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Optimal grouping of interventions on road networks (OPINRONET)

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I Abstract

With the continuously increasing size and complexity of road networks the maintenance management becomes more and more difficult. The development of models helping to determine when, where and what has to be done to keep the entire network working properly plays a key role in the computer-aided road infrastructure management. In order to plan, group and optimize the maintenance works the processes behind the deterioration and the resulting consequences from performing interventions have to be considered. The state of research and practice is stated as a basis for the introduction of a model which allows the optimization of intervention strategies for entire road networks taking all stakeholders into account. The model is a further extension of an algorithm exemplarily presented by R. Hajdin and B. T. Adey in their work *"Optimal worksites on highway networks subject to constraints"*. The main characteristics of the extended model are explained and illustrated through an example. In order to proof its applicability, a road network in the Canton of Valais, Switzerland, is examined using the introduced model. The effects of the different consequences of performing interventions on road networks are discussed. A methodology for the implementation of the model in a program is given including a disquisition on the problems occurring with nonlinear constraints.

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1 Introduction

1.1 Problem statement

In modern society, the network of transportation infrastructure takes on a key role for economic development and mobility of people. Transportation infrastructure networks are often comprised of multiple objects – such as bridges, tunnels or road sections – that are linked together to form a manageable system. In order to provide an adequate level of service for all stakeholders (e.g. owners, users and the public) the networks have to be maintained at the right time and place. The adequate level of service is for all stakeholders defined as soft and hard constraints, for example a defensible amount of noise emissions or a certain level of safety. Definitions including critical values are often given in building codes. If these general conditions are no longer fulfilled due to reasons like advanced deterioration, obsolescent objects or changes in the demand, interventions (e.g. repair, renewal, preservation, etc.) have to be carried out (Adey, Hajdin, & Bruhwiler, 2003; Lethanh, 2009). Among all factors that necessitate interventions on transportation networks, deterioration is considered to have some of the most far reaching consequences.

The type and rate of the deterioration of infrastructure objects is affected by various factors such as construction methods and materials, traffic loads, climates, symptoms of fatigue, etc. Interventions are performed periodically (preventive interventions, PI) or due to the necessity when the adequate level of service can no longer be provided (corrective interventions, CI). Critical levels are defined for all aspects of the road network objects to trigger CIs when required. These boundary values are physically measurable (e.g. the percentage of cracks on a bridge deck, the longitudinal unevenness of a pavement section or the depth of chloride infiltration in a concrete wall). With respect to infrastructure management the goal is to determinate the optimal intervention strategy (OIS) for a network. The OIS is referred to as the intervention strategy (IS) that offers maximum benefits to all involved stakeholders in a long term management. The determination of an OIS includes the evaluation of the most appropriate intervention type (IT) for every object (e.g. complete resurfacing or only performing patching and healing cracks), the time and duration of the interventions and the combination of interventions into one or more intervention packages (Adey, Lethanh, & Phillippe, 2012). Hence, the OIS defines where, when and how the interventions are performed in order to minimize all negative impacts incurring to all stakeholders.

As a user of the road network, interventions result usually in longer travel times, alternative routes or even traffic jams. Furthermore is the accident rate in work zones significantly higher, especially on highway work zones where the lanes are narrower than on the open highway (Bakaba et al., 2012). The costs resulting out of these irregularities have to be quantified in order to expand the optimization to all stakeholders.

As a road network manager – in the majority of cases federal road authorities – it is important to provide a safe, sustainable and well accessible infrastructure network. Traditionally, the major focus in road network optimization was set to resource allocation meaning time, material and manpower management during intervention works (Hajdin & Lindemann, 2007; Kallas, 1985). In recent years other topics have gained attention in research. One topic of interest led to the development of different approaches in scheduling methodologies to minimize traffic delays (Chang, Sawaya, & Ziliaskopoulos, 2001; Fwa, Cheu, & Muntasir, 1998; Wang, Cheu, & Fwa, 2002). Also the scheduling of interventions has emerged to a very important field of research: In 2004, (Ouyang & Madanat, 2004) presented a mathematical approach to minimize the life-cycle costs of highway pavement rehabilitation including an empirical model of the deterioration process; An algorithm to optimize worksites on highway networks while taking constraints such as a maximum work zone length and the maximum resources to be allocated into consideration was developed in 2006 by (Hajdin & Adey, 2006); (Hajdin & Lindemann, 2007) later expanded the algorithm including minimal distances between work zones and travel direction dependent costs. In order to provide a firm approach of estimating the costs, (Adey et al., 2010) proposed a basic methodology to evaluate the total benefits of road preservation interventions in Switzerland.

The authorities responsible to achieve an optimization while providing an adequately functioning road network are the connecting point between the models and methodologies shown above and the physical execution of the interventions. The providing of a sustainable and safe network, however, has to be achieved using limited resources such as the amount of money that can be spent over a certain time period. In addition political and legal regulations have to be complied with. Bearing in mind that in Switzerland the "Bundesamt für Strassen (ASTRA)" is in charge of the whole highway network, it can be seen that it is a huge task to find an OIS taking all stakeholders into account. The same problems occur on lower political levels, when cantonal road authorities have to optimize their road network intervention plans.

One of the biggest issues with the sheer size of the road networks that have to be dealt with by the authorities is collecting the necessary data for the optimization. The federal road network of Switzerland ranges over 1'799 km, the complete road network has an overall length of 51'638 km (BFS, 2012a). To simplify the collecting and editing process the condition of roads is categorized. The condition of every pavement segment, bridge or other engineered element can be expressed through a number. Several different rating techniques are in use (e.g. the National Bridge Inspection Standards). These condition states (CSs) are then used to define different intervention types (ITs) and their impact on the road network for every object. The data behind this categorization has to be collected periodically to ensure feasible intervention strategies (ISs) resulting from the optimization.

Another crucial issue is quantifying the impact of hardly measurable effects. Interventions on road network elements are often associated with changes in the traffic configuration (TC) and therefore have negative impacts on the users of the road network (e.g. loss of time for people travelling on the road sections under intervention). Expressing the loss of travel time in monetary terms has been an active field of research for decades and the results are still subject to considerable variations (Axhausen, König, Abay, Bates, & Bierlaire, 2006; de Jong, 2000; König, Axhausen, & Abay, 2004; Small, Noland, Chu, & Lewis, 1999). The same difficulty is observed within the determination of the impacts incurring to the public: Emissions (e.g. dust, carbon dioxide, noise, etc.) are indeed measurable but its impacts on the economy, the environment and the society are hard to quantify.

The request therefore is to find an overall optimal intervention plan that satisfies all constraints and results in the highest benefit or the lowest negative impacts, respectively, for the sum of all stakeholders. This intervention plan should guarantee an adequate level of service for the entire network as well as an optimal grouping of interventions, including when, how and where the interventions are being executed.

1.2 Objective

The objectives of this research are

- The development of an extended network optimization model that can be used to select the best worksites in a transportation network within a planning period. The model is a further extension work of (Hajdin & Adey, 2006).
- The estimation of major impacts incurring to all stakeholders.
- The implementation of the developed model on the road network of the Canton of Valais, Switzerland, taking the major impacts into consideration.
- The determination of the impacts on the results due to variations of the input parameters.

1.3 Scope of research

The theoretical model proposed by (Hajdin & Adey, 2006; Rafi, Hajdin, & Welte, 2004) is extended to allow the grouping of several interventions into multiple worksites. The concept of the model is conceptually and mathematically described and its applicability shown on an empirical example.

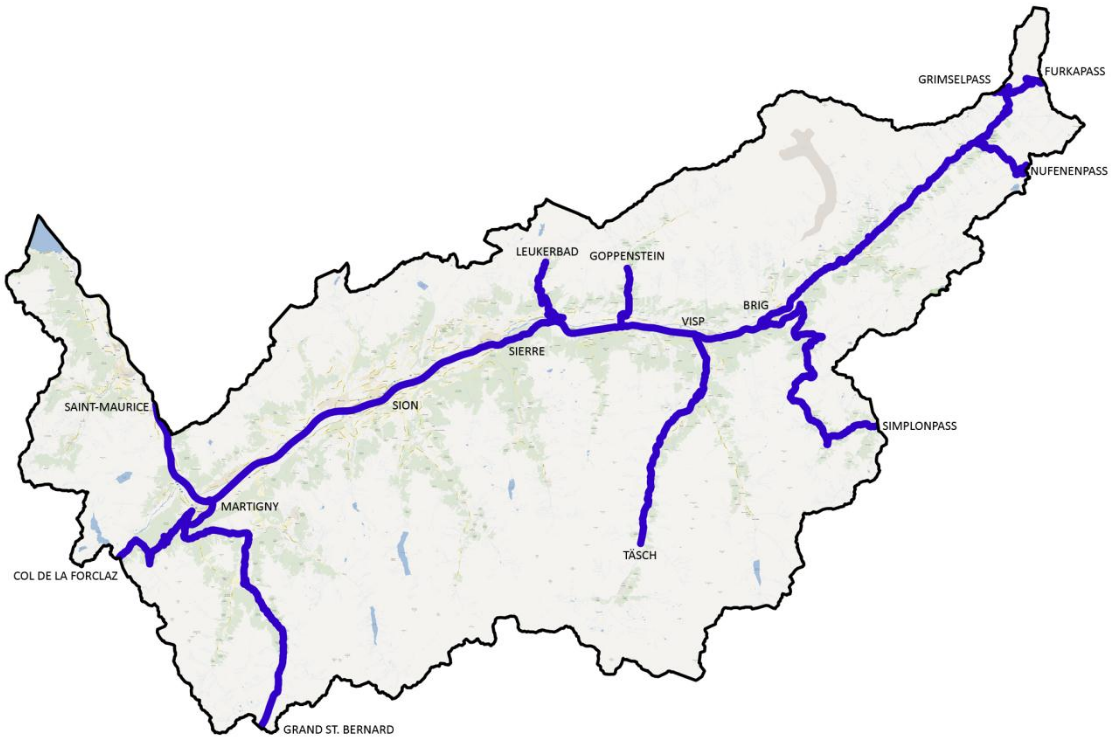


Figure 1: The considered road network

A part of the road network of the Canton of Valais, Switzerland, is selected to exemplary demonstrate the application of the theoretical model. The road network in the Canton of Valais is predestined for the purpose of applying this model since its main road links can be modeled as a simple combination of series and parallel links. The considered network (Figure 1) consists of highway and cantonal roads, going from Saint-Maurice near the Lake Geneva through the whole valley up to the Furka Pass. Compared to other existing networks in Switzerland – for example the highway network in the city of Zurich – the chosen network is relatively simple.

Another reason the network of Valais is selected is the diversity of geographical conditions. A lot of different road types can be found in the Canton of Valais, from the highway crossing the main valley to narrow, sinuous roads going up to villages located over 1000 meters higher. The region is subject to natural hazards (avalanches, floods, rock falls, etc.) and therefore the road network is more vulnerable in comparison to other networks. This fact allows including multiple different aspects of the theoretical model in only one real world application and simplifies further extension works based on the same example.

Geographically the considered network includes nine intersections connecting cantonal roads to the main link from Saint-Maurice to the Furka Pass. The roads to the six big passes (Grimsel, Furka, Nufenen, Simplon, Grand St. Bernard, Col de la Forclaz) connecting the Cantons Bern, Uri and Ticino as well as France and Italy to Valais are linked at these intersections. Furthermore, two villages (Zermatt, Leukerbad) and two car transport train stations (Goppenstein, Oberwald) are included in the network. The total length of the road network is 334.1 km.

1.4 Time schedule

The work spans from the end of September 2012 until the end of January 2013. The following table lists the main components of the work.

Table 1: Master plan

No.	Description	Time
1	Literature review	27.09.12 – 03.10.12
2	Model formulation	04.10.12 – 29.10.12
3	Graphical representation of the model and application to the road network of the Canton of Valais	04.10.12 – 29.10.12
4	Development of the optimization tool (Excel based)	30.10.12 – 09.12.12
5	Findings	10.12.12 – 21.12.12
6	Discussion and Conclusions	22.12.12 – 09.01.12

2 State of research and practice

2.1 Deterioration and intervention on infrastructure objects

Roads, houses, bridges, office buildings, water pipes, generally all built objects the society requires to function properly are a part of the whole infrastructure. Since physical deterioration can damage every object so it can no longer function at an adequate level of service, interventions have to be performed to bring the object back to an acceptable state. In order to optimize the planning of interventions it is important to understand the mechanisms behind the deterioration processes and the different preventive and corrective intervention methods. The following chapter gives a short insight into the deterioration processes and intervention methods of interest when it comes to road networks consisting of road sections, bridges and tunnels.

2.1.1 Deterioration processes

All objects of a road network such as the pavement, retaining walls, bridges, galleries and tunnels are constantly exposed to natural (temperature changes, moisture, frost, direct sunlight, etc.) and utilization-related influences (contact pressure, vibrations, salt, emissions, etc.). This ultimately leads to physical and chemical deterioration.

Both structural and reinforcement steel can corrode over time even if incorporated in concrete, especially when the steel is in contact with chlorides. The main sources of chlorides are usually emissions from cars and trucks using the road and salt used during winter months to prevent the formation of ice. If the concrete or asphalt structure is too porous or has too many cracks, water with dissolved chlorides contaminates the originally intact concrete. However, the deterioration on infrastructure objects is not limited to corrosion. The different natural and utilization-related influences can lead to:

- Cracks
- Longitudinal and transversal unevenness
- Corrosion of steel elements
- Settling
- Structural damages
- Loss of material
- Loss of skid resistance
- Loss of bearing capacity
- Etc.

The scale of these defects can reach from insignificantly small (e.g. a few small cracks in a parapet) without any major consequences to huge (e.g. corrosion of the reinforcement steel in the floor girder of a bridge). In the worst case these extensive defects can lead to structural failure.

A multiplicity of nondestructive and destructive inspection methods is available to determine the possible existence and progress of deterioration processes. Using these measuring and inspection techniques gives the owner an overview over the condition of the infrastructure objects. Based on the data collected during the inspections the person in charge is able to decide whether maintenance work is necessary or not to keep the object providing an adequate level of service.

2.1.2 Intervention types

Two different groups of interventions are defined in road infrastructure management: The preventive and the corrective interventions. Preventive interventions are performed on a routine basis to prevent an unnecessary acceleration of the deterioration rate. Corrective interventions are performed when the condition of the road reaches a certain threshold (Adey et al., 2010).

Table 2 gives an exemplary overview over different ITs for road surfaces defined by the VSS (ASTRA, 2008). The typology remains the same for all different objects (e.g. interventions performed on bridges or tunnels) with its subtypes, specifications and extents.

Table 2: Examples of intervention types

Object type	Subtype	Specification	Extent	Method	Damage characteristics
Road	Pavement	Bituminous pavement	Repairs	Cracks – repair	Cracks, open jointing
				Small area patching	Map cracks, pavement damage
				Large area patching	Map cracks, pavement damage
				Foundation trench patch repair	Damaged foundation trench patches
				Grouting of jointings	Damaged jointings
			Maintenance	Replacing covering layer without milling	Damaged structure and pavement, bearing capacity insufficient
				Replacing covering layer with milling	Damaged structure and pavement, pavement deformations
		Concrete pavement	Repairs	Repair of spallings	Spallings
				Surface improvement	Lacking of road grip, settlings

The damage characteristics are linked to the condition state (CS) the object is in. For different damages multiple different ITs can be possible, all having varying benefits and negative impacts.

2.1.3 Traffic configuration and management

Every intervention that is performed on a section of a road network results in a change in the TC. The characteristic of this change mainly depends on the magnitude of the works that have to be carried out: Small works performed on the side of the road lead to a small disturbance of the traffic flow, e.g. resulting from a slightly narrower lane. On the other hand, however, major interventions can include radical changes in the TC. The 4-0 system (Figure 2) – a common TC for interventions performed on highways, described in (BMVBS, 1995) – leads to narrower lanes, lower speed limits and remarkably higher accident rates (Bakaba et al., 2012).

Figure 2: 4-0 system (diePresse.com, 2010)

There always exist multiple possible traffic configurations (TCs) that allow performing a certain intervention on an object, but not all different options are equally suitable for a particular problem. Every TC has negative impacts on some or all groups of stakeholders. These differences and variations in the impacts incurred to stakeholders require managers to determine the optimal TC that has the most minimal impacts. In order to do so, the use of mathematical optimization models is necessary.

2.1.4 Worksites and intervention packages

If several sequenced objects are subject to interventions, these objects are grouped to one intervention package. Since on most roads the distance between two work zones has to be greater than a certain boundary value (given by design codes and laws), it can be necessary to include objects which are not subject to an intervention into a work zone. That is to say a work zone can include both objects being maintained and objects being left in their original condition. An example of such a grouping can be seen in Figure 3.

