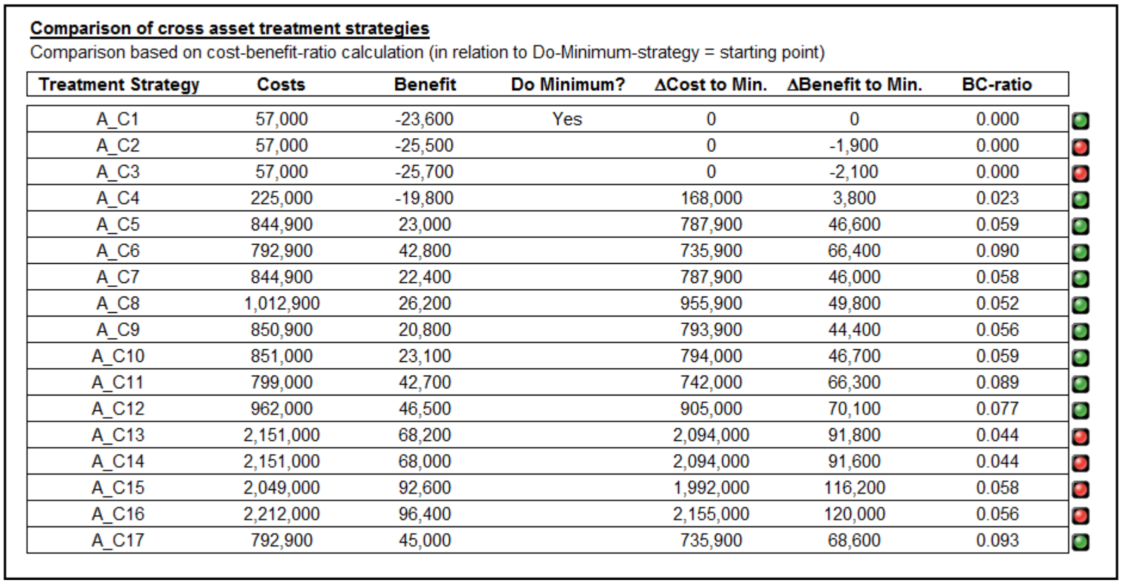
Comparison of cross asset treatment strategies

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 of 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 (red light) because of a negative benefit-cost ratio (A_C2 and A_C3) or because of an exceeding of the yearly available budget (A_C13 to A_C16).



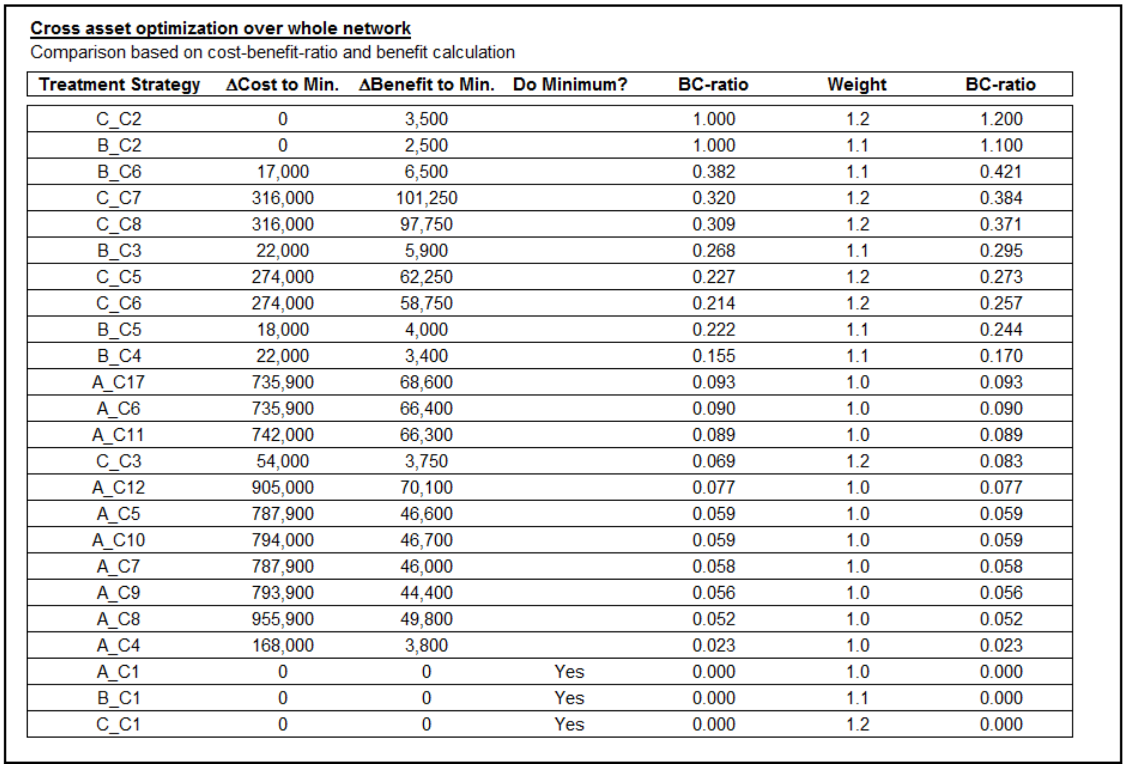
Comparison of cross asset treatment strategies

