Evaluation of intervention strategies for a road link in the Netherlands

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Abstract

Purpose – The purpose of this paper is to investigate the use of the impact hierarchy and the optimization model to determine the optimal intervention strategy for a road link composed of multiple objects. The paper focusses on the results of a case study of intervention project on A20 road link in Rotterdam, the Netherlands.

Design/methodology/approach – The study was a case study research. It describes briefly the impact hierarchy and its link to the optimization model, and then focussed on analyzing the results obtained from running the model. In order to understand the influence of various factors affecting the results of optimization, sensitivity analysis was performed.

Findings – The proposed hierarchy is suitable to be used to support the determination of optimal intervention strategies (OISs) for public road. From the case study, it was also realized that optimal intervention strategy can be changed due to not only intervention costs incurred by the owner, but also due to the setup of traffic configuration during the execution of interventions since the impacts incurred to users, directly affected public, and indirectly affected public are significantly different from one traffic configuration to the others. The optimal intervention strategy also depends greatly on the factors of deterioration during the operation of the infrastructure objects.

Research limitations/implications – In the impact hierarchy, some impact factors are difficult to be quantified, e.g., the long-term economic impacts on the region where having intervention projects. The use of only exponential function for impacts could be oversimplified the actual behavior of the impacts. Other functional form should be investigated to be used within the framework of the optimization model.

Practical implications – The proposed hierarchy and the optimization model could be used in practical situation for determination of OISs for multiple objects within a road link.

Originality/value – This paper contributes to the body of knowledge of stakeholder analysis in the field of infrastructure asset management. It also gives a guideline and tool for infrastructure administrators to select the OISs for their infrastructure network.

Keywords Asset management, Optimization, Infrastructure management

Paper type Case study

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1. Introduction

In the management of public road infrastructure it is important to determine intervention strategies[1] (ISs) that minimize the total of all negative impacts on all stakeholders within an investigated time period. In order to determine such optimal intervention strategies (OISs) it is necessary to take into consideration the different types of stakeholders (e.g. owner and users) and the different types of impacts (e.g. intervention cost, loss in travel time, vehicle operation cost) that they incur, both during the execution of interventions and between the execution of interventions. This requires the development of an impact hierarchy, which is complete, orthogonal, and quantifiable (Antti, 1999; Hass *et al.*, 2009).

In this paper, an example is presented in which the impact hierarchy proposed by (Adey *et al.*, 2012), and a deterministic mixed-integer non-linear programing (MINLP) model proposed in (Lethanh and Adey, 2012) are used to determine the OISs for a road link composed of an urban asphalt highway road section and a number of reinforced concrete (RC) overpasses in the Netherlands. The impact hierarchy was developed by the authors as no complete hierarchy could be found in literature that could satisfactorily be used in the determination of OISs for public roads. The deterministic model was used to avoid the problem of dimensionality when dealing with multiple objects that may be in multiple condition states in multiple time periods. It is shown that such an approach can be used to determine OISs for road links comprised of multiple objects and taking into consideration the impacts on multiple stakeholders simultaneously; something that if implemented consistently would significantly reduce the negative impacts related to road infrastructure.

2. Literature review

Recently, there have been ever more people that have attempted to take ever more impact types into consideration in decision making with respect to the maintenance of infrastructure. This can be seen in the methodologies developed to evaluate projects (Antti, 1999; Bickel *et al.*, 2002; Hass *et al.*, 2009; ECOPLAN, 2010), to determine OISs using computerized management systems (Thompson *et al.*, 1998), and to develop methodologies to determine OISs (Ouyang and Madanat, 2006; Sathaye and Madanat, 2011). The impetus for this movement has multiple sources but in general it is due to the increasing interest of society in making more sustainable decisions.

Unfortunately, all of the hierarchies used in the above cited work are either incomplete or not completely orthogonal, which means they cannot be used to determine OISs for public road infrastructure. The lack of completeness and orthogonality is a problem because if used, they will lead to the determination of non-optimal ISs as optimal. An example of an incompleteness is, if the hierarchy in (Antti, 1999; Bickel *et al.*, 2002) is used, the absence of the physical and psychological effects regarding operation quality. An example of non-orthogonality is, if the hierarchy is used, due to the inclusion of the physical condition of the objects in the things to be considered; something that only matters when it results in other impacts, such as the production of noise, which is counted directly.

Parallel to this, there have been ever more people that are developing methodologies to be used in decision making with respect to maintenance of infrastructure for multiple objects; something that is necessary when taking into consideration impact types where the value of the impact type is related to the performance of multiple objects simultaneously, e.g., travel time. For example, if the road is closed for an intervention on one object than no additional travel time is lost because an intervention is executed on a neighboring object at the same time. Most, if not all, of the existing maintenance management systems only attribute impacts to the performance of single objects. For example, many of the state of the art infrastructure management systems determine OISs for elements or objects and then attempt to group them when they construct work programs (Thompson *et al.*, 1998).

Some of the researchers that have conducted work in the direction of considering multiple objects simultaneously, are (Hajdin and Lindenmann, 2007), which proposed an algorithm to allow bundle of multiple objects within a workzone, and (Adey and Hajdin, 2005) which recommended the use of inventory theory to group objects in a way that allows considering the impacts related to multiple elements within a bridge simultaneously. Two other examples, include (Ouyang and Madanat, 2006; Sathaye and Madanat, 2011), which proposed methodologies for determining OISs for resurfacing of multiple road sections.

These methodologies have not, however, been developed specifically to be integrated in computerized management systems to determine OISs for multiple objects, which means that they have not fully taking into consideration the requirements related to dealing with multiple objects over multiple years, and therefore have not given explicit consideration to the combinatorial explosion that occurs when considering ever more objects. For example, if the (Adey and Hajdin, 2005) methodology is used with only three objects, it will be necessary to develop $3^2-1=8$ strategies to investigate if only one intervention type is considered per object.

The methodology proposed in this paper is based on an impact hierarchy that encompasses all of the impacts related to public roads, and takes into consideration how they are related to pavement condition and how they change over time. It also uses a model which makes it possible to determine OISs for multiple objects, simulataneously.