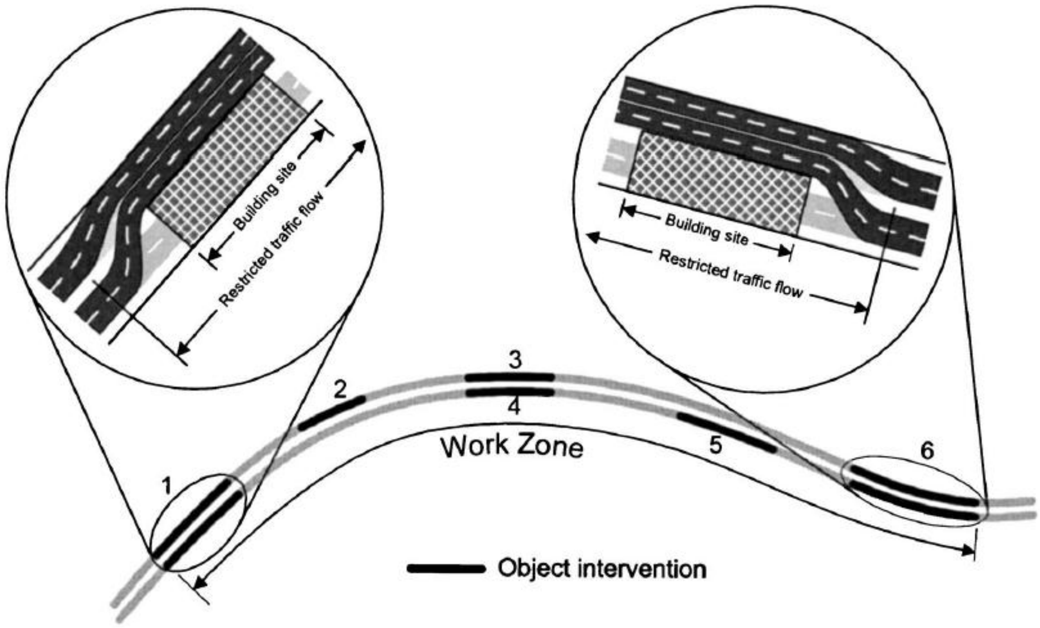


Figure 3: Work zone illustration (Hajdin & Lindemann, 2007)

A work zone (further on called worksite) is defined as the grouping of adjacent objects where, at least at the first and the last object, interventions are being performed and the TC is not the same as the default traffic management on that particular road.

2.1.5 Intervention strategy

An IS is a particular combination of the IT that is performed, the TC that is chosen and the object under intervention itself. For every object in a road network there exist several different ISs. The strategies can vary depending on the CS of the road, the daily traffic volume (DTV) and the different intervention possibilities (available techniques, materials, know-how, etc.) even for objects of the same type (e.g. 4-lane highway pavement section). There are always one or more optimal intervention strategies (OISs), representing the combination of TC and IT on a particular object with the highest benefit for all stakeholders. Each IS has multiple attributes affecting the optimization: The duration of the whole intervention to take place, higher accident rates due to narrower lanes and disturbance of the drivers, the cost of the works to be completed, the travel speed inside the worksite, loss of travel time due to traffic jams, etc. If the worksites are not considered to be independent (i.e. a short distance between two worksites), there are in addition external influences from the previous and following worksites to be taken into account (Hajdin & Lindemann, 2007).

2.2 Impacts of interventions

The CS of road network objects can have a significant impact on various properties of the object – for example on the accident rate or the travel speed. These effects can be expressed in monetary terms. Secondary effects, resulting from such an impact but not occurring on the object itself, can also be taken into consideration. A bridge with a weight restriction of 10 tons, for example, prohibits a heavier truck to pass. The truck is forced to take a detour, which leads to a longer travel time, higher CO_2 emissions and higher deterioration on the entire road network (due to the longer travel distance).

All impacts can directly be related to one or more of the stakeholder groups. From the view of the owner the impacts consist of the costs for the intervention itself and the resulting reduction of routine maintenance costs. The users are affected by a worksite through changing TCs leading to an increasing duration of travel as well as higher vehicle operation and accident costs. The better road condition, as a result of the interventions that have been performed, lowers the monetary equivalent of the utilization-related impacts (e.g. ride comfort, vehicle operation costs). Regarding the affected public (e.g. residents) an intervention primary results in higher emissions (noise, dust, carbon dioxide, etc.) during and lower emissions after an intervention is performed. Since a part of all accident costs is also carried by the public (loss of GDP), this impact is also taken into account considering the public stakeholders.

2.3 Determination of optimal intervention strategies for road links

Attempts to determine OISs for an individual object have been widely addressed in abundant literature. However, the approach of considering each object separately does not inevitably lead to an overall optimal solution when it comes to optimizing entire infrastructure networks. Furthermore, the possibility of the implementation of global constraints and dependencies between single objects is not given. A model that allows embedding all objects linked together to a network delivers a more accurate representation of the real world situation. With this type of model it is possible to group multiple objects in one or more intervention packages (i.e. worksites) and determine the OIS for the entire road network.

2.4 Determination of optimal highway work zones

The following methodological and mathematical approach is a work of (Rafi et al., 2004). The model is shortly explained, based on an illustrative example by (Hajdin & Adey, 2006) as an introduction to chapter 3.

2.4.1 Definition of network, nodes and links

A road network is selected where a single intervention is being performed in the next planning period. The goal of using the following algorithm is to determine if, when, where and how the intervention should be performed.

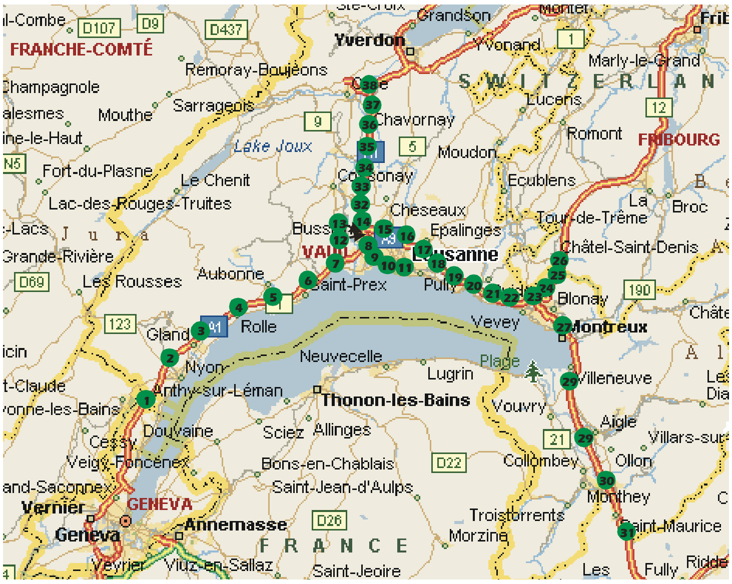


Figure 4: Example of a network (Hajdin & Adey, 2006)

The term network refers to a number of road links connected together. An example is shown in Figure 4 and represents part of the highway network in the Canton of Vaud, Switzerland. The network is divided into sections, where a section refers to the road segment between two nodes. In the example, 38 nodes divide the network into 37 road sections. The location of the nodes is selected to be at intersections, network limits as well as start and endpoints of interventions and changes in the TC. Road sections are grouped into links, where a link is defined as a part of the network comprised of all sections between an intersection and a network limit, two network limits or two intersections, that consists of a single path (Hajdin & Adey, 2006).

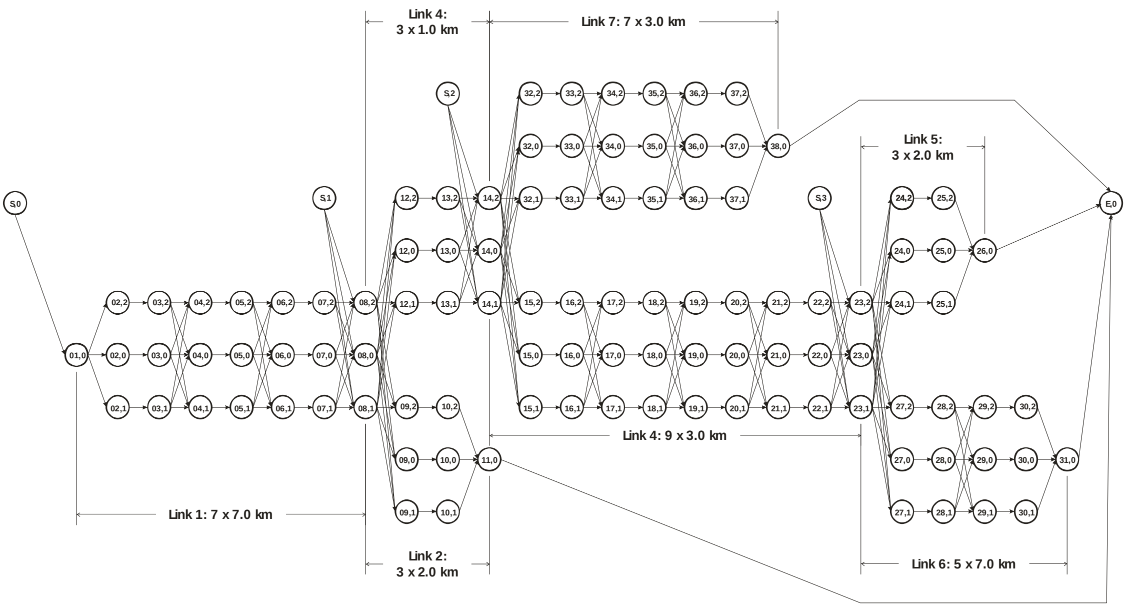


Figure 5: Artificial network (Hajdin & Adey, 2006)

With the network being divided into several road sections, it is possible to create the artificial network including all possible ISs. In the artificial network (Figure 5), these strategies are represented by an index after the number of the node, e.g. 01,1 refers to node 01, intervention strategy 1. The nodes in the artificial network are called vertices in order to avoid confusion with the physical nodes.

The arcs connecting the vertices represent the physical road sections. If the arc going from vertex $[i,1]$ to vertex $[j,1]$ belongs to the path that maximizes the total benefit, means that IS 1 is being performed on the object between node i and j in the next planning period.

The artificial network representing the physical network (Figure 4) is shown in Figure 5. The characteristics of the road network are given in Table 3.

Table 3: Characteristics of the road network (Hajdin & Adey, 2006)

Link	Start node	End node	Length [km]	Number of nodes	Road sections where interventions possible
1	1	8	49	8	2 – 3, 4 – 5, 6 – 7
2	8	11	6	4	9 – 10
3	8	14	3	4	12 – 13
4	14	23	27	10	15 – 16, 17 – 18, 19 – 20, 21 – 22
5	23	26	6	4	24 – 25
6	23	31	35	6	27 – 28, 29 – 30
7	14	38	21	8	32 – 33, 34 – 35, 36 – 37

2.4.2 The mathematical model

2.4.2.1 Objective function

In order to find the optimal solution, the objective function maximizes the total benefit, which is calculated as the subtraction of the total net benefit and the accumulating costs. Two stakeholder groups are considered in this particular model, the owner (here referred to as the agency) and the users. For both stakeholder groups the negative impacts are considered (i.e. the costs accumulating due to the intervention being carried out). The net agency benefit is considered as the positive impact. This term refers to the difference between the most expensive and the OIS, i.e. the monetary savings from choosing a particular IS.

$$\max Z = \sum_{([i,k];[j,l])\in A} y_{[i,k];[j,l]} \cdot \left(\overline{N}_{[i,k];[j,l]} - C_{[i,k];[j,l]} \right) \tag{1}$$

$$\mathrm{C}_{[i,k];[j,l]} = V^{i}_{[i,k];[j,l]} + V^{l}_{[i,k];[j,l]} + U^{i}_{[i,k];[j,l]} + U^{l}_{[i,k];[j,l]} \tag{2}$$

Where,

$y_{[i,k];[j,l]}$: Binary variable representing the object going from vertex i with IS k to vertex j with IS l. The variable takes the value 1 if the arc $[i,k];[j,l]$ belongs to the path that maximizes Z, otherwise it takes the value 0.

$\overline{N}_{[i,k];[j,l]}$: Net benefit

$C_{[i,k];[j,l]}$: Total costs accumulating from performing the intervention

$V^{i}_{[i,k];[j,l]}$: Initial agency costs

$V^{l}_{[i,k];[j,l]}$: Subsequent agency costs

$U^{i}_{[i,k];[j,l]}$: Initial user costs

$U^{l}_{[i,k];[j,l]}$: Subsequent user costs

2.4.2.2 Constraints

There are three constraints considered in this model:

- The continuity constraint:
  This constraint is required to ensure that exactly one vertex per physical node is selected in the solution of the optimization procedure.
- The budget constraint:
  The total amount of (usually monetary) resources that can be allocated during one intervention period is limited. The total amount spent on interventions has to be smaller than the limiting value.
- The maximum worksite length constraint:
  In real world problems it is not defensible to plan arbitrarily long worksites. The length of such worksites is therefore restricted to a certain maximum length that has to be complied with.

The mathematical formulations are dispensed with, they can be found in (Hajdin & Adey, 2006; Rafi et al., 2004).

3 The extended model

3.1 Description and definition of the network and nodes

3.1.1 Composition of a road network

A complete transportation infrastructure network consists of several road links (from now on referred to as road network segments and segments, respectively, to avoid confusion with the links in the artificial network). Each of these segments itself is a combination of different infrastructure objects, e.g. bridges, tunnels, pavement sections, etc. There are specific ITs for each object due to the considerable differences in building materials and techniques, deterioration processes and intervention possibilities. For all ITs exist multiple options how to deal with the traffic restraints (e.g. closing one or two lanes at the same time).

Figure 6 shows the separation of a transportation infrastructure network into segments, objects, ITs and TCs graphically. The numbering variables are explained in Table 4.

Table 4: Definitions of indices

Road network segments	Infrastructure objects	Intervention types	Traffic configurations
$l = 1,...,L$	$n_l = 1,...,N_l$	$k_{l,n} = 1,....,K_{l,n}$	$t_{l,n} = 1,...,T_{l,n}$
L: Total number of segments in the network	N_l: Total number of infrastructure objects in segment l	$K_{l,n}$: Total number of ITs on infrastructure object n in segment l	$T_{l,n}$: Total number of TCs on object n in segment l
		$k_{l,n} = 1$ refers to "no intervention"	$t_{l,n} = 1$ refers to the default TC

3.1.2 Node and connection attributes

In the model of (Hajdin & Adey, 2006) (hereafter referred to as the reference model) the nodes in the artificial network correspond to the nodes in the physical network, the arrows refer to the actual objects. In the extended model the definition of nodes and links (arrows) is redefined: The nodes in the artificial network represent the objects in the physical network; the links (represented by the arrows between the nodes) connect all different objects together. Connecting points define the points where the network is connected to another network. Connecting points are therefore objects with an infinitesimal length where vehicles enter and leave the system. Every object and every connection has attributes (Figure 7). The attributes are explained in Table 5.

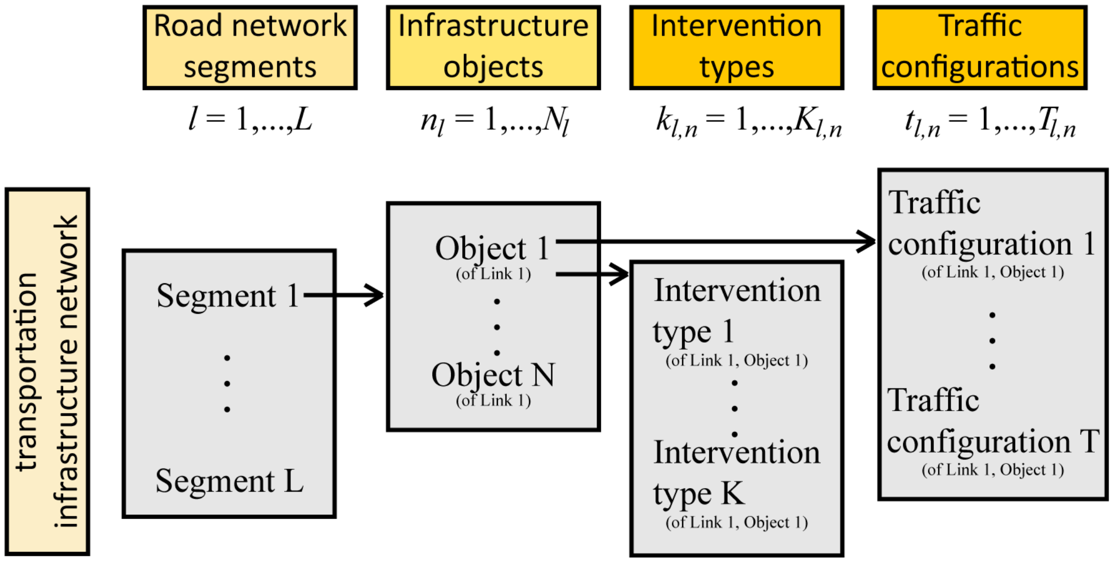


Figure 6: Conceptual definition of the road network

The links connecting all objects do not have a physical length but nevertheless can have impacts on one or more stakeholder groups. Especially the change from one TC to another one can have a significant impact (e.g. higher accident rates). The change from one TC to another is assumed not to be affected by the length of one or both of the objects. The impacts can therefore be calculated using standardized lengths (e.g. 500 meters for the transition zone for changing from the default TC to a 4-0 system). The physical length of these transition zones is usually much smaller than the actual length of the previous or following intervention zone; a major change of the impacts occurring in the adjacent intervention zones is assumed to be negligible.