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 of comparison of cross-asset treatment strategies of project A

The remaining strategies have to be brought together and optimised under given restrictions. The *benefit-cost* ratio is the decisive factor for the selection of the most adequate solution and to include the importance of specific roads, a weighting factor was used to weight the *benefit-cost* ratio. The selection of the optimised solution was carried out by an iterative process, where the highest *benefit-cost* ratio is achieved under budgetary constraints (Figure 11).



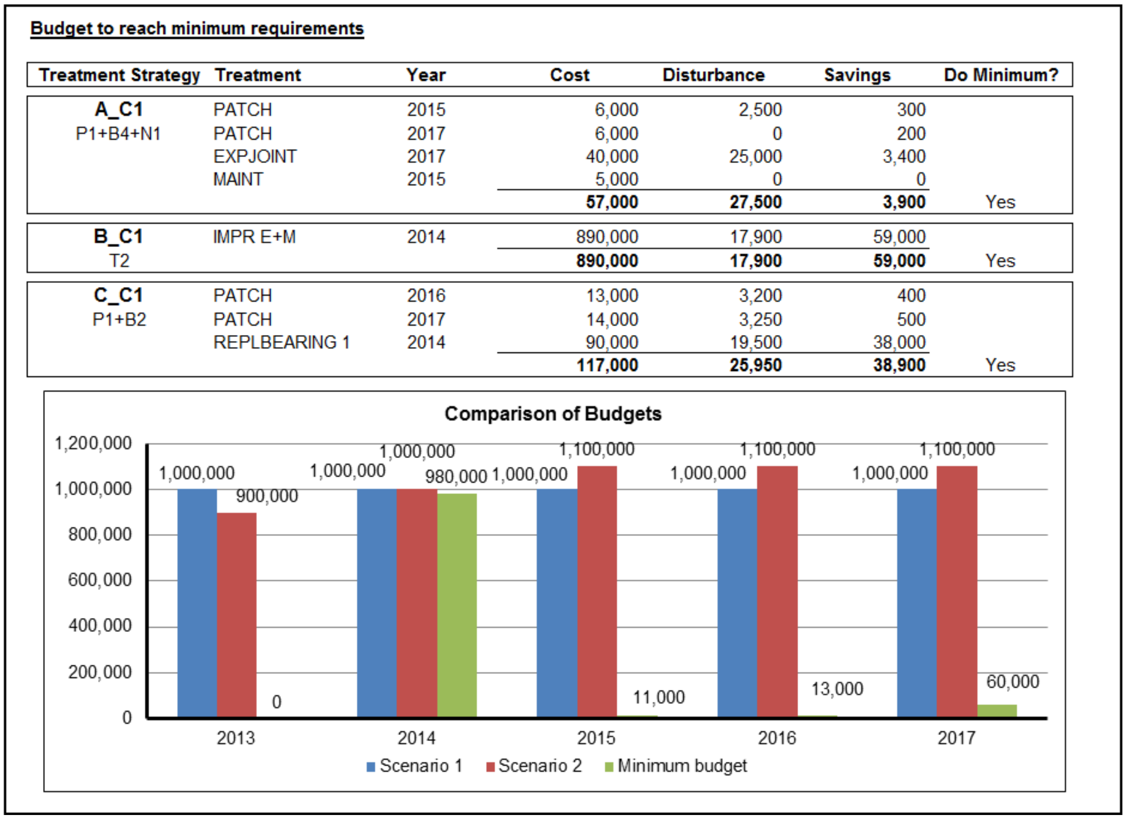
Cross asset optimization over whole network

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 optimised solution can be seen in Figure 12.