3. Impact hierarchy

In the impact hierarchy, a stakeholder is defined as an individual, group, or organization, which is affected by changes to public roads. Being a stakeholder is time dependent. For example, when a person is driving a vehicle on a road the person is a user at that point in time, and when the person is off of the road and in his/her house far from the road, the person is part of the indirectly affected public (IAP). It is considered that all stakeholders can be grouped as either first-level or second-level stakeholders. The first-level stakeholders are those whose net negative impacts should be minimized. The second-level stakeholders are those whose impacts are the outcome of the minimization of the net negative impacts of the first-level stakeholders, and should be monitored.

The four first-level stakeholder groups are the owner, the user, the directly affected public (DAP), and the IAP. It is assumed that all impacts to be minimized can be attributed to one of these four principle stakeholder groups. The definitions of each stakeholder group are given in Table I. The impacts attributed to each stakeholder group are given in Tables II and III. Detailed descriptions can be found in (Adey *et al.*, 2012), where explanations of each impact type, how they can be broken down to a level that is quantifiable and a classification of the impact type as either economic, environmental, and societal to help to ensure orthogonality are given.

As can be seen from Tables II and III, under each stakeholder group, the impact types are defined at different levels. The impact types can be subdivided at increasingly fine levels until the impact of each type can be reasonably and objectively quantified. In the tables, two levels of impact types are shown but more can be further defined if required. The first level consists of composite impact types such as level of

Stakeholder group	Definition	Examples
Owner	The persons who are responsible for decisions with respect to physically modifying the infrastructure	A federal road authority
Users	The persons who are using the roads	A driver and passengers of a vehicle on a road
DAP	The persons who are in the vicinity of the road but are not using it	Persons in a house next to the road that hear vehicles driving on the road
IAP	The persons who are not in the vicinity of the road but are affected by its use	Persons in a house far away from the road that do not hear vehicles driving on the road, but are affected by a changing climate due to the emissions produced by vehicles driving on the road

Table I.
Stakeholder groups

Stake-holders	Level 1	Level 2	Description
Owner	Level of service (intervention)	Labor	The economic impact of people performing tasks
		Material	The economic impact of people ensuring that materials are available for use
		Equipment	The economic impact of people ensuring that equipment is available for use
User	Safety	Property damage	The economic impact of repairing the vehicle
		Injury	The societal impact due to the injury
		Death	The societal impact due to death
	Operation efficiency	Work	The economic impact of wasting work time travelling
		Leisure	The economic impact of wasting leisure time travelling
		Operation	The economic impact of people ensuring that fuel and oil is available for use
		Maintenance	The economic impact of people repairing vehicles and ensuring that materials, e.g. tires and brake pads, are available for use
	Operation quality (comfort)	Physical	The societal impact of obtaining for example, bruises from an extremely bumpy ride
		Psychological	The societal impact of having for example, anxiety due to a perceived increase in the probability of being involved in an accident, or of seeing things while travelling
	Environment preservation (noise)	na	The societal impact due to the user coming in contract with sound emissions

Table II.
Impact hierarchy to two levels for the owner and user

service, safety, or operation efficiency, which are considered as overall representations of important aspects. The second level of impact types is defined in greater detail compared to that of the first level. The impact type at this level can be directly quantified if there is no further requirement to acquire their value and measuring units. If there is

Stake-holders	Level 1	Level 2	Description
DAP	Safety	Property damage	The economic impact of repairing property damaged due to a vehicle coming off of the road
		Injury	The societal impact due to the injury
		Death	The societal impact due to death
	Operation quality (conform)	Physical	The societal impact of physical changes due to people travelling on the road, e.g., due to vibrations
		Psychological	The societal impact of having, for example, anxiety due to a perceived increase in the probability of being involved in an accident, due to others travelling
	Environment preservation (noise)	na	The societal impact due to the directly affected public coming in contract with sound emissions
IAP	Safety	Injury	The economic impact due to an injury
		Death	The economic impact due to a death
	Socio-economic activity	Persons	The impact of not on persons of not being able to transport people
		Goods	The impact of not being able to move goods
		Employment	The impact of interventions in terms of employing people
	Environment preservation	CO_2	The impact due to the emissions
		PM10	
		Nitrogen	
		CO	
		Aldehydes	
		Nitrogen dioxide	
		Sulphur dioxide	
		Polycyclic aromatic	
		Hydro carbons	
		Dust	

Table III.
Impact hierarchy to two levels for the DAP and the IAP

need, impact types in level 2 then become a secondary composite types, whose values are computed by aggregating the values of impact types in the third level of impact types.

4. Model

4.1 General

The MINLP model consists of two main steps:

- *Step 1*: determine the optimal intervention return (OIR) periods for each object, or group of objects, in the road link for each intervention type (e.g. resurfacing, partial depth repair), as well as the times of intervention for each object, or group of objects, taking into consideration the condition states of each at the beginning of the investigated time period. The distinction between objects and groups of objects is made because in order to analyze all possible ISs for a road link it is necessary to consider ISs where interventions are executed on objects individually or simultaneously.
- *Step 2*: determine the intervention times for each object, or group of objects, taking into consideration impact constraints, something that can be done using priority rules.

A short description is provided here for the reader's convenience. A full description of the model can be referred to the original paper.

4.2 OIR periods for each object or group of objects

The objective function of the MINLP model is shown in the following equation:

$$Min\Psi = \sum_{l=1}^{L}\sum_{n_l=1}^{N_l}\left[\int_{0}^{T}\sum_{x=1}^{X}f_{n_l}^{k_{n_l}}(t,x)\cdot e^{-\rho\cdot t}dt + e^{-\rho\cdot t}\sum_{x=1}^{X}g_{n_l}^{k_{n_l}}(d,x)\right] \tag{1}$$

where ψ is the total impact; l the index of the link ($l \in (1, \ldots, L)$), L is total number of links; n_l the index of object in link l ($n_l \in (1, \ldots, N_l)$), N_l is total objects of link l; T the total of investigated time period (years); x the index of impact indicator (e.g. labors, materials), X is total numbers of impact indicators considered in the impact hierarchy; k_{n_l} the index of intervention type pre-selected for object n in the link l; ρ the discount factor; d the duration of intervention; $f_{n_l}^{k_{n_l}}(t,x)$ the values of impacts associated with impact indicator x between the execution of IS k on object n of the link l. It is expressed as a function of time t; $g_{n_l}^{k_{n_l}}(d,x)$ the values of impacts associated with impact indicator x during the exectution of IS k on object n of the link l.