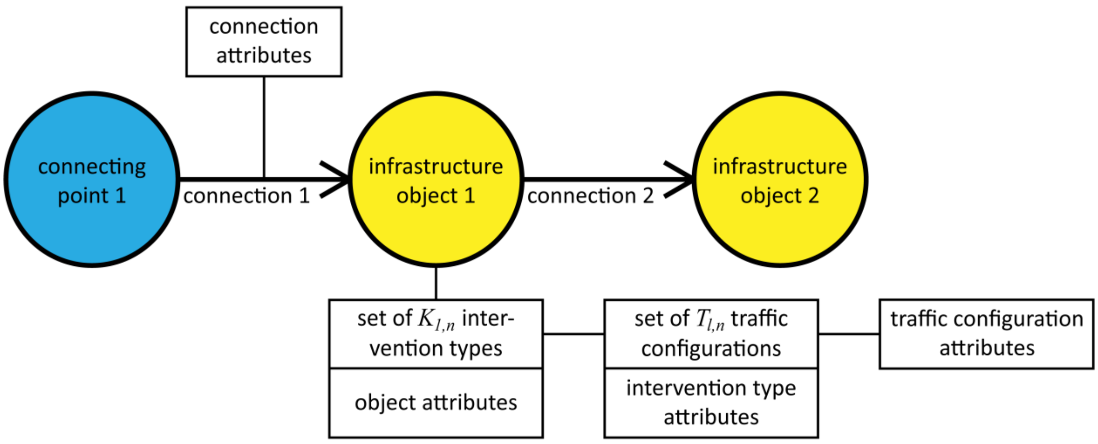


Figure 7: Conceptual definition of the artificial network

Table 5: Attribute types

	Type	Examples
nodes	Object attributes	Object length, number of lanes, DTV, type of infrastructure (e.g. tunnel, bridge, etc.), CS
	Intervention type attributes	Costs (e.g. CHF/m^2), improvement in CS (e.g. from CS 4 to CS 1), production capacity (e.g. m^2/day)
	Traffic configuration attributes	Travel speed, change in accident rate, work space per meter of road (as a result of closing one or more lanes)
links	Connection attributes	Specific attributes that result from a change in TC, e.g. costs for traffic jam at the beginning of a worksite, higher accident rates resulting from the change of the TC

3.1.3 Stakeholders and impacts

The extended model features several differences from the reference model of (Hajdin & Adey, 2006). While the reference model only takes the users and the agencies (in the new model equal to the owners) into consideration, the extended model is equipped with four different groups of stakeholders (Table 6). The four groups of stakeholders are considered as the main interest groups (Adey et al., 2012). For each of the stakeholders there are impacts that have to be monetary quantified. Impacts generating costs are represented through negative values, benefits and cost reductions through positive values. The notation of the impacts for all stakeholders can be seen in Table 7 and corresponds to the notation used in (Adey et al., 2012). The denotation with the arrow in top refers to the impacts related to the connection between two objects a and b $\left(a, b \in N_l\right)$, the denotation without an arrow refers to the impacts occurring on a specific object.

Table 6: Stakeholder groups

Stakeholder group	Definition	Example
Owner	The institution that is responsible for decisions with respect to physically modifying the infrastructure	A federal road authority
Users	The people who are using the infrastructure	Drivers and passengers of vehicles on the road
Directly affected public (DAP)	The people living in the vicinity of the road but who are not using it	People living in a house next to the road, directly affected by emissions (e.g. noise and dust)
Indirectly affected public (IAP)	The people not living in the vicinity of the road, but who are affected by the use of it	People far away from the actual road network, but affected by global consequences such as global warming

Table 7: Impacts

Stakeholder group	Notation of impacts
Owner	$C_{l,n,k,t}$, $\vec{C}_{a-b}$
Users	$U_{l,n,k,t}$, $\vec{U}_{a-b}$
Directly affected public (DAP)	$D_{l,n,k,t}$, $\vec{D}_{a-b}$
Indirectly affected public (IAP)	$I_{l,n,k,t}$, $\vec{I}_{a-b}$

The impacts incurring to the owner include benefits and detriments accumulating due to the use of the road (e.g. road charges paid by the users or taxes paid by the owner) as well as irregular and periodical intervention costs and the benefit from performing an intervention. The resulting impacts for people using the road network are summed up under users. These impacts include the multiple consequences of the regular use (e.g. costs accumulating for vehicle maintenance and fuel) as well as the additional effects of intervention works being performed (e.g. loss of travel time or higher accident rates). The DAP is usually affected by side effects of road usage such as noise emissions, smog or a locally higher amount of particulate matter. These effects have to be measured, adequately valued and made comparable, requiring an evaluation of the monetary equivalent of the impacts coming from the road network.

When it comes to the costs for the IAP the quantification in general turns out to be more complicated than for the other three groups of stakeholders. All effects such as climate change due to car emissions on the specific road network, loss of GDP as a result of accidents, etc. have to be quantified and expressed through monetary values. These values are typically based on several estimations and are subject to strong variations since both the direct and indirect consequences are difficult to measure (Tol, 2000).

3.2 The extended optimization model

3.2.1 Objective function

The objective function maximizes the sum of all positive and negative impacts for all stakeholders:

$$\max Z = \sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{t=1}^{T}\left\{\delta_{l,n,k,t}\cdot\left(C_{l,n,k,t}+U_{l,n,k,t}+D_{l,n,k,t}+I_{l,n,k,t}\right)\right.$$
$$\left.+\sum_{e=1}^{E}\varphi_{l,n,k,t-e}\cdot\left(\vec{C}_{l,n,k,t-e}+\vec{U}_{l,n,k,t-e}+\vec{D}_{l,n,k,t-e}+\vec{I}_{l,n,k,t-e}\right)\right\} \quad (3)$$

where $\delta_{l,n,k,t} \in \{0,1\}$ is a binary variable that represents the object n in segment l, undergoing IT k in TC t. If $\delta_{l,n,k,t} = 1$, it is this particular combination getting carried out, if $\delta_{l,n,k,t} = 0$, it is the particular combination not being chosen. $\varphi_{l,n,k,t-e} \in \{0,1\}$ is the binary variable representing the link going from node $[l,n,k,t]$ to all following nodes with a physical connection, where $e = 1,...,E$ is the number of the link and E equals the total amount of links going from node $[l,n,k,t]$.

$\vec{C}_{l,n,k,t-e}$, $\vec{U}_{l,n,k,t-e}$, $\vec{D}_{l,n,k,t-e}$, $\vec{I}_{l,n,k,t-e}$ are the impacts incurring to the stakeholders on the link between node $[l,n,k,t]$ and e (e.g. due to a change in the TC).

3.2.2 Constraints

3.2.2.1 *Continuity constraint*

It is only possible to do one IT k in one TC t per object n in the considered planning period.

$$\sum_{k=1}^{K}\sum_{t=1}^{T}\delta_{l,n,k,t} = 1 \; \forall l, \mathrm{n} \tag{4}$$

The variable representing the links between the nodes is the product of the variable of its start and ending nodes:

$$\varphi_{l,n,k,t-e} = \delta_{l,n,k,t} \cdot \delta_{e} \tag{5}$$

3.2.2.2 *Budget constraint*

The amount of money spent on interventions is less or equal to the maximum budget B. The maximum budget can be allocated to the entire network or specifically to every road link l.

$$\sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{t=1}^{T}\left\{\delta_{l,n,k,t} \cdot \left|P_{l,n,k,t}\right| + \sum_{e=1}^{E}\varphi_{l,n,k,t-e} \cdot \left|\vec{P}_{l,n,k,t-e}\right|\right\} \leq B \tag{6}$$

where $P_{l,n,k,t} \in C_{l,n,k,t}$ and $\vec{P}_{l,n,k,t-e} \in \vec{C}_{l,n,k,t-e}$ represent the costs for the intervention being carried out on infrastructure object n in road network segment l and on the link to the adjacent object e, respectively.

3.2.2.3 Maximum worksite length constraint (MWL constraint)

The maximum worksite length is restricted to a network and/or road type specific value Λ^{MAX}. Every network has a number of worksites $w = 1,...,W$. A worksite is defined as all objects physically connected to each other without being in the default TC $t \neq 1$. For all worksites w applies:

$$\sum_{l=a_l^w}^{e_l^w} \sum_{n=a_n^w}^{e_n^w} \lambda_{l,n} \leq \Lambda^{MAX} \quad \forall w \tag{7}$$

Where $\lambda_{l,n}$ represents the length of object $[l,n]$; object a^w $\left(l = a_l^w, n = a_n^w\right)$ is the first object of the worksite w and object e^w $\left(l = e_l^w, n = e_n^w\right)$ is the last object in the worksite w.

3.2.2.4 Minimum distance between work zones constraint (MDBW constraint)

The minimum distance between two worksites has to be greater or equal to a network and/or road type specific value Λ^{MIN}.

Every network has a number default sections $d = 1,...,D$. A default section is defined as all objects physically connected to each other with being in the default TC $t = 1$. For all default sections d applies:

$$\sum_{l=a_l^d}^{e_l^d} \sum_{n=a_n^d}^{e_n^d} \lambda_{l,n} \geq \Lambda^{MIN} \quad \forall d \tag{8}$$

Where object a^d $\left(l = a_l^d, n = a_n^d\right)$ is the first object of the default section d and object e^d $\left(l = e_l^d, n = e_n^d\right)$ is the last object in the default section d.

3.3 Illustrative example

Figure 8 shows exemplarily both a physical network and its artificial representation. The network consists of two objects. Two ISs are given for both objects: Either nothing is done, or an intervention in a particular TC is performed. The nodes and arrows in black represent parts of the ISs that are not associated with impacts, where the red arrows and nodes are linked to both positive and negative impacts (benefits and costs, respectively).

There exist four possible solutions for this particular example: Both objects are subject to an intervention, either one of them is and the other is not, or both objects are left in their current condition. With the blue arrows and nodes representing the OIS for this network, the OIS can be described as a change in the TC at the beginning and the end of object 1, object 1 being subject to an intervention and object 2 being left in its current condition without a change in the TC.

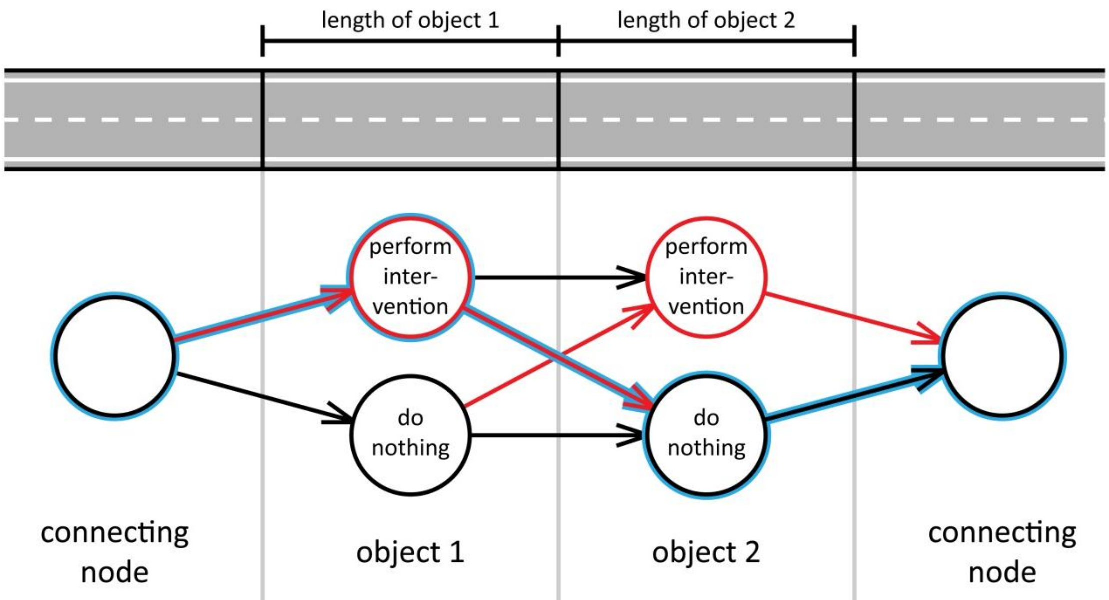


Figure 8: Illustrative example (physical and artificial network)

4 Empirical example: Road network of Valais

4.1 General assumptions and simplifications

A few assumptions are made in order to simplify the model:

- Costs (negative impacts) are represented with negative values; benefits (positive impacts) are represented using positive values.
- The change in the TC is instantly between two objects and there are no impacts connected to it.
- The ITs are only depending on the objects attributes (CS, road type).
- For every object, there are five ISs to be considered (Table 8). The different ISs are explained in Chapter 4.3.1.

Table 8: Intervention strategies

Intervention strategies	Physical changes	TC to be considered	
IS_0	No	TC_0	No intervention, default TC
$IS_{1.1}$	Yes	TC_1	Object specific intervention in TC_1
$IS_{1.2}$	No	TC_1	No intervention, but in TC_1
$IS_{2.1}$	Yes	TC_2	Object specific intervention in TC_2
$IS_{2.2}$	No	TC_2	No intervention, but in TC_2

- The MWL constraint and the MDBW constraint are only considered for vehicles entering the network at connecting node 1 and going to all other connecting nodes.
- The MWL constraint and the MDBW constraint are set equally for the complete network, omitting the fact that the road type has an impact on these regulations.

4.2 The physical network

The physical network (Figure 1, Annex A.1) represents the road system in the Canton of Valais, Switzerland, consisting of highways and cantonal roads. As start and ending points, respectively, the main road links to the cantonal border are considered. Two bigger touristic villages, Zermatt and Leukerbad, are introduced as well as ending nodes. In between these ending nodes, the roads are divided into several links, each representing a section which can be considered as one intervention object. These objects have four attributes:

- Each object is a plain road, a bridge or a tunnel.
- The road type is "highway", "cantonal road", "regular road" or "mountain road", depending on the legal declaration and the topography.
- The number of lanes (e.g. 4 lanes and 2 emergency lanes)

- The CS the object is currently in

On this basis, the physical network is divided into 160 objects. Each object meets a few constraints: The length must not exceed 10 km; the average object length on a regular road should not exceed 3 km. Large bridges and tunnels are considered as one object, small bridges and tunnels can be grouped with road sections to one object. All intersections are defined as nodes and therefore are never included in an object.

4.3 The artificial network

4.3.1 Problem specific definition of nodes and arrows

In this example the ITs are only depending on the CS the object is currently in and the type of the object (plain road, tunnel or bridge). Since the CS is assumed not to change during the optimization procedure there is only one IT per object possible. Independent of the CS – and therefore of the IT – there are three TCs possible per object (exception: object 21 has only two different TCs). TC_0 always refers to the default TC where no intervention is performed. TC_1 and TC_2 refer to the two different TCs possible and are only depending on the road type of the considered object.

IS_0, $IS_{1.1}$, $IS_{1.2}$, $IS_{2.1}$ and $IS_{2.2}$ correspond to the five different ISs:

- IS_0 is the "do nothing" option with the default traffic configuration TC_0
- $IS_{1.1}$ refers to performing the object specific IT in traffic configuration TC_1.
- $IS_{2.1}$ is similar to $IS_{1.1}$; however, traffic configuration TC_2 is applied.
- $IS_{1.2}$ refers to the "do nothing" option, but in traffic configuration TC_1.
- $IS_{2.2}$ is similar to $IS_{1.2}$; however, traffic configuration TC_2 is applied.

It is to note that $IS_{1.1}$ and $IS_{1.2}$ as well as $IS_{2.1}$ and $IS_{2.2}$ are mutually exclusive, only the ISs with the lower total impacts (or higher benefits, respectively) can be chosen. This means for one optimization procedure the set of possible ISs consists of IS_0, $IS_{1.1}$ or $IS_{1.2}$ and $IS_{2.1}$ or $IS_{2.2}$. To simplify matters, the three possible ISs are further on referred to as IS_0, IS_1 and IS_2.

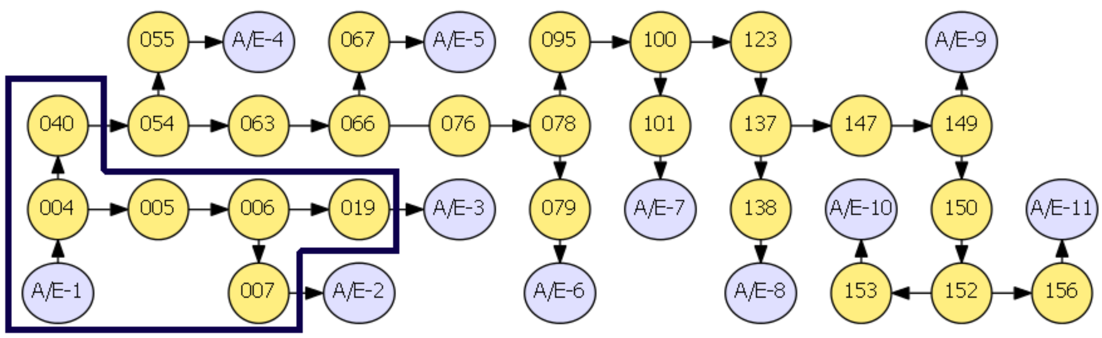


Figure 9: Simplified complete artificial network

4.3.2 Graphical representation

Due to the repetitive structure of the artificial network only a simplification is shown in the report. The complete artificial network model can be seen in Annex A.2. Figure 9 shows the simplified network with its intersection objects (yellow) and its connecting nodes (light blue). The enveloping blue border indicates the part of the network that is used to explain the simplification. Figure 10 shows the connecting nodes, the intersection objects and the linking objects (green).

The different ISs are represented by splitting the artificial nodes into multiple nodes (Figure 11), indicated by a point and a number at the end of its name. The denotation .0 refers to the default intervention strategy IS_0 ("no intervention"), so the object is not subject to an intervention or a change in TC. The denotations .1 and .2 refer to the object specific intervention strategies IS_1 and IS_2, respectively.