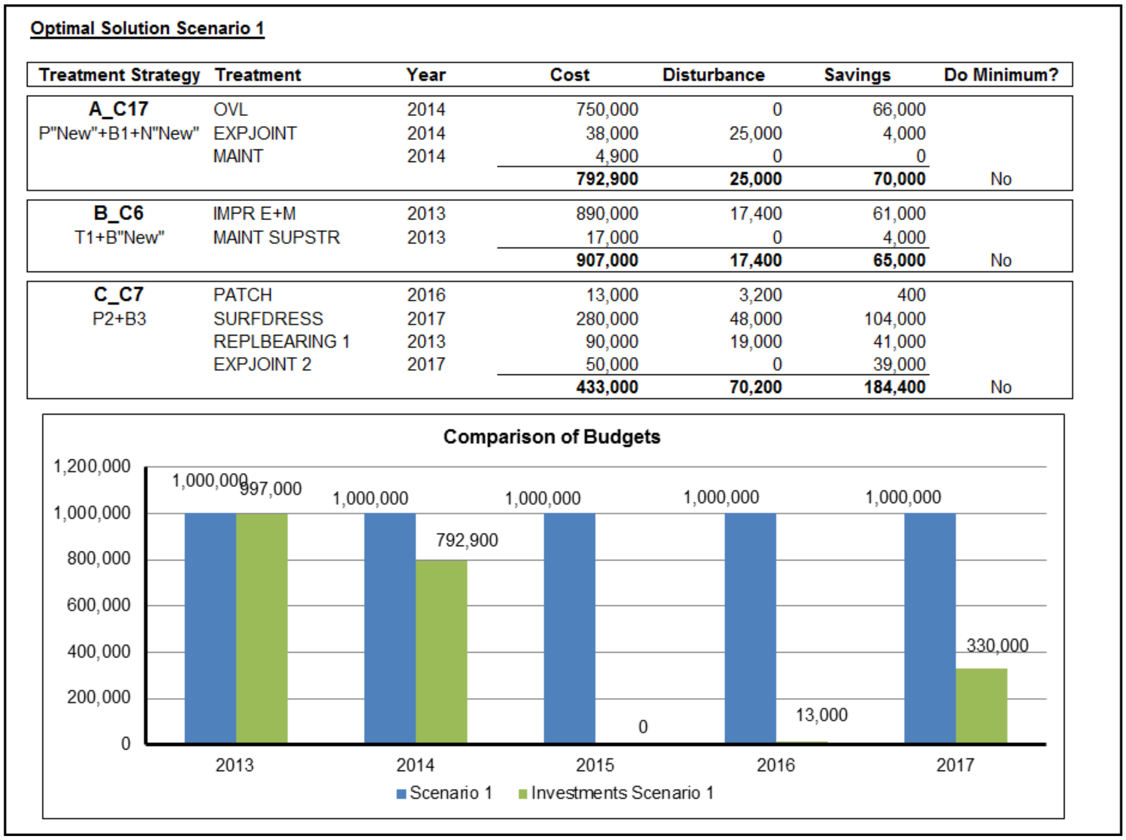


Budget to reach minimum requirements

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

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 based on the lowest *benefit-cost* ratio with a positive value. 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.