The full form of Equation (1) includes both binary and non-negative variables that are required to solve the equation (Lethanh and Adey, 2012). The function *f(t,x)* and *g(d,x)* can be of any form supported by the data produced from empirical studies.

The OIR for each object is determined by comparing the average annual impact (AAI) that results from each possible ISs and selecting the one that results in the smallest AAI. The AAI Θ is calculated according to following equation:

$$\Theta_{n_l}^{k_{n_l}} = \frac{\Psi_{n_l}^{k_{n_l}}}{T_{n_l}^{k_{n_l}}} \tag{2}$$

where $T_{n_l}^{k_{n_l}}$ is return period when intervention type k_{n_l} is executed on object n of link l. The OIS is then determined as follow:

$$k_{n_l}^{*} = \arg_{k_{nl}\in K_{nl}} MIN\left(\Theta_{nl}^{k_{nl}}\right) \tag{3}$$

Once the OIR for each object, or group of objects, is determined, their condition states at the beginning of the investigated time period can be taken into consideration and the exact times of intervention in T can be determined. For example, a concrete bridge has OIR of 15 years and at present it has been in service for nine years, then the elapsed time to the next intervention is six years.

4.3 Intervention times with impact constraints

It is not always possible to execute all of the interventions that are theoretically optimal due to constraints on impacts, e.g., the amount of impacts incurred by the owner through the execution of interventions, i.e., intervention costs. Such constraints are introduced in the model on a yearly basis as:

$$\sum_{n=1}^{N} g_n^k(d,x) \leqslant B^k(t,x) \tag{4}$$

where *B(t)* is the allowable limit per impact type k in year t.

The introduction of impact constraints also makes it necessary to deal with the situation when allowable limits are reached, i.e., a decision has to be made as to which theoretically optimal interventions will not be executed and if they are not executed a decision has to be made as to when they will be executed, and with the situation when allowable limits are not reached, i.e., a decision has to be made as to what will be done with the portion of the allowable impacts that are not used, e.g., the excess money. These two situations are dealt with using priority rules as follows.

If the sum of all impacts of one impact type:

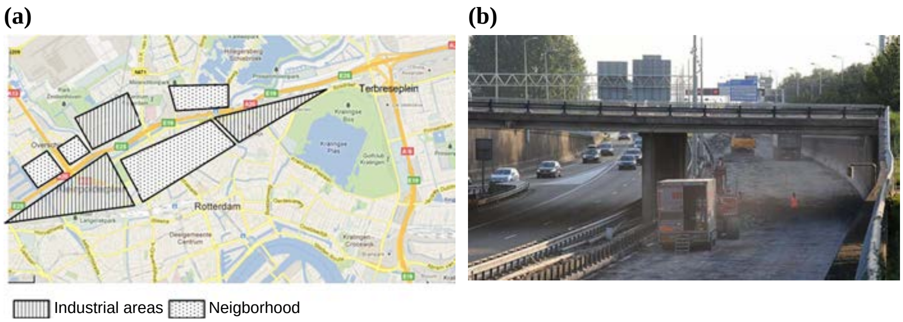
- Is greater than the allowable limit of at least one impact type, i.e., not all objects that should have an intervention can, the object on which an intervention would have the highest reduction in total impacts within the selected year is selected for intervention, if the execution of the intervention does not result in an exceedance of the allowable limits for an impact type, otherwise the object is rejected within the selected year (and becomes a candidate for intervention within the next year) and the object with the next highest reduction in total impacts within the selected year is selected, and so on.
- Is less than or equal to the allowable limits of all specific impact types, then all possible interventions are executed. The difference between the allowable limit and the sum of the specific impacts are added to the allowable limit in the following year, when applicable, e.g., budget, otherwise they are not, e.g., noise, accidents.

This procedure is repeated at each year during the investigated time period.

5. Case study

5.1 Infrastructure

The case study is the determination of the OIS for an 7.9 km section of the A20 highway from the intersection Kleinpolderplein to the intersection Terbregseplein, in the ring of Rotterdam, the Netherlands (Figure 1(a)). The link is located in a densely populated area and was considered to consist of eight objects; seven RC bridges and one 5.72 km long asphalt road section, i.e., the pavement over the entire road link is seen as a single object. It has six traffic lanes (four main lanes and two narrow emergency lanes). Between July 30 and August 14, 2011, the 5 cm top layer of asphalt was renewed for all six lanes on the road section, including the asphalt on the bridge decks, and the construction joints of all eight bridges were replaced (Figure 1(a)). General information of the objects is summarized in Table IV and Figure 2.



A20 load link

Intervention

Figure 1.
Intervention of A20 road link, Rotterdam

5.2 Intervention strategy types (ISTs)

The investigated ISTs (Table V) were comprised of three different groupings of objects on which interventions were to be simultaneously executed (IG) and four traffic configurations (TC) implemented during the execution of the interventions.

5.3 Traffic simulation

In order to evaluate the impacts during the execution of the interventions traffic flow over the network was modeled. This was done using a static traffic assignment (STA) model. The STA model was considered reasonable for this case study, as it was only necessary to determine macroscopic changes of flows from which extra travel related impacts due to the execution of an intervention on the entire network could be estimated (Cascetta, 2001).

In the STA model, the average travel time $S_a(v_a)$ for a vehicle on a road link was estimated as:

$$S_a(v_a) = t_a\{1 + 0.15(v_a/c_a)\} \tag{5}$$

where t_a is the total impact; v_a the index of the link ($l \in (1, \ldots, L)$), L is total number of links; c_a the index of object in link l ($n_l \in (1, \ldots, N_l)$), N_l is total objects of link l.