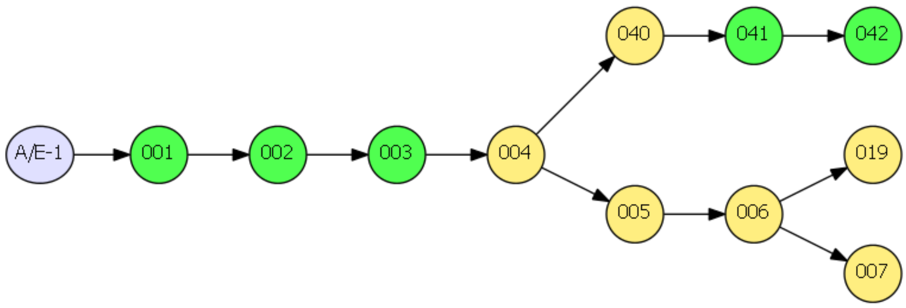


Figure 10: Simplified object structure

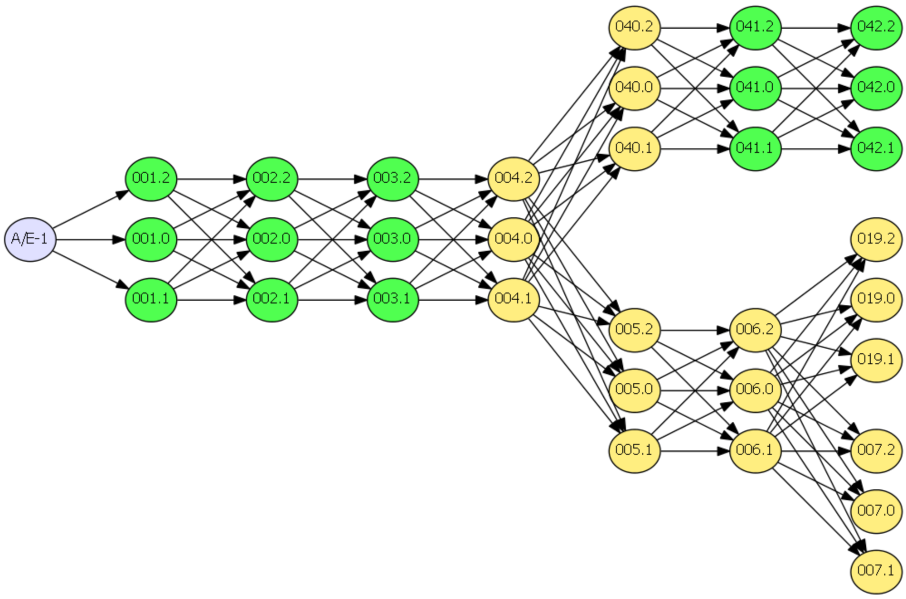


Figure 11: Concept of artificial network

4.4 Road types

The roads are divided into four groups according to the number of lanes, the speed limit and the topography. The reason for this differentiation is the composition of different TCs depending on the number of lanes and the road type. Since – especially on the narrow, sinuous mountain roads – the mean travel speed can be considerably lower than the actual speed limit, the travel time on roads is calculated using an assumed mean travel speed.

The different road types and their specifications are shown in Table 9.

Table 9: Road type specifications

Road type	Specifications
Highway	Regular highway roads have four lanes and two emergency lanes, the speed limit is 120 km/h. Highway tunnels have four lanes but no emergency lanes. The speed limit in the tunnels is therefore typically lower, 100 or 80 km/h. All vehicles are assumed to travel with the same speed, regardless of the fact that trucks have a lower speed limit on highways in Switzerland.
Cantonal road	In the context of this work the term cantonal road doesn't correspond to the legal declaration of a cantonal road. Wide roads without tight curves are referred to as cantonal roads in order to separate them from the narrower, sinuous roads. The cantonal roads don't have a significant ascending slope. The speed limit is 50 km/h when passing villages and 60 to 80 km/h on the open road.
Regular road	Regular roads are defined as not to highly frequented roads, but still not as narrow and sinuous as the mountain roads. The ascending slope can be higher than for cantonal roads. Speed limits lie in-between 50 and 80 km/h
Mountain road	The narrow, sinuous roads climbing the passes are referred to as mountain roads. The travel speed does often not directly correlate with the speed limit; the speed limit is usually considerably higher than the mean travel speed.

4.5 Traffic configurations

In order to provide the necessary free space to perform an intervention on a road that should still be kept open for traffic, different options of leading the traffic have to be worked out. The possibilities are restricted by a number of constraints such as the width of the road, the hourly traffic volume that has to be able to pass the worksite, the maximum lowering of the speed limits, enough safety area between traffic and workers, etc.

In this example, 9 different TCs (excluding the default TCs) are selected. A categorization is done using the object and road type, where each category has one or two TCs (Table 10). The TCs with their specifications are explained in Table 11.

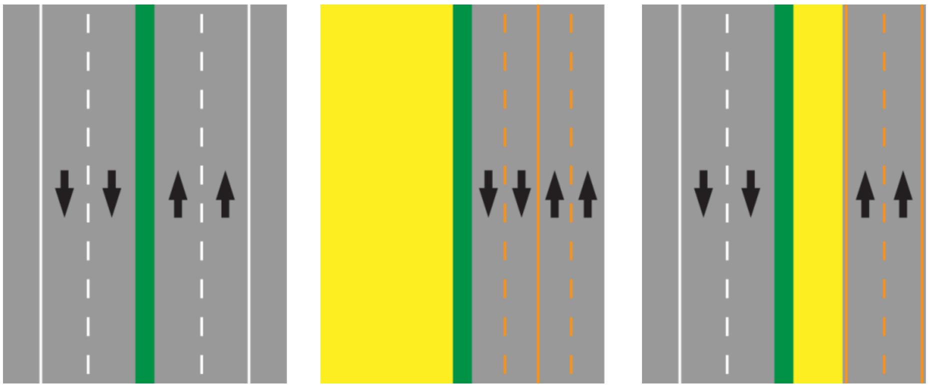
Table 10: Traffic configurations

Road/object type	Number of lanes	TC_1	TC_2
Highway	4 + 2 emergency lanes	4-0	H2-N2
Highway/cantonal road, highway bridges and tunnels	4	2-0	H2-N1
Cantonal road	3 or 2 + 1 emergency lane	1-1	N1-N1
Cantonal road	2 + 2 emergency lanes	2-0	-
Regular road, cantonal road; excluding two lane bridges and tunnels	2	1-0	N2
Two lane bridges and tunnels, mountain roads	2	1-0	NW

Table 11: Traffic configuration types and specifications

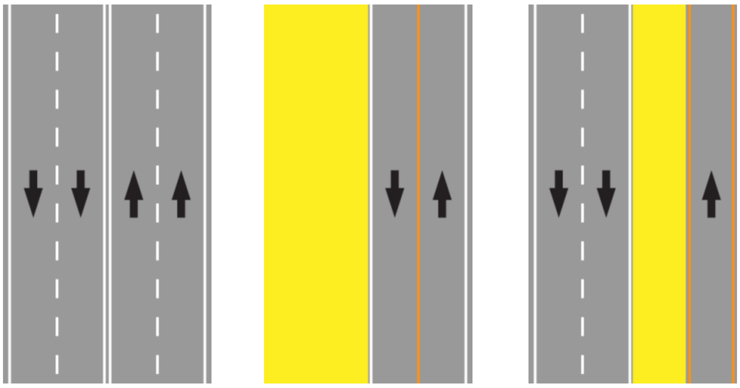
TC	Figures	Specifications
4-0	Figure 12b	All three lanes of one direction are completely closed. One side is free of traffic which allows performing all interventions nearly undisturbed. The open side with its originally one emergency and two regular lanes is regrouped to four narrower lanes, two in each direction. Due to the missing emergency lanes and the smaller lane width the speed limit is reduced from 120 km/h to 80 km/h.
H2-N2	Figure 12c	One lane at the time is closed on one side of the highway while the other side remains completely open. Within three steps the intervention for one travel direction can be completed. One third of the road is closed for work zones, two narrower lanes with lower speed limits (80 km/h) are used for traffic. Only one travel direction of the highway is affected but six instead of two steps are necessary to complete an intervention on the whole object.
2-0	Figure 13b, Figure 16b	One side of the road is closed for intervention while on the other side two lanes – one in each travel direction – are being operated.
H2-N1	Figure 13c	This TC requires four steps to complete an intervention on the whole road. Two lanes in one travel direction remain untouched, in the other travel direction one lane is closed and the other remains open, but is slightly narrower than in regular operation.
1-1	Figure 14b	Two lanes – one in both travel directions – remain open; the third lane provides the required space for the intervention.
N1-N1	Figure 14c	Half of the road is closed. On one half the intervention takes place, on the other half two narrow lanes are installed. The speed limit is significantly lower than in the "1-1" setup due to the narrower lanes.
1-0	Figure 15b, Figure 17b	One lane remains open for the traffic in both travel directions; a traffic light system regulates the traffic flow.
N2	Figure 17c	A third of the road is closed for intervention, two narrow lanes are installed on the remaining two third of the road.
NW	Figure 15c	The whole intervention only takes place during the nighttime, during the day the road is completely open to the traffic. The works have to be divided in a way, that during daytime cars and trucks are still able to cross the intervention zone.

Figure 12 to Figure 17 show the actual execution of each TC referred to in Table 11. The arrows indicate the direction of traffic; the white and orange lines show the original and TC specific layout of the road, respectively. The yellow area is the traffic-free space required to perform the intervention.



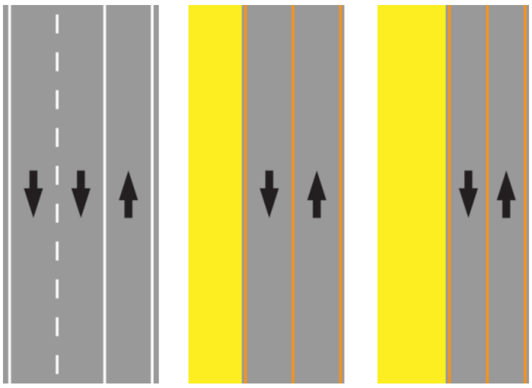
a) TC_0 **b) 4-0** **c) H2-N2**

Figure 12: TCs on highways (4+2)



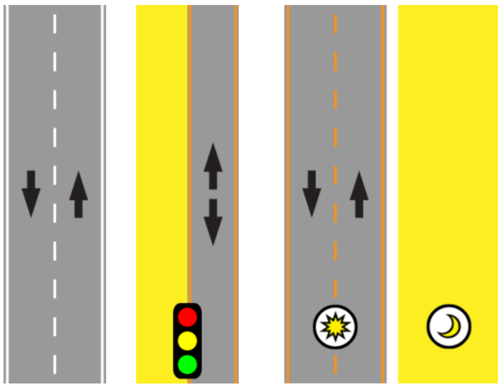
a) TC_0 **b) 2-0** **c) H2-N1**

Figure 13: TCs on 4 lane roads



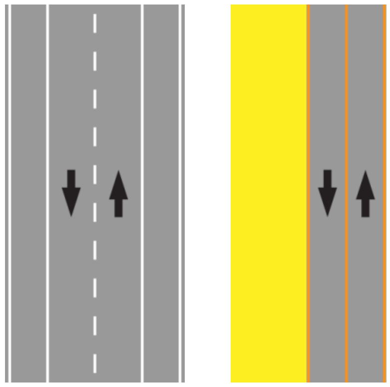
a) TC_0 **b) 1-1** **c) N1-N1**

Figure 14: TCs on 3 lane roads



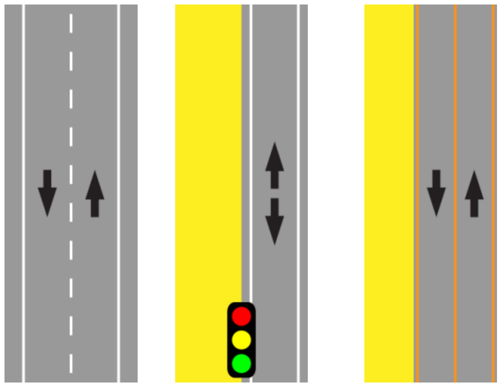
a) TC_0 **b) 1-0** **c) NW**

Figure 15: TCs for mountain roads



a) TC_0 b) 2-0

Figure 16: TCs for 2+2 road



a) TC_0 b) 1-0 c) N2

Figure 17: TCs for regular 2 lane roads

4.6 Condition states

In Switzerland, the condition of pavement is assessed using an indexing-system based on the standards SN 640 925b (*"Erhaltungsmanagement der Fahrbahnen (EMF), Anleitung zur visuellen Zustandserhebung und Indexbewertung mit dem Schadenkatalog"*) and SN 640 926 (*"Erhaltungsmanagment der Fahrbahnen (EMF), Visuelle Zustandserhebung: Einzelindizes"*). Five indices (I_1: Surface damages, I_2: Longitudinal evenness, I_3: Lateral evenness, I_4: Adhesion, I_5: Bearing capacity) are used to measure and describe the CS of a certain pavement section. The index I_1 is divided into sub-indices, five if the pavement is made of bitumen, six if it is made of concrete.

The condition assessment for tunnels and bridges is organized in a similar but far more intricate way. Since these objects are more complex than a plain pavement section a lot more different indices and measuring techniques have to be applied to have a clear and significant statement on the condition of the object. To simplify matters in this work, five indices are used to describe the CS of the objects, regardless of the type of the object. The different indices and their explanations are given in Table 12.

Objects that are in condition state CS_1 and CS_2 are assumed to provide an adequate level of service. There is no need to perform an intervention on these objects. There is, however, the possibility of changing the TC on these objects. This can be necessary to carry out interventions on both adjacent objects without violating the MDBW constraint.

Interventions can be performed on all objects that are in condition state CS_3, CS_4 and CS_5. The object type and CS specific ITs are explained in the following chapter.

Table 12: Condition state indices

Index	Meaning	Level of service
CS_1	The object is in an excellent condition.	Adequate
CS_2	The object is in a good condition.	
CS_3	The object is in an acceptable condition, but maintenance works have to be considered.	Barely adequate
CS_4	The object is in a bad condition, maintenance works are required.	Inadequate
CS_5	The object is in an unacceptable condition, extensive maintenance works are necessary.	

4.7 Intervention types

For all objects that are in a CS lower than CS_2 (i.e. CS_3 to CS_5) there are ITs defined which vary depending on the object type and the CS the object is currently in. All ITs are assumed to restore the original condition of the object, i.e. condition state CS_1.

On plain road sections multiple types of pavement works are considered as possible interventions. For an approximate estimation of the costs and possible working progress, a report published by the "Bundesamt für Strassen" is used (ASTRA, 2008). The report features collected costs and production capacities for different pavement works on bitumen and concrete roads. The specific ITs for plain road sections chosen in this example are given in Table 13, the costs and production capacities are listed in Table 14.

For bridges and tunnels more extensive maintenance works are scheduled. Since a similar report for the estimation of intervention costs on bridges and tunnels is not yet published, rough estimations without precise definitions of what works have to be performed are used in this example. The sheer complexity and diversity of maintenance works on bridges and tunnels would make a profound research necessary to estimate the costs related to the condition of the particular objects. The values in this example are based on rough assumptions provided by members of the institute of construction and infrastructure management (IBI) and the institute for geotechnical engineering (IGT) at the ETH, Zurich. The values are listed in Table 15.

Table 13: Road section intervention types

CS	Intervention type	Abbr.
CS_3	Facing improvement of rough pavement	FI
CS_4	Resurfacing on top of existing subgrade with milling (100 mm)	RT
CS_5	Complete renewal of the surface, binder and base course (200 mm)	CR

Table 14: Road section intervention types – costs and production capacities

Intervention type	Fix costs	Variable costs	Additions: Under traffic	Production capacity
	CHF	CHF/m^2	%	m^2/day
FI	3’500.00	8.00	20	3’000
RT	4’100.00	52.00	20	6’000
CR	9’600.00	108.80	20	1’000

Table 15: Bridge and tunnel intervention costs

Object type	CS	Fix Costs	Variable Costs
Bridge		CHF	CHF/m^2
	CS_3	20’000	2’100
	CS_4	30’000	2’800
	CS_5	40’000	3’500
Tunnel		CHF	CHF/m’
	CS_3	100’000	20’000
	CS_4	150’000	35’000
	CS_5	200’000	50’000

4.8 Intervention strategies

With the consideration of the MDBW constraint a special characteristic has to be included into the optimization procedure. The situation can occur that the optimal solution includes an object that is not in the default TC but no intervention is performed. If, for example, an object is not considered to be part of an intervention but both adjacent objects are being intervened with high benefits, this would violate the MDBW constraint. The change in TC without performing an intervention is afflicted with negative impacts. However, if these negative impacts are smaller than the difference between the positive impacts from performing interventions on only one and both adjacent objects, this solution could be part of the OIS.

Two different ISs are defined for every object. Each IS is object specific and consists of a certain TC and IT. The IT can be “none” ($k \geq 1$), whereas the TC cannot be “default” ($t > 1$). Every IS results in multiple negative and positive impacts. The denotation of the impacts is given in chapter 3.1.3, the different ISs are object specific and referred to as IS_1 and IS_2, respectively.

4.9 Costs

4.9.1 Vehicle Costs

In 2011 the mean fuel consumption for petrol and diesel cars was determined to be 6.7 liters per 100 km (VCA & DFT, 2011). For trucks an average fuel consumption of 33 liters per 100 km is used (VBA, 2008). To take the higher fuel consumption on mountain roads (lots of curves, higher ascending slope) into consideration the average fuel consumption of trucks is increased by 6 liters per 100 km (VBA, 2008). A similar proportion of the increase is assumed for the fuel consumption of cars (+18%). The fuel consumption also increases with a bad road condition. As a rough estimation the fuel consumption is assumed to increase by 5% when the road is in CS_3, by 12% in CS_4 and by 20% if the road is in CS_5.

The mean petrol and diesel price in Switzerland from January to October 2012 is 1.88 CHF/l (BFS, 2012b).

The vehicle maintenance costs represent the costs resulting from regular maintenance, for example tire or brake pad replacement, oil change or simply car cleaning. According to the Touring Club Schweiz 67% of the fuel costs additionally accumulated for car maintenance in 2011, not including the depreciation in value (TCS, 2011). Based on numbers given by the Royal Automobile Club of Queensland (RACQ, 2012) an average 74% of the fuel costs is spent on vehicle maintenance in the state of Queensland, Australia. The depreciation in value due to driving the car generates additional costs in the height of another 51% of the fuel costs (TCS, 2011). The same values are assumed to apply for trucks.

The DTV is estimated with data provided by (ASTRA, 2012a; DSFB, 2011; MGB, 2004, 2010).