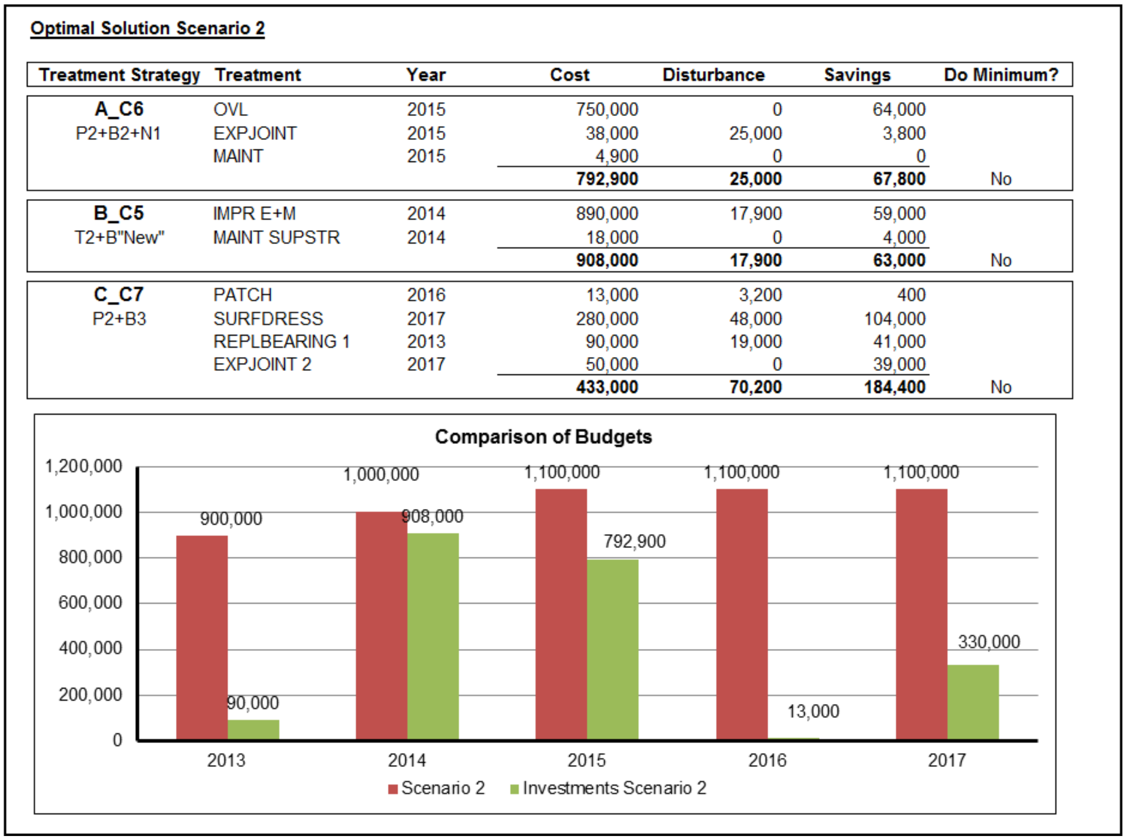


Optimal Solution Scenario 1

Treatment Strategy	Treatment	Year	Cost	Disturbance	Savings	Do Minimum?
A_C17 P"New"+B1+N"New"	OVL	2014	750,000	0	66,000	
	EXPJOINT	2014	38,000	25,000	4,000	
	MAINT	2014	4,900	0	0	
			792,900	**25,000**	**70,000**	No
B_C6 T1+B"New"	IMPR E+M	2013	890,000	17,400	61,000	
	MAINT SUPSTR	2013	17,000	0	4,000	
			907,000	**17,400**	**65,000**	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 13 Example of solution scenario 1

The higher investments are because of the higher intensity of *asset*-specific maintenance treatments. The total investment is more than 2.1milliom units as compared to the previous solution (1.064mil). Figure 14 shows the results for scenario 2 where for a lower budget in 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 already in 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 of solution scenario 2

The results of the analysis are significant in that they identify the strategies which exhibit the highest level of coordination potential as being the most beneficial treatment strategies, in relation to the minimal strategies to satisfy the technical requirements. This is noteworthy because it proves that, by using coordinated maintenance strategies, stakeholders can optimise the net benefit of various treatment combinations across a network to minimise road user costs while maximising savings by bundling maintenance activities, when possible and against projected budget constraints.

The example selected is based on the feedback and requirements from stakeholders of the current infrastructure networks of EU and was agreed upon based on its broad reach in terms of uniform interpretation and implementation into a variety of infrastructure networks with disparate management structures. While detailed optimisation can always be formulated up to the element level for these infrastructure, such over-parameterisation may not necessarily be always helpful for taking decisions at a network level by the owners and managers. While the example provided reflects the actual requirements of the current stakeholders of the infrastructure network of EU, this proposed generic framework does not claim to be the most complete and comprehensive approach towards handling cross-asset optimisation of infrastructure networks. It is expected, however, that significant research will be carried out in this area, particularly in relation to investment and organisation models for managing such large networks more efficiently, while acknowledging the need of all stakeholders.

5. Conclusion

This paper presents a cross-*asset* management framework for road infrastructure networks considering the objectives of different stakeholders. The framework is built on the real requirements of the stakeholders of various road networks of the EU. A mathematical basis for the framework is presented and practical implementation of the proposed methodology is illustrated by considering a network. A benefit-cost analysis demonstrates the effectiveness of the proposed framework over a *do-minimum* approach. The proposed framework can be applied to existing network management systems without modification and can adapt itself to widely varying definitions of key performance indicators, as well as with philosophical differences of network management. The framework acknowledges the existence of uncertainties in any road network and allows the use of probabilistic markers. A cross-*asset* management is identified in this paper to be an adaptive and a practical tool for addressing real and holistic needs of road networks.

Acknowledgements

The authors acknowledge the funding of PROCROSS (Development of Procedures for Cross-Asset Management Optimisation), an ERA-NET Road project funded by the European Commission under FP7.

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