Table IV. Objects

	Objects							
Description	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Road section
Width (m)	15	30	15	30	30	30	30	60
Length (m)	210	330	240	550	190	310	350	5,720

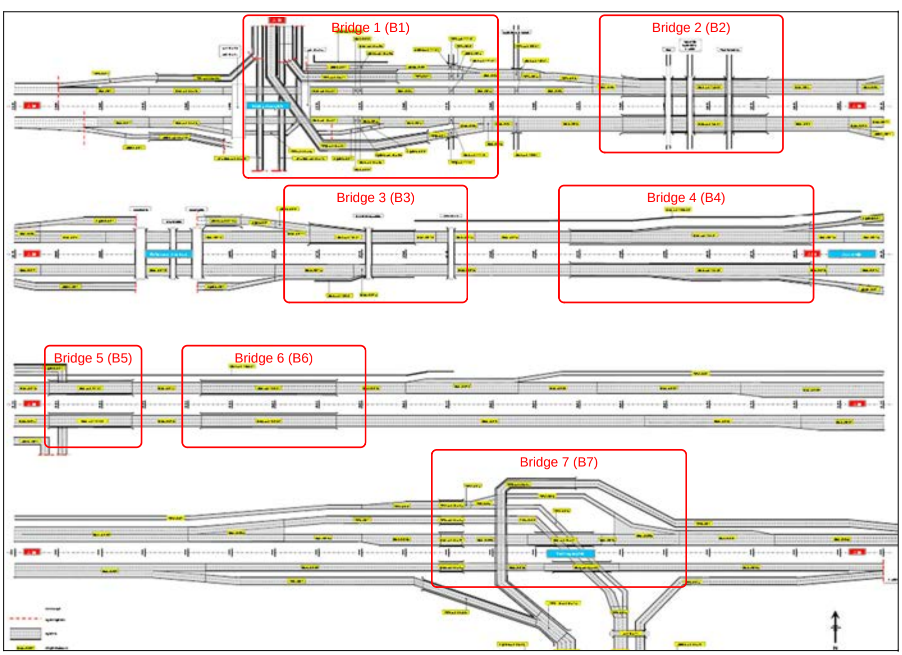


Figure 2. Locations of objects on the link

Table V. Investigated intervention strategy types (IST)

	Traffic configuration		Intervention bundle		
			IG-1	IG-2	IG-3
Abbreviation	Name	Description	Interventions on all objects executed independently	Interventions on all bridges executed simultaneously Interventions on pavement are executed independently from bridges	Interventions on all objects executed simultaneously
TC-1	4-0	In the weekends, both directions (a and b) of traffic are closed. In the weekdays, both directions are opened in 4 narrow lanes	IST-1	IST-5	IST-9
TC-2	Closed on weekends	In the weekends, 1 direction is closed and 1 direction is opened. In the weekdays, both directions are opened	IST-2	IST-6	IST-10
TC-3	Closed for multiple days	In the weekends, 1 direction closed and 1 direction open. In the weekdays, 1 direction is closed and 1 direction is opened	IST-3	IST-7	IST-11
TC-4	Combination of closed for multiple days and on weekends	In weekends, direction a is closed and direction b is opened. Also, if direction b is closed, then direction a is opened. In the weekdays, direction a is closed and direction b is opened	IST-4	IST-8	IST-12

The first component in Equation (5) represents the minimal travel time on road links when there is no congestion (or free-flow travel time), while the second component represents the non-linear increase of travel time due to the queuing and speed reduction of vehicles when congestion occurs.

The average additional travel time per vehicle for each TC for IG3, i.e., IST 9, 10, 11, and 12, are summarized in Table VI, in which the number of travelers are derived using the STA model for each scenario.

5.4 Impact types and unit values

The impact types and the value of a unit of each are given Table VII. The unit values were initially obtained from several Dutch and European documents (Bickel *et al.*, 2002) and were modified by experts at the University of Twente and the Dutch Ministry of Infrastructure and the Environment to take into consideration of the actual situation in the Netherlands, including the inflation that has occurred since the time of publication of the sources documents. The impacts incurred to each group of stakeholders (Table I) during interventions and in between interventions from each object are calculated based on empirical models (ERA-NET, 2012). An example of using the empirical model is the estimation of the probability of accident occurence as a function of traffic volume, speed of travel, length of object, duration of intervention, etc., as done in the model of (Lindenmann, 2008) and the multiplication of this probability of occurrence with the values of the expected injuries, deaths, and property damage.

The impacts incurred by each stakeholder group during the execution of each intervention, i.e., for each grouping of interventions and each TC are given in Table VIII.

As can be seen, the impacts incurred by each stakeholder group vary significantly. For example, when an intervention is executed on the road section alone, which occurs if IG-1 and TC-1 are used, the owner impact is €2,829 $\times$ 10^3. However, when an intervention is executed on the road section alone, and TC-2 is used, the impact is €2,761 $\times$ 10^3, which is about 2.4 percent lower than if TC-1 is used. It is interesting to note that during the execution of interventions on bridges, the impacts incurred by the owner are considerably greater than they are on other stakeholders (on average, 80 vs 10 percent). This is partially due to the fact that because the intervention costs (labor, materials) on bridges are relatively high (e.g. bridge 1 costs the owner €406,201) with respect the amount of time that it takes to execute an intervention and during which

IST	TC	Intervention duration (days)	Average DTV on road link (vehicles/day)	Average DTV deviated on other links (vehicles/day)	Average additional time per vehicle (minutes)
9	1	16 days (3 weekends/2 weeks)	124,854	34,358	0.97
10	2	24 days (12 weekends)	0	159,212	1.31
11	3	14 days (2 weekends/2 weeks)	64,626	94,586	1
12	4	17 days (1 week/6 weekends)	80,058	79,154	0.81

Note: DTV, daily traffic volume

Table VI. Based value resulted from traffic simulation

Table VII.
Unit value of impact types

Stakeholders	Impact type (level 1)	Impact type (level 2)	Indicator	Unit value (€)
User	Vehicle operating cost (VOC)	VOC per light-weight vehicle	Hour	1.65
		VOC per medium-weight vehicle	Hour	2.67
		VOC per heavy-weight vehicle	Hour	5.32
		VOC per bus	Hour	5.32
	Petrol cost*		Litre	0.46
	Diesel cost*		Litre	0.51
	Vehicle maintenance cost		Vehicle per year per km	0.86
	Travel time cost	during work time	Hour	33.07
		during leisure time	Hour	9.55
	Accident	Property damage	Accident	41,690
		Injury	Injured person	276,568
		Fatality	Fatality	2,690,108
DAP	Noise	Noise	dB per year per person	27.97
IAP	Emissions	CO_2	Ton	24
		PM	Ton	308,189
		NOx	Ton	4,093
		CO	Ton	3.1
		VOC	Ton	1,139
		Dust	Ton	30,675

the user is adversely affected (e.g. an intervention on bridge 1 takes eight days and the impacts incurred by the user and public are € 36,424 and € 2,470 on the bridge and € 10,733 and € 2,308 on the detour, respectively).