The operation costs for the heavy traffic (trucks) are calculated using equation (9), equation (10) is for calculating the operation costs of cars.

$$CV_i^T = \left(\frac{33l}{100km} + F_{i,MR}^T \right) \cdot L_i \cdot DTV_i^T \cdot \left(1 + f_{i,CS}^T \right) \tag{9}$$

Where,

CV_i^T : Truck operation costs on object i [CHF/day]

L_i : Length of object i [km]

$F_{i,MR}^T$: Fuel consumption increase for trucks on mountain roads [l/100km]

DTV_i^T : DTV (heavy vehicles) [veh/day]

$f_{i,CS}^T$: Increase of fuel consumption of trucks due to the CS [%]

$$CV_i^C = \frac{6.7l}{100km} \cdot \left(1 + f_{i,MR}^C\right) \cdot L_i \cdot DTV_i^C \cdot \left(1 + f_{i,CS}^C\right) \tag{10}$$

Where,

CV_i^C : Car operation costs on object i [CHF/day]

$f_{i,MR}^T$: Fuel consumption increase for cars on mountain roads [%]

DTV_i^C : DTV (cars) [veh/day]

$f_{i,CS}^C$: Increase of fuel consumption of cars due to the CS [%]

$$CV_i^M = \left(\lambda^{SR} + \lambda^{DV}\right) \cdot \left(CV_i^C + CV_i^T\right) \tag{11}$$

Where,

CV_i^M : Vehicle maintenance costs on object i [CHF/day]

λ^{SR} : Increase factor for service and repair [%]

λ^{DV} : Increase factor for depreciation in value [%]

$$CV_i = 365 \cdot \left(CV_i^C + CV_i^T + CV_i^M\right) \tag{12}$$

Where,

CV_i : Total vehicle costs on object i [CHF/year]

4.9.2 Loss of travel time

In the report "Swiss value of travel time savings" the opportunity costs for people driving cars is estimated for commuting, business, leisure and shopping trips. An average 18.2 CHF per hour of travel time is suggested. For business trips a value of 32.5 CHF per hour of travel time is stated (Axhausen et al., 2006). Another empirical study by König, Axhausen and Abay suggests an estimation of costs of 45.2 CHF per hour for business trips. The costs for commuting, shopping and leisure trips are stated 29.9, 25.4 and 17.2 CHF per hour, respectively (König et al., 2004). The values for trucks vary even more; different studies suggest additional costs of 38 (De Jong, 2000) up to 371 (Small et al., 1999) US-Dollars. The huge differences come from the different nature of the cargo and industry. High values are reached especially when it comes to "just-in-time" processing.

Since no information is available on the composition of the traffic, 18.2 CHF/hour is assumed as the value for travel time savings for cars, for trucks the value is assumed to be 32.5 CHF/hour for being a business trip and additional 100 CHF/hour as an estimation for the strongly varying extra costs.

$$CLT_i^d = \left(\frac{L_i}{v_0} - \frac{L_i}{v_{TC}}\right) \cdot \left(DTV_i^T \cdot TTS^T + DTV_i^C \cdot TTS^C\right) \tag{13}$$

Where,

CLT_i^d : Costs for loss of travel time on object i [CHF/day]

v_0 : Travel speed in default TC [km/h]

v_{TC} : Reduced travel speed due to changes in TC [km/h]

TTS^C : Travel time savings (cars) [CHF/h]

TTS^T : Travel time savings (trucks) [CHF/h]

$$CLT_i = CLT_i^d \cdot \phi_{i,I,TC} \tag{14}$$

Where,

CLT_i : Total loss of travel time on object i [CHF]

$\phi_{i,I,TC}$: Duration of the intervention I in traffic configuration TC [days]

4.9.3 Emission costs

In Switzerland around 16.6% of all passenger cars are diesel operated, the rest (83.4%) is assumed to be run by petrol, since hybrid and electric cars are not being used in significant numbers (BFS, 2009). Trucks are assumed only to be diesel operated. A standard petrol car using 6.7 liters of petrol per 100 kilometers emits 164.8 grams of CO_2 per kilometer (VCA & DFT, 2011). Trucks are assumed to produce – proportionally to the fuel consumption – on average 653.3 grams of CO_2 per kilometer. The emissions of interest with the biggest impact are: Carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x), volatile organic compounds (VOC) and particulate matter (PM). The composition of the exhaust fumes for petrol cars is 20% CO_2, 0.020% NO_x, 0.258% CO and 0.018% VOC. For diesel cars and trucks the composition is 20% CO_2, 0.061% NO_x, 0.025% CO, 0.005% PM and 0.005% VOC (Geringer & Tober, 2010).

The estimation of the consequences of emitting these gases and particles is vague since the effects are partially hard to measure. In the context of this work only the economic impacts are monetary considered, the social and indirect impacts on the environment are not included. The price for one short-ton (907.18 kg) of CO_2 on the global market is also subject to strong variations. The estimations lie between 10 and 50 USD per short-ton, with most estimations being around 20 USD per short-ton for the year 2012 (Johnston, Hausman, Biewald, Wilson, & White, 2011). With a currency rate of 1:1, 20 USD per short-ton is equal to 22.05 CHF per metric ton. The monetary impact of CO, NO_x, VOC and PM is estimated using the UBP system (BAFU, 2009a). The economic impact is assumed to be proportional to the "Umweltbelastungspunkte" (UBP2006) of the correspondent compound. The monetary impact per ton is for CO 1.58, for NO_x 145.16, for PM 483.87 and for VOC 409.68 times higher than the impact of carbon dioxide (BAFU, 2009b).

Table 16: Emissions and monetary impacts

	w_{pt}^{C} [g/veh-km] (cars)	w_{pt}^{T} [g/veh-km] (trucks)	Costs [CHF/ton]
CO_2	164.8	653.3	22.05
PM	0.007	0.203	10'669.35
NO_x	0.221	2.476	3'200.81
CO	1.807	1.015	34.85
VOC	0.131	0.203	9'033.39

$$CE_i = p_{i,MR}^{MR} \cdot p_{i,CS}^{CS} \cdot \sum_{pt} \left\{ \left(w_{pt}^{C} \cdot DTV_i^{C} + w_{pt}^{T} \cdot DTV_i^{T} \right) \cdot C_{pt} \cdot 10^{-6} \right\} \qquad (15)$$

Where,

CE_i : Emission costs on object i [CHF/year]

$p_{i,MR}^{MR}$: Increase factor for higher emissions on mountain roads [%]

$p_{i,CS}^{CS}$: Increase factor for higher emission due to the CS [%]

w_{pt}^{C} : Amount of emissions of pollution type pt (cars) [g/km]

w_{pt}^{T} : Amount of emissions of pollution type pt (trucks) [g/km]

C_{pt} : Costs for emission type pt [CHF/ton]

4.9.4 Accident costs

A total distance of 55’893 million vehicle kilometers has been covered by motor vehicles in Switzerland in 2011 (BFS, 2012c). 54’916 incidents have been reported to the police (ASTRA, 2012b), generating costs of approximately 12.8 billion Swiss francs (ARE, 2002, 2006). Averaging these numbers leads to the mean costs of 233’083 CHF per incident, or 0.23 CHF per vehicle kilometer.

Narrower lanes, traffic jams and stressed drivers are often a by-product of worksites on roads. The consequence is usually a higher accident rate over the whole length of the worksite. According to a German study on the impact of highway worksites on the accident rate, the amount of incidents increases by 56% over the length of the worksite (Bakaba et al., 2012). Applied to the values gained before, the accident costs increase by 0.13 CHF per vehicle kilometer over the length of the worksite.

In tunnels the consequences of incidents are usually higher than on the open road. The fatality rates in tunnels vary a lot – especially between tunnels with uni- and bi-directional traffic – and the accident cost rates are (up to 50%) lower than on open road (Nussbaumer, 2007). Since most of the considered network consists of plain roads this effect is neglected, the accident cost rate for tunnels is assumed to be equal to the rate for the plain roads.

$$CA_i = L_i \cdot \left(DTV_i^C + DTV_i^T \right) \cdot C_A \cdot 365 \tag{16}$$

Where,

CA_i : Accident costs on object i [CHF/year]

C_A : Accident costs per vehicle kilometer [CHF/km]

$$CA_i^I = L_i \cdot \left(DTV_i^C + DTV_i^T \right) \cdot C_A^I \cdot \phi_{i,I,TC} \tag{17}$$

Where,

CA_i^I : Additional accident costs due to performing intervention type I on object i [CHF]

C_A^I : Additional accident costs per vehicle kilometer during intervention [CHF/km]

4.9.5 Intervention costs

The intervention costs are divided into a fix, intervention size independent and a variable, size dependent part. The fix intervention costs include all construction site equipment (sanitary equipment, electric power supply, stacking ground, access roads, etc.). These costs are not directly related to the size of the intervention itself but to the amount of employees working on the construction site. For employee-related equipment (e.g. toilets) there are regulations on how many have to be installed depending on the size of the working crew (e.g. one toilet per four fulltime workers). These regulations are categorized (e.g. one toilet for up to four workers, two toilets for five to eight workers, etc.). However, the amount of workers deployed on a construction site is related to the size of the intervention. Since workers are usually grouped into crews and deployed together on construction sites, the amount of workers increases in steps and not linearly with the size of the intervention. The same fact applies for machines.

If two objects connected to each other are both part in an intervention, then some of the fix costs could be omitted. But if the length of the objects is chosen equally in regard to the interventions, this reflects the change in crew sizes and therefore the stepwise increase in fix costs.

$$CI_i = CI^f_{i,I,TC} + CI^v_{i,I,TC} \tag{18}$$

Where,

CI_i : Total intervention costs on object i [CHF]

$CI^f_{i,I,TC}$: Fix intervention costs for intervention type I and traffic configuration TC [CHF]

$CI^v_{i,I,TC}$: Variable intervention costs [CHF]

$$CI^f_{i,I,TC} = CIF^R_{I,TC} + n_B \cdot CIF^B_{I,TC} + n_T \cdot CIF^T_{I,TC} \tag{19}$$

Where,

$CIF^R_{I,TC}$: Fix intervention costs for road sites [CHF]

$CIF^B_{I,TC}$: Fix intervention costs for bridges [CHF]

$CIF^T_{I,TC}$: Fix intervention costs for tunnels [CHF]

n_B : Number of bridges in object i [-]

n_T : Number of tunnels in object i [-]

The variable costs are strictly depending on the size of the intervention (e.g. the amount of asphalt concrete needed, liters of diesel used or labor costs). The size of the intervention also includes the hours of manpower needed to complete all tasks. A methodology of calculating the man hours and the resulting costs can be found in (Girmscheid & Motzko, 2004; Girmscheid, 2010, 2011). The widths of the road sections in this particular example are not measured but estimated using the regular cross sections (FGSV, 1996), depending on the road type. The total area the intervention has to be performed on is taken as the decisive parameter to calculate the variable costs.

$$CI_{i,I,TC}^{v} = \left(\left(ci_{CS}^{R} \cdot \frac{L_i^R}{L_i} + ci_{CS}^{B} \cdot \frac{L_i^B}{L_i} \right) \cdot W_i + ci_{CS}^{T} \cdot \frac{L_i^T}{L_i} \right) \cdot L_i \qquad (20)$$

Where,

ci_{CS}^{R} : Variable road intervention costs [CHF/m^2]

ci_{CS}^{B} : Variable bridge intervention costs [CHF/m^2]

ci_{CS}^{T} : Variable tunnel intervention costs [CHF/m]

W_i : Width of object i [m]

L_i^R : Total length of plain road sections in object i [km]

L_i^B : Total length of bridges in object i [km]

L_i^T : Total length of tunnels in object i [km]

4.9.6 Future impacts

To get reasonable results when comparing objects of different types (in this case: roads, bridges, tunnels) undergoing interventions with strongly varying impacts and consequences, future impacts have to be included in the optimization procedure. Future impacts take the effects into consideration which would result from not performing the intervention in the current planning period. This includes an increase of the intervention costs as well as impacts resulting from a lower level of service (higher accident rate, higher emissions, etc.).

These impacts can be estimated using probabilistic models to describe the evolution of the CS over time. All impacts can then be calculated using the formulas given in this chapter. The difference between the impacts accumulating in future planning periods when no intervention is performed in the current planning period and the impacts accumulating with the intervention being performed is equal to the future impacts. The future impacts can therefore be seen as the benefit occurring in all future planning periods when the particular intervention is performed in the current planning period. In this calculation the timespans are long enough that all future impacts have to be discounted to the current planning period.

In this particular example an accurate estimation of the future impacts would go beyond the scope of this work. However, the future impacts cannot be neglected, since these impacts have a significant effect on the optimal solution (a short example is given in the following paragraph). With taking a few constraints and assumptions into consideration an exclusively mathematical formula is used to calculate the future impacts. The constraints and assumptions include:

- All impacts accumulating on all different stakeholder groups will increase with a decreasing condition of the object and therefore increase in time.
- The increase of the impacts is not linear, future impacts increase more for objects already being in a bad condition.
- Future impacts are only taken into consideration for the condition states CS_3, CS_4 and CS_5.
- In condition state CS_5 every object with a considerable DTV should have a positive total impact.

The effect of future impacts can be explained using a simple example: Two nearly identical objects are compared. Both objects have the same attributes (length, number of lanes, DTV, CS) and are undergoing an intervention with the same benefit (e.g. same reduction of emission costs), but object 1 is a plain road section, object 2 is a tunnel. The main difference lies in the intervention that has to be performed to achieve the same benefit. Maintenance or renewal works on pavement sections include works on the surface, the binder and/or the base course as well as on the signaling and safety equipment. An intervention performed on a tunnel is usually much more complex. The safety, signaling and operation equipment (e.g. emergency power generator, escape routes, ventilation system) as well as the load-bearing structures of a tunnel are composed of a diversity of technical elements. Interventions performed on such objects require much more (inter alia monetary) input to keep the equipment and structure providing an adequate level of service.

When it comes to the optimization, objects with a high overall benefit and low intervention costs (a high benefit to cost ratio, respectively) are much more likely to be found in the optimal solution. Carrying out an intervention on a tunnel (or a bridge) costs a lot more and has – excluding the future impacts – a nearly identical positive impact compared to an open road section. This would lead to the fact that tunnels and bridges (or in general: more complex infrastructure objects) are never found in an optimal intervention plan because of the low benefit-cost-ratio. The only reason that would lead to a consideration of a complex object in the OIS would be when it is in such a bad condition that the probability of structural failure starts to increase significantly. Structural failure could lead to many seriously injured or even killed users and (with a high probability of structural failure) this generates a huge amount of theoretical accident costs. The future impacts take this effect of an increase of theoretical costs accumulating due to a decreasing object condition into account.

In order to correct this imbalance and make different objects and ITs comparable, future costs have to be included in the calculation of the costs and benefits. The mathematical formulation of the future costs is given with equations (21), (22) and (23).

$$CF_i^I = CI_i \cdot \left(\frac{\nu_{CS}}{8} \cdot \frac{L_i^B + L_i^T}{L_i} + \frac{\nu_{CS}}{20} \cdot \left(1 - \frac{L_i^B + L_i^T}{L_i} \right) \right) \cdot \left(1 + \left(\frac{\nu_{CS}}{2} \right)^2 \right) \quad (21)$$

$$CF_i^U = \begin{cases} \left(CA_i + CE_i + CV_i \right) \cdot \left(\frac{\nu_{CS}+1}{50} \right)^3 \cdot \left(\frac{1}{2} + \frac{\nu_{CS}-1}{20} \right) & \text{for } \nu_{CS} > 0 \\ 0 & \text{for } \nu_{CS} = 0 \end{cases} \quad (22)$$

$$CF_i = CF_i^I + CF_i^U \quad (23)$$

Where,

CF_i : Expected future costs of object i [CHF/year]

ν_{CS} : Value for the current CS [-]

$\nu_{CS} = 0$ when the object is in condition state CS_1 or CS_2

$\nu_{CS} = 1$ when the object is in condition state CS_3

$\nu_{CS} = 2$ when the object is in condition state CS_4

$\nu_{CS} = 3$ when the object is in condition state CS_5

It has to be noted that these mathematical formulations are only constructed taking the theoretical model into consideration in order to make feasible solutions of the example possible. Due to the lack of research data and the limited time frame of this work it is not possible to base the estimation of the future impacts on any probabilistic models representing the developing of the CS and the associated costs. For further work on the application of the model to a real world example a profound estimation of the future impacts is inevitable.

4.10 The program

The optimization program is set up in Microsoft Excel spreadsheets and runs using the What'sbest!-solver (Lindo Systems Inc., 2010). The calculation steps are shown in Table 17, the excel worksheet names refer to the excel file that can be found on the attached CD. Three types of steps are differentiated: *Constant*, *variable* and *automatic*. Parameters entered in a *constant* step are not changed in the different scenarios shown in the next chapter. An example for a parameter entered in a *constant* step is the DTV. Values in *variable* steps are subject to variations in the following optimization procedure, e.g. the maximum budget or the maximum worksite length. *Automatic* steps do not allow any interference and function without any special inputs.

Table 17: Calculation steps

Step	Type	Content	Excel worksheet
1	*Constant*	Defining the unit costs, e.g. mean petrol price, travel time saving cost assumptions, etc.	Unit costs
2	*Constant*	Definition of the different ITs, their costs and impacts for CS_3, CS_4 and CS_5.	Intervention costs
3	*Variable*	Defining the maximum budget, choosing the maximum worksite length and entering the estimated CSs of all objects	Constraints
4	*Automatic*	Calculation of all impacts resulting in "total costs and benefits" and "intervention costs" for all ISs on every object	Cost calculations
5	*Automatic*	Optimization considering all constraints	Constraints, Continuity matrix, Length constraint, Distance constraint, Cost calculations
6	*Automatic*	Graphical and numerical representation of the results	Constraints, Graphviz_Code, Continuity matrix

For a graphical representation of the results, an algorithm using dot-code is generated. This code can be turned into a network graph using a software like GVEdit (Bilgin et al., 2012).

Parts of the program are explained in Annex B, all necessary programs and plugins are listed in Chapter 7.

4.11 Scenarios

In order to identify the impacts of the different input parameters, multiple planning scenarios are examined. The different input parameters are shown in Table 18.