The impacts incurred by the owner and users are not significantly different on the road section (on average 55 vs 40 percent). This is partially because the relatively extra work travel time incurred (0.7 minute/user/day, making up € 1.5×10^6 extra) off set the owner cost of intervention (e.g. an intervention on the road section costs € 2.83×10^6).

The impacts incurred by the DAP and IAP are significantly smaller than those incurred by owner and users (1-5 percent). This is partially due to the fact that there is a relatively small number of people (1,500) considered to be adversely affected by the execution and partially due to the fact that the interventions would not generate much more noise than normal use of the road. The impacts incurred on the road section and on each of the bridges are roughly the same per day (€ 1,015/day and € 2,500/day/km for DAP and IAP, respectively).

The proportions of impacts incurred by IAP when an intervention was executed on the road section were higher than the total amount due to the execution of interventions on all bridges (€ 136,906 vs € 41,805). This is principally due to the fact that the impacts incurred by the IAP, e.g., emissions, are considered to be directly related to additional time vehicles travel and the speed at which they are traveling.

The impacts incurred by stakeholders between interventions are assumed to change over time due to the deterioration of the road condition. This change was modelled using exponential functions. The use of exponential functions have been used by past researches (Sathaye and Madanat, 2011) and in the abscence of more detailed information was considered to be a reasonable choice. The evolution of the impacts

Table VIII. Impact per object during intervention

		Intervention grouping										
		IG-1								IG-2		IG-3
TC	Stake holders	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Road section	Bridge 1-Bridge 7	Road Section	Bridge 1-Bridge 7 + Road Section
TC-1	Owner	406	676	424	919	522	654	698	2,829	2,810	2,829	5,390
	User	47	68	52	95	44	58	71	1,995	437	1,995	2,432
	DAP	8	8	8	8	8	8	8	16	57	16	73
	IAP	5	6	5	9	5	6	6	137	42	137	179
	Total	466	759	490	1,031	578	727	784	4,977	3,345	4,977	8,074
TC-2	Owner	288	558	306	800	404	536	580	2,761	2,691	2,761	4,762
	User	124	124	124	124	124	124	124	1,243	870	1,243	2,114
	DAP	20	20	20	20	20	20	20	20	142	20	163
	IAP	33	36	34	43	32	36	37	436	251	436	687
	Total	465	739	484	988	581	716	762	4,460	3,955	4,460	7,725
TC-3	Owner	268	538	286	780	384	516	560	2,661	2,672	2,661	5,221
	User	49	60	52	80	47	58	62	1,645	408	1,645	2,053
	DAP	8	8	8	8	8	8	8	16	57	16	73
	IAP	9	10	9	13	9	10	10	262	70	262	332
	Total	334	616	355	882	447	592	640	4,584	3,207	4,584	7,679
TC-4	Owner	258	528	276	770	374	506	550	2,701	2,312	2,701	4,912
	User	45	69	60	90	56	67	71	1,996	459	1,996	2,455
	DAP	8	8	8	8	8	8	8	16	57	16	73
	IAP	8	9	8	12	8	9	9	241	63	241	304
	Total	319	614	352	881	445	590	639	4,954	2,890	4,954	7,744

Note: Unit = € 1,000

on the eight objects over 30 years if no interventions are executed are shown in Figure 3. The figure shows the evolutions of impacts incurred by four main stakeholders, values at any point on the curves represent the cummulative values of impacts under the four main stakeholders. Impact values of owner are considered as routine maintenance cost.

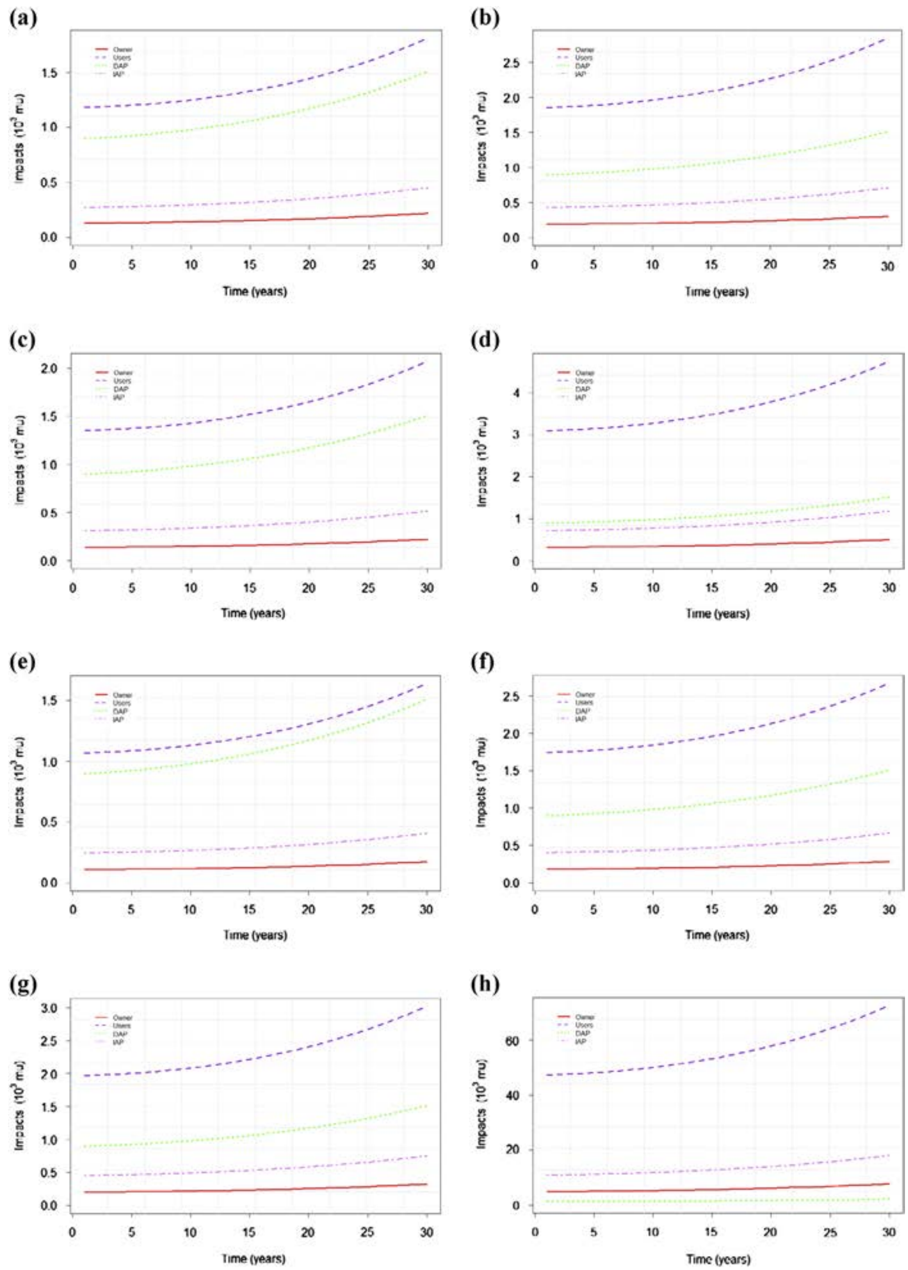


Figure 3.
Evolution of impacts following the execution of interventions

As can be seen in the figure, for both the road section and the bridges, impacts incurred by the users are the largest (approximately 73 percent due to the use of the road section and 47 percent due to the use of the bridges). The second largest impacts are incurred by the DAP (approximately 16 percent due to the use of the road section and 36 percent due to use of the bridges). The impacts incurred by the IAP are approximately 4 percent due to the use of the road section and 10 percent due to use of the bridges. The impacts incurred by the owner, due to routine maintenance on both the road section and the bridges are approximately 7 percent.

5.5 Results

The total absolute AAIs that are incurred when each OIS of each IST are followed, as well as the relative AAI when each OIS of each IST is compared with the reference IS (the OIS of IST1) are given in Table IX. The OIS, of all OISs, that results in the lowest overal impact is of IST-9 (€ 56 $\times$ 10^3 less than the reference IS).

As can be seen from Table IX, the OIS of IST-9 is the one with the lowest AAI on stakeholders (a reduction of € 56,350 with respect to the reference IS). It can be also seen that the OISs that include grouped interventions, i.e., ISs of IST-9, IST-10, IST-11, and IST-12, result in lower AAI than that the OISs where interventions are not grouped, e.g., absolute AAI when the OIS of IST9 is followed are € 527,912 which is about 9 percent lower than the absolute AAI when the OIS of IST1 is followed € 584,271. This is, in general, because by grouping interventions there are significant reductions to the owner impacts, e.g., only one work site has to be made, as opposed to multiple work sites (e.g. the total impacts incurred by the owner during the execution of interventions on road section in IST-5 (TC-1 and IG-2) were estimated as 5,639 $\times$ 10^3 under IST-9 (TC-1 and IG-3)). Such reductions occur, for example, due the reduction in effort in setting up traffic barriers to establish and maintain the TC, e.g., The impacts incurred by the owner of setting up traffic barriers during the execution of the interventions in the ISs of IST-5 were estimated to be 278.5 $\times$ 10^3 and 35.55 $\times$ 10^3 for the road section and each bridge, respectively, making the total impact related to setting up traffic barriers 527 $\times$ 10^3 ($=(278.5+7 \times 35.55) \times 10^3$). It is noted that the impacts incurred by the owner due to the setting up of traffic barriers were calculated

IST	Intervention time on objects (years) Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Road section	Absolute average annual impact (€)	Relative average annual impact (€)
1	28	31	28	30	33	32	31	10	584,271	0
2	28	31	27	29	34	31	31	8	672,854	88,583
3	22	28	21	27	29	28	28	8	644,259	59,988
4	21	28	21	27	29	28	26	10	585,667	1,396
5	24	24	24	24	24	24	24	10	582,492	−1,779
6	27	27	27	27	27	27	27	8	671,120	86,849
7	23	23	23	23	23	23	23	9	616,546	32,275
8	26	26	26	26	26	26	26	10	584,993	722
9	14	14	14	14	14	14	14	14	527,921	−56,350
10	13	13	13	13	13	13	13	13	544,630	−39,641
11	13	13	13	13	13	13	13	13	547,212	−37,059
12	13	13	13	13	13	13	13	13	545,924	−38,347

Table IX. Average annual impacts of IST based on the assumption that the execution of interventions on each object is carried out separately and not grouping the objects in one package. These impacts during the execution of the interventions in the ISs of IST-9 were estimated to be €278.50 $\times$ 10^3 for the interventions to be executed simultaneously on the road section and the bridges in each intervention return period; a reduction of nearly 50 percent over those estimated for the interventions in the ISs of IST-5, in which interventions are executed on all bridges simulateneously and the road section seperately.

It can also be seen that the absolute and relative AAI of the OISs of IST-9, IST-10, IST-11, and IST-12 are not significantly different (e.g. in comparison with the OIS of IST-9, the variations of impacts of the other OISs of each IST are only about 1 percent). These small differences are mainly due to the differences in impacts incurred by the user through the extra travel time incurred by different TC (refer to Table VI). As the differences are only small, due to the redundant road network around Rotterdam there is only a slight effect on OIS, i.e., the OIR oscillates between 13 and 14 years. For example, the AAI of the OIS of IST-9 were estimated to be €527,921 and the extra travel time per vehicle was 0.97 minutes (Table VI) , while, the AAI of the OIS of IST-10 were estimated to be €544,630 and the extra time per a vehicle was 1.31 minutes.

6. Sensitivity analysis

As the estimation of the unit values of the impacts, the discount rate, and the effectiveness of interventions is something that is in most cases highly subjective, a sensitivity analysis was conducted on the values of the parameters given in Table X. These ranges were deemed sufficient to show the significance of over and underestimation of the unit values, measured with respect to the change in the impacts related to the OIS of each IST and therefore their optimality. The effect of these variations on the optimal IST, the OISs and the AAI are shown in Figure 4 and summarized in Table X.