The minimum distance between two worksites is for all scenarios set to zero. This is due to the complexity of the program. All other constraints can be implemented linearly, the MDBW constraint, however, is a non-linear problem. Linear programs can be solved within a short time using linear optimization algorithms (e.g. branch-and-bound). The optimal solutions of non-linear problems can be found but it takes much more time since the algorithms used for non-linear problems usually are based on numerical and not analytical solving.

Table 18: Scenarios

No.	B [Mio. CHF]	L^{max}	D^{min}	Condition states	Additional specifications
SC_1	unlimited	15 km	0 km	All objects in CS_3	-
SC_2	unlimited	10 km	0 km	All objects in CS_3	-
SC_3	unlimited	20 km	0 km	All objects in CS_3	-
SC_4	75% of budget used in SC_1	15 km	0 km	All objects in CS_3	-
SC_5	75% of budget used in SC_2	10 km	0 km	All objects in CS_3	-
SC_6	75% of budget used in SC_3	20 km	0 km	All objects in CS_3	-
SC_7	75% of budget used in SC_4	15 km	0 km	All objects in CS_3	-
SC_8	Unlimited	15 km	0 km	All objects in CS_3	Impact-cost-ratio ≥ 8
SC_9	Unlimited	15 km	0 km	All objects in CS_3	Impact-cost-ratio ≥ 9
SC_{10}	Unlimited	15 km	0 km	Random R_1	p_{CS} = 0.2
SC_{11}	Unlimited	15 km	0 km	Random R_2	p_{CS} = 0.2
SC_{12}	120 Mio. CHF	15 km	0 km	Random R_1	p_{CS} = 0.2
SC_{13}	120 Mio. CHF	15 km	0 km	Random R_2	p_{CS} = 0.2
SC_{14}	120 Mio. CHF	15 km	0 km	Random R_3	p_{CS} = 0.2

The first three scenarios optimize the problem using an unlimited budget. The whole network is in CS_3, only the maximum length of the worksites is changing between 10, 15 and 20 kilometers. Scenario 4 to 6 cut the budget down to 75% of the costs generated in the corresponding scenario 1, 2 and 3, respectively. This enforces a change in the optimal solution since otherwise the budget constraint would not be satisfied. Scenario 7 then again cuts down the maximum budget to 75% of the intervention costs accumulating in the optimal solution of scenario 4.

Scenario 8 and 9 include an additional constraint. The ratio between the total impacts and the accumulating intervention costs has to be greater or equal to a boundary value estimated using the results of the previous scenarios (equation (24)).

$$cr = \frac{\text{total costs and benfits}}{\text{total intervention costs}} = \frac{\sum C + U + D + I}{\sum P} \tag{24}$$

In scenario 10 to 14 the procedure of the first scenarios is repeated, but this time using a random distribution of the CSs. The probability is identical for every CS and is equal to p_{CS}=0.2.

Three sets of CSs are used (R_1, R_2, R_3). All three sets are stored in the program and were generated using the Excel built-in random function

```
=ROUND(RAND()*4;0)+1
```

which generates a random number between 1 and 5, where 1 corresponds to CS_1 and 5 to CS_5.

4.12 Results and discussion

The total costs and benefits, the total intervention costs and the impact-cost-ratio for all different scenarios can be seen in Table 19.

Table 19: Costs and benefits of the different scenarios

Scenario	Total costs and benefits [Mio. CHF]	Intervention costs [Mio. CHF]	Impact – cost ratio cr [-]
SC_1	157.67	30.04	5.25
SC_2	137.03	17.49	7.83
SC_3	172.48	19.98	8.63
SC_4	156.71	18.75	8.36
SC_5	130.92	13.10	9.99
SC_6	164.68	14.99	10.98
SC_7	149.66	14.10	10.62
SC_8	156.71	18.76	8.36 > 8
SC_9	152.76	16.88	9.05 > 9
SC_{10}	370.47	744.06	0.50
SC_{11}	692.10	1’141.01	0.61
SC_{12}	214.26	119.97	1.79
SC_{13}	276.52	119.99	2.30
SC_{14}	260.03	119.95	2.17

4.12.1 All objects in CS_3 (SC_1 – SC_9)

The first three scenarios only differ in the maximum worksite length, the budget is unlimited and therefore the solution with the unbounded, highest benefit is found. The three optimal intervention plans are overlaid to show the difference of the three strategies and can be found in the Annex A.3. The unsurprising result is still worth mentioning: The similarities between all three scenarios are remarkable, only around one fifth of all objects (28 out of 160) differ in the chosen IS.

The DTV seems not to have a significant impact on whether an intervention should be performed or not. Table 20 lists three links, two with a relatively low DTV and the link with the highest DTV in the whole network. There seems to be no direct correlation between the DTV and the number of objects subject to an intervention.

Table 20: Influence of the DTV

Link	Number of objects in the link	Total length [km]	Objects subject to intervention			DTV_{min}	DTV_{max}
			SC_1	SC_2	SC_3		
001-004-040-048	13	53.1	7	5	7	24’230	38’790
007-018	12	21.5	10	10	8	3’050	3’820
101-121	21	42.1	4	4	4	2’500	2’500

An interesting fact is the strong variation of the impact-cost-ratio. While scenario 3 only costs 14.2% more than scenario 2, is scenario 1 71.7% more expensive than scenario 2. The changes in the total costs and benefits result from the higher maximum worksite length. The less restrictive the constraints are the higher is the possible benefit that can be gained. The constraints like the maximum budget or the maximum worksite length are mostly non-discussible from the optimization point of view and are usually based on laws and political regulations.

More interesting is the difference between scenario 1 and scenario 4. While the total costs and benefits are only subject to slight variations (-0.6%), the total intervention costs decrease remarkably (-37.6%). This leads to the question if it is economically arguable from the viewpoint of the owner to optimize the problem by only searching for the highest total benefit. The intervention costs are included in the total costs and benefits, but a lot of the positive and negative impacts are accumulating over longer time periods and often don’t directly lead to monetary benefits.

A different optimization strategy could include two different steps:

1. Perform an optimization as described in this example where the benefit is maximized considering several constraints.
2. Use the optimal solution from step 1 to define boundary values in-between which the optimization is performed using another variable.

An example could be taking the maximum benefit from step 1 as an upper boundary and 90% of this value as the lower boundary value. In step 2 the impact-cost-ratio is maximized between these two boundary values.

A considerable argument against an optimization of the impact-costs-ratio is the increase of the ratio with a decreasing amount that is spent on interventions. This can be illustrated taking the setup of scenario SC_{10} and running the optimization with a budget going from unlimited to 1 Mio. CHF (Figure 18).

Another approach for handling the optimization with considering the impact-cost-ratio is given with scenario SC_8 and SC_9, where the impact-cost-ratio has to be greater or equal to a limiting value. This additional constraint enables including a designated performance. But this leads to the question how or on what basis this solution is optimal, since the result strongly depends on choice of the correspondent impact-cost-ratio.

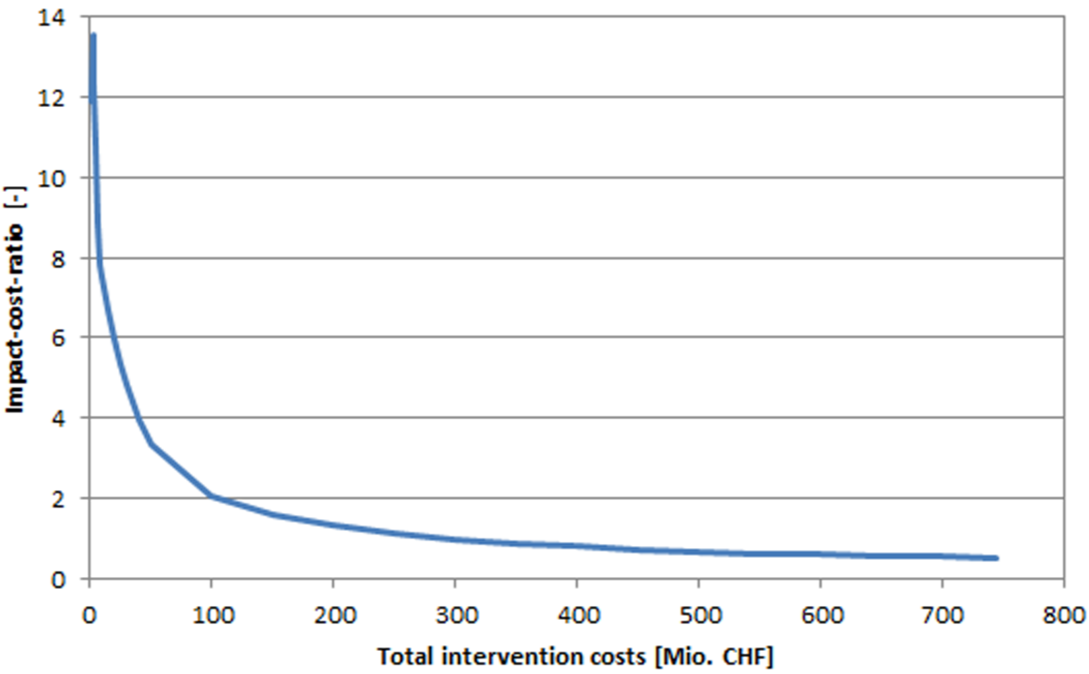


Figure 18: Impact-cost-ratios for decreasing intervention costs

4.12.2 Random distribution of condition states ($SC_{10} - SC_{14}$)

In the scenarios SC_{10} to SC_{14} the CSs are assumed to be randomly distributed. In all cases the CSs are equally distributed with a probability of 0.20 per CS. Three different sets of random distributed CSs are used, referred to as R_1, R_2 and R_3, respectively. SC_{10} and SC_{11} with an unlimited budget show a remarkable difference both in the total intervention costs as well as in the total benefits. But with a budget constraint being only a fraction of the maximum amount of resources that could be spent (SC_{12}, SC_{13} and SC_{14}) the variation of the total benefit is not tremendously high. However, the amount of money that could be gained or saved (62 Mio. CHF when comparing SC_{12} and SC_{13}) with the differing distribution of the CS shows how important an exact estimation of the condition of all objects would be. This also means that even if the budget is significantly lower than the amount of resources that should be allocated in the unconstrained OIS a proper optimization procedure can help raising the total impacts considerably.

The huge difference in the intervention costs in the scenarios SC_{10} and SC_{11} is due the fact that in one scenario more complex objects are in a bad condition. If a lot of bridges and tunnels are in a bad condition this means that a lot of money has to be spent to keep the whole network providing an adequate level of service. If only pavement works have to be performed the amount of money that has to be spent is obviously smaller.

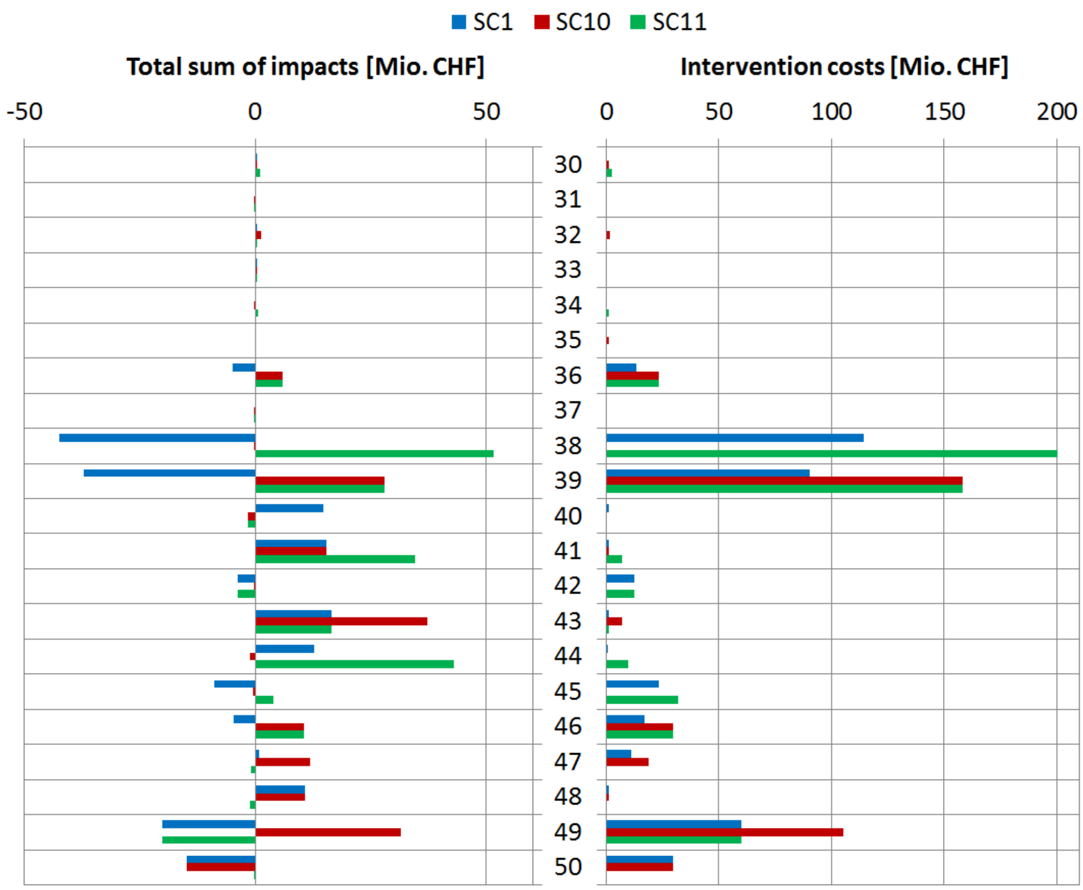


Figure 19: Intervention costs and total impacts (excerpt)

Further on has to be noted that the equal distribution of the condition states represents a network that is overall in a really bad condition (only 2/5 of the network provides an adequate level of service). But the mean condition state is still CS_3 since all condition states are equally distributed. The impact of objects in really bad condition is remarkable: The intervention costs rocket upwards from 25 times (SC_{10}) to 38 times (SC_{11}) the primary intervention costs of SC_1. This is mainly due to the fact that in SC_1 the objects with high intervention costs usually have a lower total benefit since they are in condition state CS_3. Some objects with really high intervention costs in the scenarios SC_{10} and SC_{11}, however, are in CS_5 with significantly high future impacts (e.g. resulting from a disproportionally high increase of the probability of structural failure) and therefore are found in the optimal solution. It can be said that, with this cost model, objects in a bad condition have high future impacts and are therefore likely to be found in the OIS. This subsequently leads to high intervention costs.

Figure 19 illustrates this effect on the example of two network segments (object 30 to object 39 and object 40 to object 50) for three different scenarios (SC_1, SC_{10} and SC_{11}). The bar graph on the right hand side shows the theoretical intervention costs of every object for all three scenarios. The graph on the left hand side shows the total sum of all positive and negative impacts (i.e. also including the intervention costs) accumulating if the intervention would be performed on the particular object. Without considering any constraints (unlimited budget, unlimited worksite length) all objects with a positive total impact would be in the OIS, all objects with a negative total impact would not be part of the OIS.

The differences for plain, regular road sections (objects 30 to 37) are not too significant. Objects 38 and 39, however, consisting of a 5.2 and a 4.1 kilometer long tunnel show remarkable changes in both the intervention costs and the total impacts. Due to the really bad condition state (e.g. SC_{11}, object 38) the total impacts turn positive, even with increasing intervention costs. The same effect is observable on the following objects (40 to 50). This means the impacts on the whole optimization and its result are for the most part depending on the amount and condition of complex, expensive objects in the network.

4.13 Sensitivity analysis

4.13.1 Daily traffic volume

Four objects are reviewed with different DTVs in order to estimate an impact on the total positive and negative impacts. The objects and their original state are shown in Table 21.

Table 21: Original state of considered objects

Object number	DTV 2012 [veh/day]	Total impacts (TC_1) [Mio. CHF]	Condition state
4	38’790	4.19	CS_3
5	13’630	3.39	CS_3
6	13’630	-15.33	CS_3
7	3’820	0.39	CS_3

The DTV is now varied for all four objects. The resulting graph is shown in Figure 20. It can be seen that the total impacts increase linearly with higher traffic volumes. The vertical offset of the line results from the intervention costs for every object. In this case, object 6 contains a long tunnel and therefore has high intervention costs (resulting in a large, negative offset). The slope of the curve is not affected by the DTV but by the TC the intervention is performed in. If the TC results in lower travel speed or longer lasting interventions, the total costs and impacts increase less. In general it can be said that objects with higher DTV have higher total impacts, but the difference between the different objects varies much stronger due to the differing object types.