In addition, a summary of the stability of OIS and the significances in changing the OIR and the AAI is also shown in Table XI.

It can be seen that a small change in the unit values of impacts, i.e., owner, user, VOC, travel time impacts, can result in changes in:

- The OIS of each IST, e.g., the sharp increase of the OIR curves in Figure 4. For example, in Figure 4(c), it can be seen that for approximately every 10 percent increment of change in the valuation of owner impacts there is an increase in the amount of time between interventions by one to three years.
- The optimal IST, e.g., an increase in the valuation of VOC by $+20$ percent from the base value results in a change in the optimal IST from IST-9 to IST-10 (Figure 4(b)). In most of the cases, however, the optimal IST is stable. This can be seen by observing the optimal IST of IST-9 shown in Figure 4, e.g., in Figure 4(a). Changes in the value of travel time, do not result in a change of the optimal IST; it is always IST 9 (in purple).
- The AAI, e.g., the sharp decrease of the impact curves in Figure 4(a, b) and (c). For example, an increase in the valuation of owner impacts by 10 percent from the base value results in a change in the AAI of approximately €50 $\times$ 10^3 for IST-9.

Changes in the value of the discount factor ρ (Figure 4(e)):

- Affect the optimal IST insignificantly, e.g., the optimal IST is still IST-9.

Table X. Parameters included in sensitivity analysis

Description		Parameters: Owner	User	VOC	Extra travel time	Discount factor	α	δ	β
Minium	Percent from default value	–50	–50	–50	–50	–75	–50	–50	–50
Base value	IST7-bridge	€ 2.67×10^6	€ 1.24×10^6	2.67 €/hour	0.27 min	0.02	14,087	8,534	0.06
	IST7-road	€ 3.47×10^6	€ 0.87×10^6	2.67 €/hour	0.70 min	0.02	40,939	23,508	0.06
	IST9	€ 4.76×10^6	€ 2.11×10^6	2.67 €/hour	0.97 min	0.02	55,026	32,042	0.06
	IST10	€ 5.39×10^6	€ 2.43×10^6	2.67 €/hour	1.31 min	0.02	55,026	32,042	0.06
	IST11	€ 5.99×10^6	€ 2.05×10^6	2.67 €/hour	1 min	0.02	55,026	32,042	0.06
	IST12	€ 5.96×10^6	€ 2.45×10^6	2.67 €/hour	0.81 min	0.02	55,026	32,042	0.06
Maximum	Percent from default value	+50	+50	+50	+50	+150	+50	+50	+50

Notes: 2.67 €/hour is base value for medium weight vehicle. For light and heavy vehicles, base values of VOC are € 1.65 and € 5.32, respectively. Parameters α, δ, and β are coefficients of exponential function $f(t) = \alpha + \delta.\exp(-\beta.t)$ (see Equation (1))

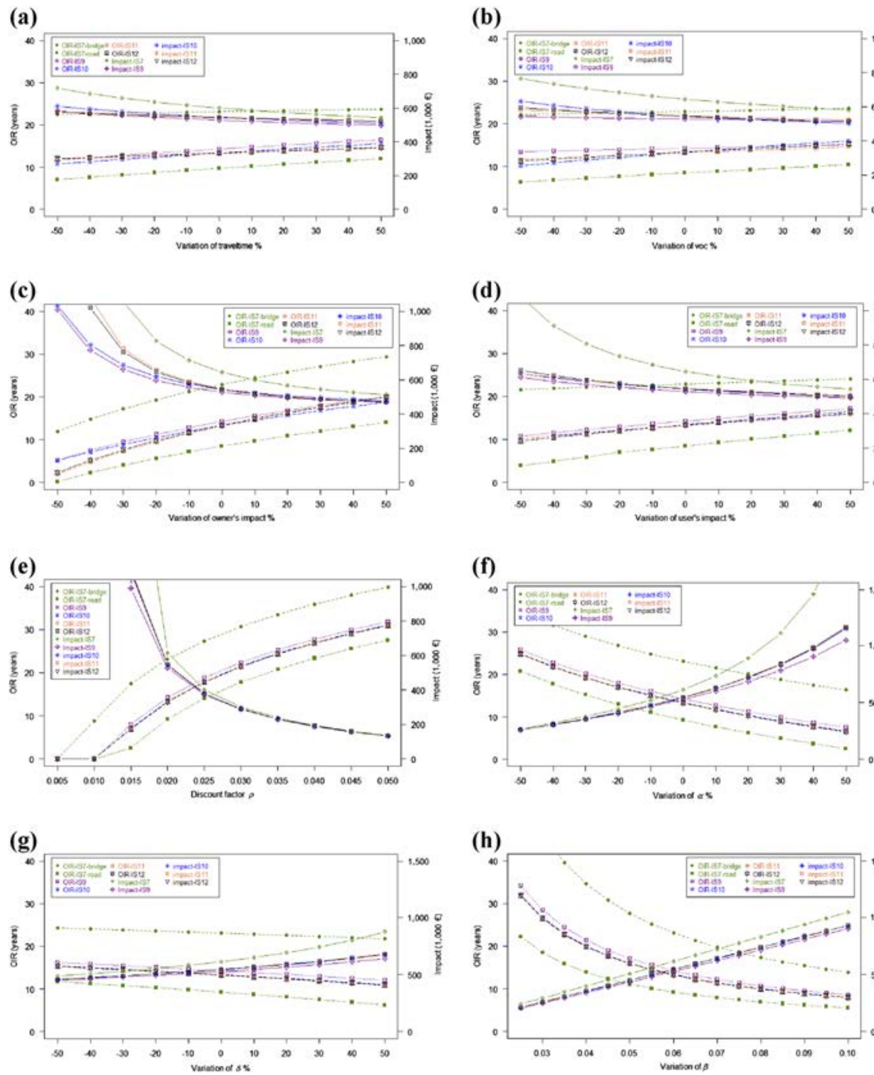


Figure 4.
Effect of variations in selected parameters on the optimal IST, the OIS and the average annual impacts

Table XI.
Effect of variations in parameters on the optimal IST, the OIS and the AAI

	Variations in							
Description Type of OIS	Owner IST-9	User IST-9	VOC IST-9	Travel time IST-9	Discount factor IST-9	α IST-9	δ IST-9	β IST-9
OIS	High	High	Low	Low	High	High	Moderate	High
Average annual impacts	High	High	Low	Low	High	High	Moderate	High

- Greatly affect the OIS, e.g., the sharp increase in the OIR curves. If the discount factor increases or decreases by a value of 0.005 from the base value (0.02), the OIR changes by approximately four to five years.
- Greatly affect the AAI, the sharp decrease in the impact curves. If discount factor increases by a value of 0.005 from the base value (0.02), the change in the impact is approximately €200 $\times$ 10^3.

This means that the smaller the value of the discount factor used the shorter the time interval between interventions becomes in the OIS and the higher the AAI.

Similarly, changes in the value of parameter α (Figure 4(f)):

- Affect the optimal IST, insignificantly, e.g., the optimal IST is still IST-9.
- Greatly affect the OIS, For every increase/decrease of 10 percent from the base value, the intervention time decreases/increases between two and three years, depending on the IST.
- Greatly affect the AAI. For every increase/decrease of 10 percent from the default value, the AAI increases between approximately 10 and 40 percent.

Changes in the value of parameter δ (Figure 4(g)) also affect the optimal IST, the OIS, and the AAI, however, the effect is moderate when compared to changes in the value of parameter α.

Changes in the values of the parameter β (Figure 4(h)) also:

- Affect the optimal IST, insignificantly, e.g., the optimal IST is still IST-9.
- Affect the OIS. Increases in the values of β by 10 percent from the base value result in approximately two year decreases in the OIR.
- Affect the AAI. Increases in the values of β by 10 percent from the default value result in increases in AAI of €75-100.

7. Conclusion

In this paper, the optimal intervention strategy was determined for a road link in Rotterdam using the impact hierarchy developed by (Adey *et al.*, 2012) and the MINLP model developed by (Lethanh and Adey, 2012). The impact hierarchy and the model used in the case study made it possible to determine the optimal intervention strategy for the link. By using the hierarchy, all possible impacts incurred by all stakeholders could be quantified and double-counting was avoided. The model could be used together with the hierarchy to determine the optimal intervention strategy of each IST and the optimal intervention strategy overall, as well as the corresponding AAIs. In addition, the case study showed that ISs in which interventions on multiple objects were executed simultaneously, i.e., grouped, often resulted in reduced impacts incurred by stakeholders, especially the owners and the users, due to the elimination of effort in executing interventions and the elimination of disruptions to traffic flow during the execution, respectively.

The work presented is a contribution to research in that it demonstrates a new way to evaluate ISs for a road link composed of multiple objects where multiple stakeholders are affected. If implemented in practice the impact hierarchy and MINLP model would bring considerably quantifiable objectivity to an area of decision making where decisions are often made ad hoc or based on rules of thumb. This quantifiable objectivity would, in turn, lead to improved decisions and the reduction of negative impacts related to interventions on road networks.

Note

1. Intervention strategies consist of the activities that should be executed on infrastructure taking to consideration the condition of the infrastructure and how these activities are to be executed.

References

Adey, B.T., Lethanh, N. and Phillippe, L.T. (2012), "An impact hierarchy for the evaluation of intervention strategies for public roads", *4th European Pavement and Asset Management Conference, Malmo, September 5-7*.

Adey, T.B. and Hajdin, R. (2005), "Potential use of inventory theory to bundle interventions in bridge management systems", *Transp. Res. Rec. J. Transp. Res. Board, Transp. Res. Board Natl. Acad.*, Vol. 1933, pp. 44-49.

Antti, T. (1999), "Performance indicators for the road sectors", *Transp.*, Vol. 26, pp. 5-30.

Bickel, P., Arampatzis, G., Burgess, A., Esposito, R., Fagiani, P., Friedrich, R., Hunt, A., Jonkhoff, W., Kelly, C., Laird, J., Lieb, C., Navrud, S., Odgaard, T., Ricci, A., Rustenburg, M., Sieber, N., Tavasszy, L. and Trædal, Y. (2002), "Developing harmonised european approaches for transport costing and project assessment", Contract No. FP6-2002-SSP-1/502481, Deliverable 5: Proposal for Harmonised Guidelines, Technical report, Febuary, available at: http://heatco.ier.uni-stuttgart.de/HEATCO_D5.pdf

Cascetta, E. (2001), *Transportation Systems Engineering: Theory and Methods*, Springer.

ECOPLAN (2010), "Sustainability indicators for road infrastructure projects", in ECOPLAN (Ed.), *Handbuch eNISTRA*, ECOPLAN, Bern.

ERA-NET (2012), *Stakeholders Benefits and Road Interventions Strategies*, ERA-NET, Luxembourg.

Hajdin, R. and Lindenmann, H.P. (2007), "Algorithm for the planning of optimum highway work zones", *J. Infrastruct. Syst.*, Vol. 13, pp. 202-214.

Hass, R., Felio, G., Lounis, Z. and Falls, L.C. (2009), "Measurable performance indicators for roads: canadian and international practice", *Annual Conference of the Transportation Association of Canada, Vancouver, October 18-21*.

Lethanh, N. and Adey, B. (2012), "The use of MINLP to determine optimal preservation strategies for road links composed of pavement sections and bridges", *IABMAS-2012, the 6th International Conference on Bridge Maintainance, Safety, and Management. Como, July 8-12*.

Lindenmann, H.P. (2008), "Planning and measurement for preservation of road network" (German name: Massnahmenplanung im Erhaltungsmanagement von Fahrbahnen), Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK, Bundesamt für Strassen.

Ouyang, Y. and Madanat, S. (2006), "An analytical solution for the finite-horizon pavement resurfacing planning problem", *Transp. Res. Part B Methodol.*, Vol. 40, pp. 767-778.

Sathaye, N. and Madanat, S. (2011), "A bottom-up solution for the multi-facility optimal pavement resurfacing problem", *Transp. Res. Part B Methodol.*, Vol. 45, pp. 1004-1017.

Thompson, P.D., Small, E.P., Johnson, M. and Marshall, A.R. (1998), "The pontis bridge management system", *Struct. Eng. Int.*, Vol. 8, pp. 303-308.

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