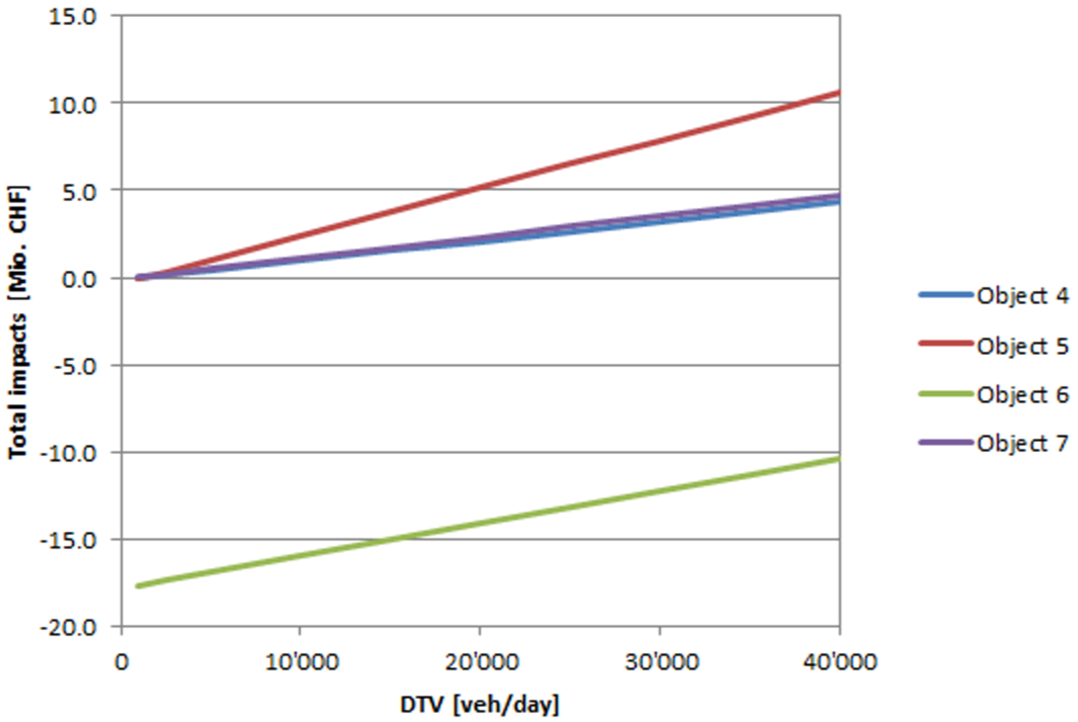


Figure 20: Effect of DTV on total impacts

4.13.2 Impact types

All considered impact types resulting from an intervention (intervention costs, loss of travel time and additional safety costs during the intervention, reduction of emissions and vehicle maintenance costs resulting from a better road condition, future impacts) are opposed to each other to estimate their effect on the sum of all impacts. Since the absolute values vary a lot, percentages are used. Figure 21 shows the negative and Figure 22 the positive impacts.

The negative impacts underlie strong variations: On some objects the intervention costs cover up to nearly 100% of all negative impacts (complex objects consisting of tunnels and/or bridges) while on objects only consisting of open road sections the costs estimated for the loss of travel time and the additional accident costs cover up to 85% of all negative impacts.

The emission impacts are – even if only compared to the vehicle costs – insignificantly small. In comparison to the vehicle costs the emission impacts lie between 2.0% and 2.1%. It is to note that the future impacts also include emission and vehicle cost savings. But it can be said that the effect of the emission cost savings from a better road condition after performing an intervention is – compared to the vehicle cost saving – negligible. Figure 23 shows the variation of the importance of the emission cost savings as a function of the estimated CO_2 price. It can clearly be seen that the consequences do not reach a significant importance.

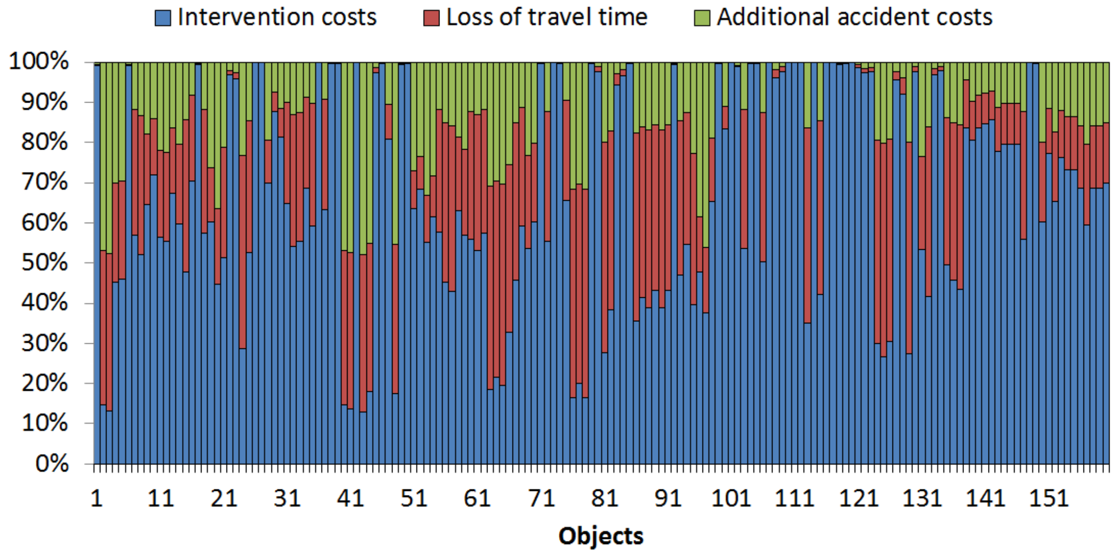


Figure 21: Negative impacts

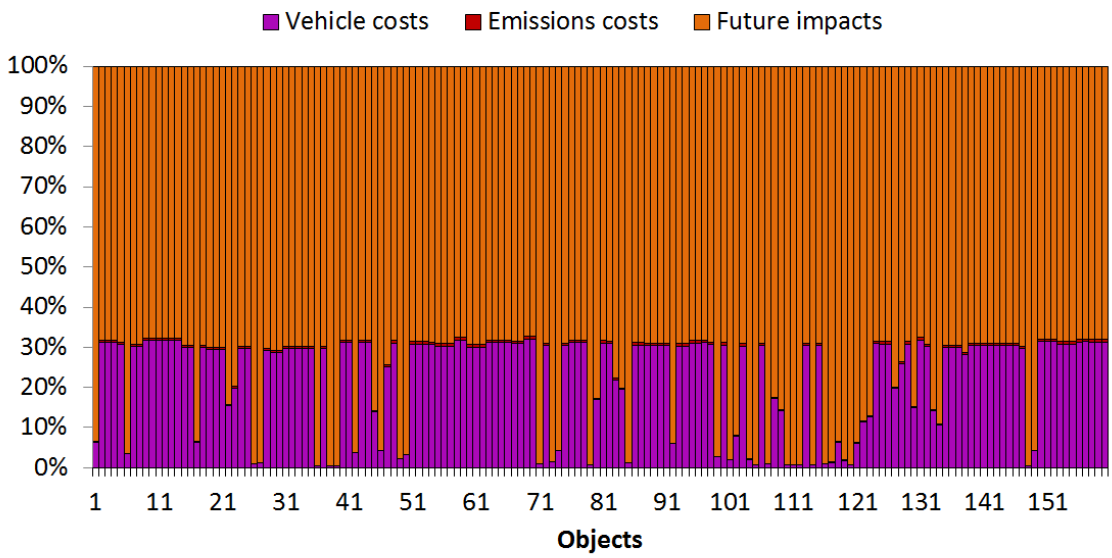


Figure 22: Positive impacts

The extent of the future impacts is quite significant. The future impacts are based on purely mathematical estimations in order to force the sum of impacts of every object into a feasible region. Further on are the future impacts depending on all other impact types. This leads to a necessity of a profound estimation of the future impacts taking the development of CSs and all connected impacts into consideration.

Figure 24 illustrates the development of the different impact types with an increasing CS. It can be seen that the effect of the future impacts is not subject to such strong variations as the intervention costs. The fact that the intervention costs gain even more importance could also be due to the fact that the regular accident costs are not depending on the CS of the object. However, the savings of the accident costs for a better road condition are included in the future impacts. The loss of travel time and the additional accident costs are only due to performing an intervention. The fact that a better road condition could possibly lead to small travel time savings and lower accident costs is not considered in the negative impacts. This again highlights the importance of an exact estimation of all future impacts even when it comes to optimizing for a certain time period.

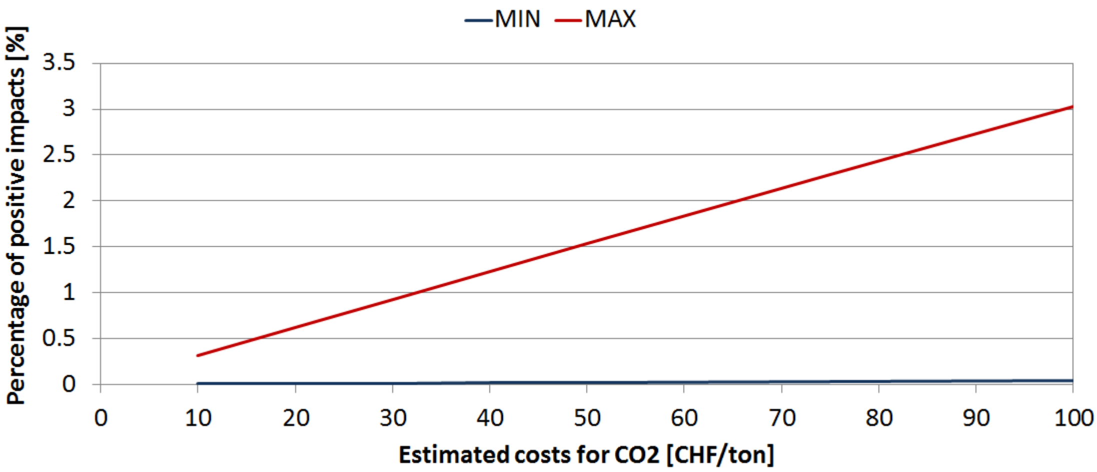


Figure 23: Emission cost savings

4.13.3 Intervention types

The negative impacts occurring to the users as well as the DAP and the IAP are depending on the duration of the maintenance works and the changed TC. The durations for setting up all necessary equipment for a worksite as well as the restoring of the default traffic condition takes quite a considerable part of the entire duration of an intervention. Using bigger workgroups mainly reduces the time needed to perform the actual intervention. To illustrate the impact of the performance (i.e. production capacity) of a worksite (in square meters per day), the performance is set to a higher (4000 m^2/day) and a lower (2000 m^2/day) value than the default performance (3000 m^2/day) used in the example. However, this effect has, as illustrated in Figure 25, no significant impact on the distribution of the different impact types.

An important point at this part of the optimization could be the implementation of a variable duration of every intervention. This would mean the size of the deployed work crews could be optimized regarding the whole worksite instead of every object separately. The worksite specific intervention duration would include a dependency of all intervention related impacts on the production capacities and the amount of work that has to be done on every object. This would result in more consistent worksite definitions, where all objects in one worksite are kept in a certain TC until a part or the entire worksite is closed and the default TC is restored. The way the program is set up now, it is not capable of changing the duration of an intervention depending of the duration of the whole intervention package.

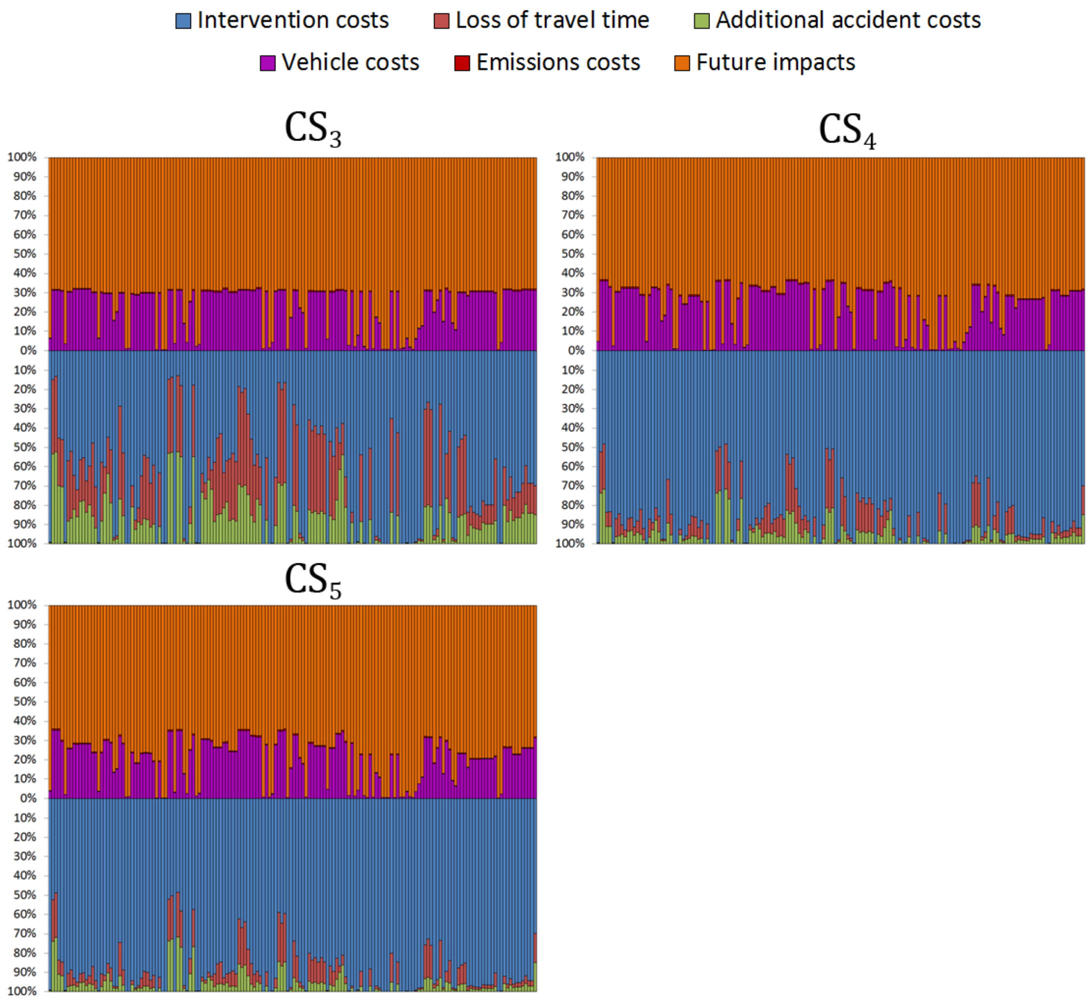


Figure 24: All impacts

4.14 Including the MDBW constraint

4.14.1 General problem

The complexity of the program increases excessively when including the MDBW constraint. It is no longer solvable with the branch-and-bound or another linear programming algorithm. With a brute force solver the maximum amount of possible solutions is $n = 3^{159} \cdot 2 \approx 1.5 \cdot 10^{76}$ (159 objects with three possible options and one with only two possible options). These solutions then have to be checked for their feasibility (maximum budget, MDBW and MWL constraint). It can easily be seen that the amount of possible solutions increases disproportionately high with an increasing amount of objects and/or ISs per object.

In order to reduce the complexity as much as possible it would make sense to reduce the possible ISs per object to a minimum and to pre-group smaller objects into larger objects to lower the total number of objects in the network.

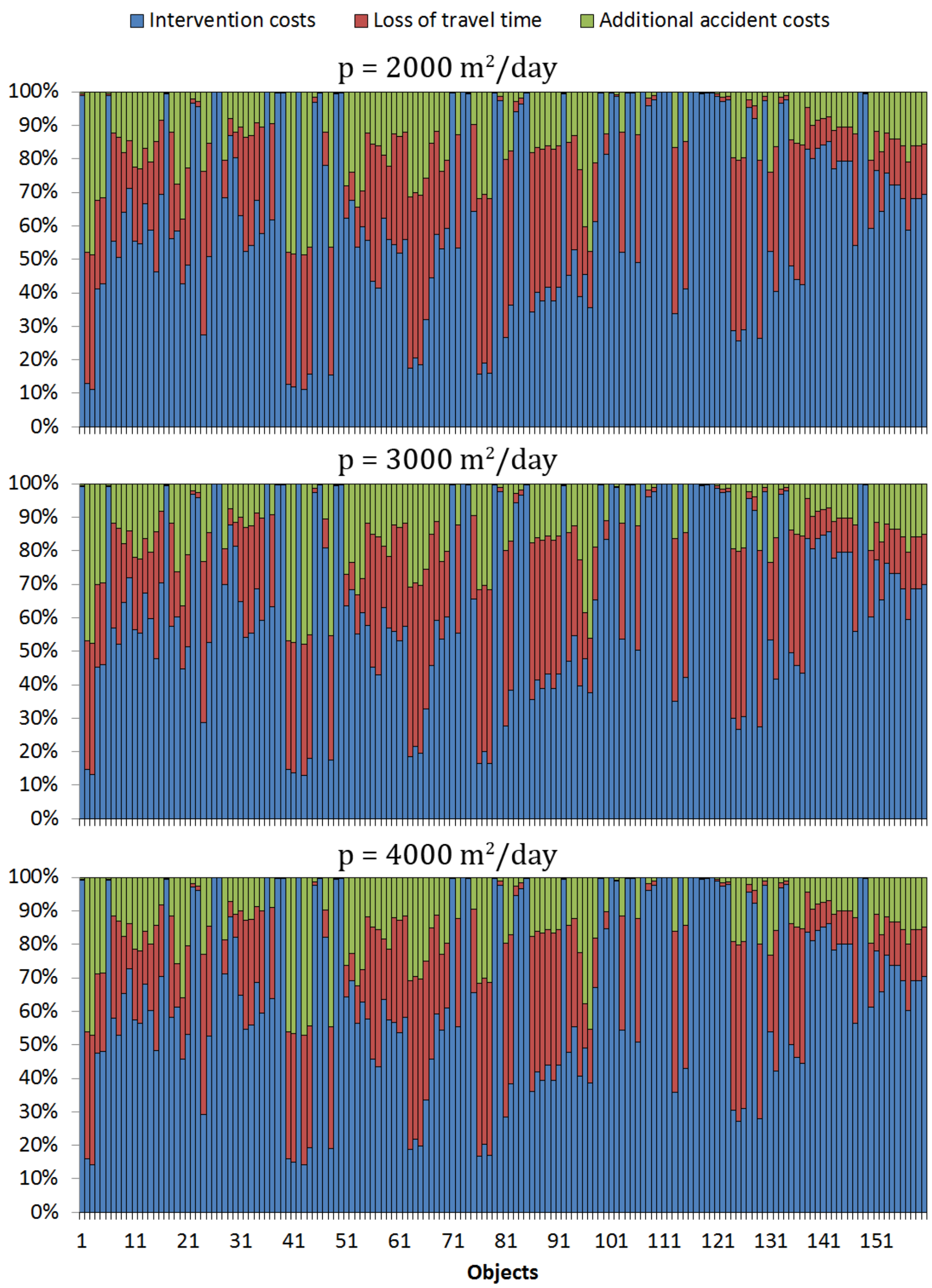


Figure 25: Work performance

Even if the optimization procedure is optimized (e.g. including the constraints into the solver and aborting the calculation as soon as one constraint is violated; searching for systematics instead of using a brute force solving method) still a remarkably large amount of computational resources has to be available to solve the problem. If the program is set up in a suitable programming language the use of a cloud service (e.g. HPC Cluster Brutus at the ETH Zurich or

Amazon EC2) could also shorten the solving time significantly. However, for this the program set up in this work is not suitable since the solving process cannot be divided into sub-processes (this would be necessary to use the advantages of cloud-computing). The use of Microsoft Excel and the What'sBest-Solver would not be recommendable.

4.14.2 Influence on the found results

The results for all scenarios presented above would differ quite significantly. Exemplarily for all solutions, Figure 26 illustrates an excerpt of the optimal solution for scenario SC_{10} without taking the MDBW constraint into consideration. Object 114 – a 1.6 kilometer long tunnel – is not subject to an intervention, even though the adjacent objects are in a worksite. Including the MDBW constraint would lead to two different options: Either is the tunnel included in the worksite but without performing an intervention, or one of the adjacent worksites cannot be included in the solution.

This particular excerpt is chosen to illustrate how important the including of the MDBW constraint is. In this small segment consisting of 22 objects the MDBW constraint is violated at least five times (objects 114, 133, 135, 138 and 139, 141 and 142). The optimal solution would differ in the picked options and in the total sum of impacts. This finding implies that the results found for the example network would differ significantly with the including of the MDBW constraint.

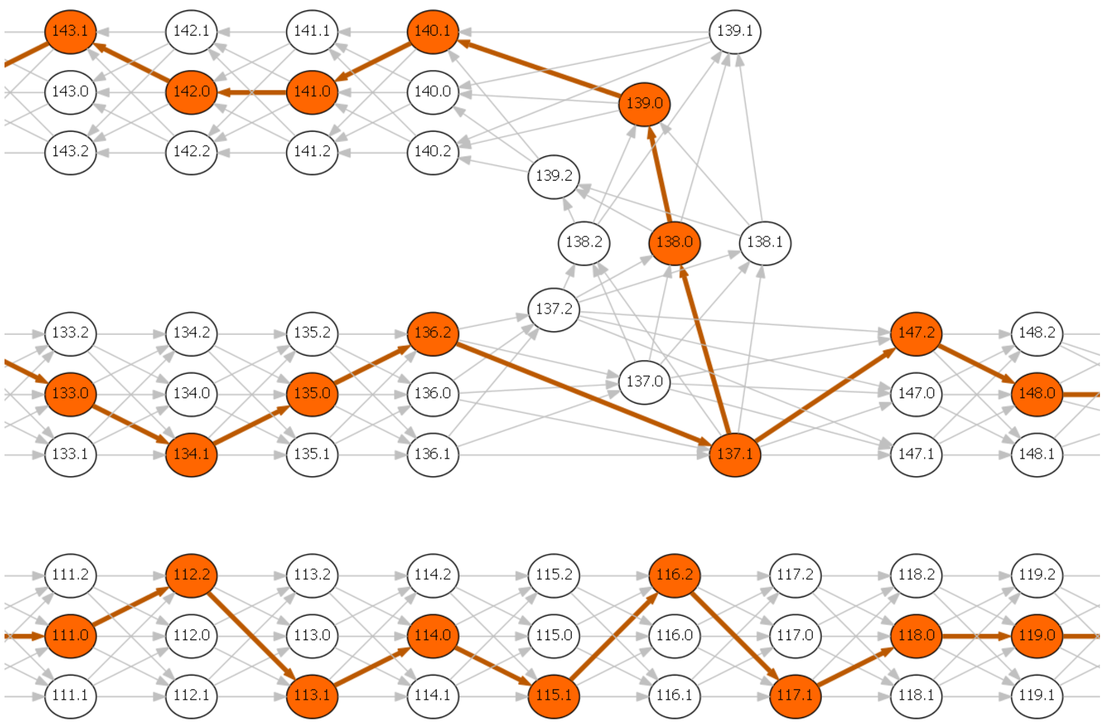


Figure 26: Excerpt of the solution of scenario 10

5 Summary and Outlook

The proposed model is application to be used in practice to determine the optimal intervention strategies for entire road networks composed of different types of infrastructure objects. It allows comparing the results of various scenarios so that decision makers are able to make a profound benchmark for sound decisions. In addition, it is possible to perform a sensitivity analysis in order to understand the stability of the optimal intervention strategies with regard to variations of the impacts. The model has been developed in the way that it can further be extended to incorporate the multiple planning periods of long-term strategic intervention scheduling.

With the continuously increasing size and complexity of infrastructure networks the use of computerized infrastructure management systems becomes more and more important. The determination of optimal intervention strategies to keep the entire network providing an adequate level of service plays a main role in the management of road network systems. The primary motive was stated in the first chapter. The second chapter gave a short overview over all basic components needed to understand and model the processes behind the maintenance management of a road network. The main challenges of maintaining an entire network and the state of knowledge of dealing with these difficulties have been illustrated, explained on multiple research projects. In chapter three the extended model with all its characteristics was explained both conceptually and mathematically. Using this model allows the implementation and optimization of additional parameters leading to a more accurate representation of real world road networks. It can be seen as a further step to a model which offers the possibility of optimizing the maintenance management of entire road networks with taking all decisive long- and short-term impacts into account. The applicability of the model was demonstrated on an empirical example in the fourth chapter. For a road network in the Canton of Valais, Switzerland, the required, problem specific parameters have been estimated and the resulting impacts have been determined. The influences of different assumptions and estimations on the optimized intervention plans have been discussed and both conceptual and computational problems have been addressed.

For further research and development two main topics have to be dealt with profound research. An accurate estimation of the impacts incurring to the different stakeholder groups is of importance since these quantitative factors play a crucial role in the optimization procedure. The significance of the long-term impacts (in this work referred to as "future impacts") has to be determined as well as further impacts that haven't been addressed in this work. Characteristics related to the geographical diversity (e.g. high probability of earth quakes or avalanches) and the condition of the road network (e.g. correlation of the road condition and the accident rate) could have significant impacts on the optimal intervention strategy.

The second essential topic is the development of a program which is able to solve the optimization using as little computational resources as possible. A methodology of implementing the constraint limiting the minimum distance between two worksites has been presented in this work. This methodology leads to difficulties regarding the use of linear solvers and therefore regarding the program running time due to its nonlinearity. A suitable program has to be coded if the constraint cannot be linearized or linearly approximated in order to enable a reliable and fast optimization of intervention strategies for road networks.

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7 Programs used

GVEdit Graph File Editor For Graphviz 1.0.1 (2012), Bilgin, A. et al.; http://www.graphviz.org/

MATLAB R2011b 7.13.0.564 (2011), Mathworks

Microsoft Excel 2010 (2010), Microsoft Corporation

Notepad++ v6.2 (2012), Ho, D. et al.; http://notepad-plus-plus.org/

Python 2.7.3 (2012), Python Software Foundation; http://www.python.org/

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Annex A: General network files

A.1 Physical network

PLACE HOLDER ANNEX A.1

PLACE HOLDER ANNEX A.1

A.2 Artificial network

PLACE HOLDER ANNEX A.2

PLACE HOLDER ANNEX A.2

A.3 Scenario 1, 2 and 3

PLACE HOLDER ANNEX A.3

PLACE HOLDER ANNEX A.3

Annex B: Programming approach

B.1 Maximum worksite length constraint matrix

A relatively simple python program can help to create the matrix needed for the maximum worksite length constraint. The whole network is modeled as a tree where the start-node (where the car enters the network) is defined as the root and all ending-nodes (where the car might leave the network) are defined as the leaves.

In Python such a network can be modeled quite simple. The matrix is then created using a function to travel from every possible object back to the root, and print out the summed up lengths of the objects. The function starts again from the next object when the maximum worksite length is exceeded for the first time. The resulting matrices are then fitted into one (since not all branches have the same length, several columns of zeros have to be added).

This procedure can be repeated defining every connecting node once as the root of the tree. A complete matrix for one specific maximum worksite length for the whole system is created. The relatively high amount of work for the setup of the program (i.e. creating the matrix) is justified because usually there is only one mandatory maximum worksite length and the program is completely linear which allows using fast solving algorithms.

A data file has to be created including the name of all objects and their lengths. It is here referred to as `python_data.dat`. The style of the file is given as:

```
[["001",1.2],
 ["002",5.5],
 ["003",6.4],
 ["004",1.2],
 ["005",3.2],
     …
 ["159",1.9],
 ["160",1.8]]
```

The following code creates the parts of the matrix using Python and Python Scripter. It can be found under `OPINRONET.py`.

```
#-------------------------------------------------------------------------------
# Name:         module1
# Purpose:      Creation of road network specific maximum
#               worksite length constraint matrix parts
#
# Authors:      Silvan Sigrist
#               Manuel Sigrist
#
# Created:      28.11.2012
# Copyright:    (c) Silvan Sigrist, 2012
#               (c) Manuel Sigrist, 2012
# License:      For personal, non-commercial use only
#               Do not publish without authors permission
#-------------------------------------------------------------------------------
#!/usr/bin/env python

import json

class Node(object):
    def __init__(self, id, value):
        self.children = set([])
        self.value = value
        self.id = id
        self.parent = None

    def add(self, node):
        if node:
            self.children.add(node)
            node.parent = self

    def findById(self, id):
        if self.id == id:
            return self
        for child in self.children:
            res = child.findById(id)
            if res:
                return res
        return None

    def __str__(self):
        return str(self.id) + '=' + str(self.value)

    def traverseBack(self, maxVal, debug=False):
        length = 1
        parent = self.parent
        while parent:
            length += 1
            parent = parent.parent
        for i in xrange(0, length):
            res = []
            for y in xrange(0, i):
                res.append('0')
            parent = self
            y = 0
            while not parent.parent is None and y < i:
                parent = parent.parent
                y+=1
            tVal = maxVal
            running = True
            while not parent is None:
                if running:
                    if debug:
                        res.append(str(parent))
                    else:
                        res.append(str(parent.value))
```

```
                    tVal -= parent.value
                    if tVal < 0:
                        running = False
                else:
                    res.append('0')
                parent = parent.parent
            res.reverse()
            print ', '.join(res)


def main():

    nodes = []
    with open('nodes.csv', 'r') as f:
        raw = json.load(f)
        for nodedata in raw:
            nodes.append(Node(nodedata[0], nodedata[1]))

    #alle aeste erstellen
    root = nodes[0]
    for i in xrange(0, 17):
        nodes[i].add(nodes[i+1])
    for i in xrange(18, 38):
        nodes[i].add(nodes[i+1])
    for i in xrange(39, 61):
        nodes[i].add(nodes[i+1])
    for i in xrange(62, 74):
        nodes[i].add(nodes[i+1])
    for i in xrange(75, 93):
        nodes[i].add(nodes[i+1])
    for i in xrange(94, 121):
        nodes[i].add(nodes[i+1])
    for i in xrange(122, 145):
        nodes[i].add(nodes[i+1])
    for i in xrange(146, 154):
        nodes[i].add(nodes[i+1])
    for i in xrange(155, 159):
        nodes[i].add(nodes[i+1])

    #alle aeste aneinanderhaengen
    n = root.findById('006')
    n.add(nodes[18])
    n = root.findById('004')
    n.add(nodes[39])
    n = root.findById('054')
    n.add(nodes[62])
    n = root.findById('066')
    n.add(nodes[75])
    n = root.findById('078')
    n.add(nodes[94])
    n = root.findById('100')
    n.add(nodes[122])
    n = root.findById('137')
    n.add(nodes[146])
    n = root.findById('152')
    n.add(nodes[155])



    #n = root.findById('155')
    #print n
    #n.traverseBack(8, True)

    #matrix erstellen
    n = root.findById('018')
    n.traverseBack(10)
    n = root.findById('039')
    n.traverseBack(10)
    n = root.findById('062')
    n.traverseBack(10)
```

```
    n = root.findById('075')
    n.traverseBack(10)
    n = root.findById('094')
    n.traverseBack(10)
    n = root.findById('122')
    n.traverseBack(10)
    n = root.findById('146')
    n.traverseBack(10)
    n = root.findById('155')
    n.traverseBack(10)
    n = root.findById('160')
    n.traverseBack(10)


if __name__ == '__main__':
    main()
```

The matrix parts have then to be completed to a rectangular matrix. This matrix is stored in a comma separated values file (.csv). Incompatible separators can be simply replaced using Notepad++. A MATLAB script is used to transpose the complete matrix. The script can be found under `CSV_transpose.m`.

```
% length constraint matrix generator transposer
AE1 = csvread('original_matrix.csv');
AE1t = transpose(AE1);
csvwrite('transposed_matrix.csv', AE1t);
```

B.2 Minimum distance between worksites constraint

This constraint doesn't require a matrix and can completely be built inside an Excel-worksheet.

The following mathematical symbols are used:

The star ($*$) refers to a regular matrix multiplication;

The circle ($\circ$) refers to the Hadamard product (entry-wise product) of the two matrices;

The dot ($\cdot$) refers to a scalar multiplication.

1. A link consisting of $n=1,...,N$ objects is considered.
2. $\vec{s}$ is a vector with N elements, every entry is equal to 1 if the corresponding object is subject to an intervention and is equal to 0 if no intervention is being performed.
3. The vector $\vec{t}$ is defined as $\vec{t}=\left[\vec{s}(2:N);1\right]$;
   Where $\vec{s}(2:N)$ refers to the vector $\vec{s}$ excluding its first entry.
4. Vector $\vec{e}$ is defined as $\vec{e}=\vec{s}\circ\left(\vec{1}-\vec{t}\right)$. $\vec{1}$ refers to a vector with N entries, all of which are equal to 1. For every entry of $\vec{e}$ applies: If the entry is equal to 1 is the corresponding object the last object of a worksite. If the entry is equal to 0 is the object either not subject to an intervention or at the beginning or in the middle of a worksite.
5. L^{min} refers to the minimum distance between two worksites.
   Matrix M is defined as $M=\vec{e}*\vec{e}^{\mathrm{T}}\circ I\cdot\left(-L^{min}\right)$.
6. $\left(N-1\right)$ vectors $\vec{r}^{\,j}$ with N entries and $j=1,...,N-1$ are calculated. For every vector $\vec{r}^{\,j}$ with $n=1,...,N$ entries applies:
   - $r^{j,n}$ refers to entry n in vector $\vec{r}^{\,j}$, e^n refers to entry n in vector $\vec{e}$, s^n refers to entry n in vector $\vec{s}$;
   - $r^{j,n}=\begin{cases} r^{j,n}=0 & \text{for } n\le j \\ r^{j,n}=e^{n-1}\cdot\left(1-s^n\right) & \text{for } n=j+1 \\ r^{j,n}=r^{j,n-1}\cdot\left(1-s^n\right) & \text{for } n>j+1 \end{cases}$
7. $\vec{l}=\left[L_1;L_2;...;L_{N-1};L^{min}\right]$ is the vector representing the lengths of all objects in the link. The length of the last object $n=N$ is set to the minimum distance L^{min} regardless of the actual length of the object.
8. $\vec{m}^j$ refers to the column $j=1,...,N-1$ of the matrix M.
9. The constraint is now set as follows:
   $c^j=\left(\vec{l}^{\mathrm{T}}*\vec{r}^{\,j}\right)+\left(\vec{1}^{\mathrm{T}}*\vec{m}^j\right)\ge 0 \quad \forall j=1,...,N-1$

Example:

1. The considered link consists of 5 objects, $n = 1,...,5$.
2. Object 1, 2 and 4 are subject to an intervention, $\vec{s} = \begin{bmatrix}1 & 1 & 0 & 1 & 0\end{bmatrix}^{\mathrm{T}}$.
3. $\vec{t} = \begin{bmatrix}1 & 0 & 1 & 0 & 1\end{bmatrix}^{\mathrm{T}}$
4. $\vec{e} = \begin{bmatrix}0 & 1 & 0 & 1 & 0\end{bmatrix}^{\mathrm{T}}$
5. The minimum distance is set to be 12 km, $L^{min} = 12$.
$$M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -12 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -12 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$
6. 4 vectors $\vec{r}^{\,j}$ need to be set up:
$$\vec{r}^{\,1} = \begin{bmatrix}0\\0\\0\\0\\0\end{bmatrix};\ \vec{r}^{\,2} = \begin{bmatrix}0\\0\\1\\0\\0\end{bmatrix};\ \vec{r}^{\,3} = \begin{bmatrix}0\\0\\0\\0\\0\end{bmatrix};\ \vec{r}^{\,4} = \begin{bmatrix}0\\0\\0\\0\\1\end{bmatrix}$$
7. All objects are 10 km long, $\vec{l} = \begin{bmatrix}10 & 10 & 10 & 10 & 12\end{bmatrix}^{\mathrm{T}}$.
8. The first 4 columns of M are stored as vectors $\vec{m}^{\,j}$:
$$\vec{m}^{1} = \begin{bmatrix}0\\0\\0\\0\\0\end{bmatrix};\ \vec{m}^{2} = \begin{bmatrix}0\\-12\\0\\0\\0\end{bmatrix};\ \vec{m}^{3} = \begin{bmatrix}0\\0\\0\\0\\0\end{bmatrix};\ \vec{m}^{4} = \begin{bmatrix}0\\0\\0\\-12\\0\end{bmatrix}$$
9. The 4 constraints can be calculated:
$$c^1 = 0 + 0 = 0 \geq 0$$
$$c^2 = 10 + (-12) = -2 \not\geq 0$$
$$c^3 = 0 + 0 = 0 \geq 0$$
$$c^4 = 12 + (-12) = 0 \geq 0$$
The second constraint is violated, which means that there is a distance between two worksites in the network that is too short.