# Digitalizing the Determination of Railway Infrastructure Intervention Programs: A Network Optimization Model

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# Digitalizing the Determination of Railway Infrastructure Intervention Programs: A Network Optimization Model

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**Abstract:** One area of railway infrastructure management that can benefit greatly from digitalization is the determination of optimal intervention programs, i.e., when, where, and which type of interventions are to be executed. The potential benefit is considerable because of the large variety of assets required for the infrastructure to function as intended, the interconnectedness of the assets, the extensive number of different types of possible interventions, and the wide range of service measures to consider when deciding between different intervention programs—all of which are difficult, if not impossible, to consider qualitatively. In this paper, a network flow optimization model is presented that determines the optimal intervention program considering different types of assets, interventions and service measures to execute the interventions, the dependencies between interventions, and the relation between interventions and service in the short and long term. The model is developed and used to determine the intervention program that maximizes the net benefit for a 17-km railway line over a 12-year planning period, divided into three four-year blocks. The example demonstrates that the model can be used to determine optimal intervention programs on real-world railway networks, taking into consideration the intervention costs and relevant measures of service, the interrelationships between the different assets, and multiple time periods. It also demonstrates that the model is a powerful management tool for leveraging the digitalization of railway infrastructure. **DOI: 10.1061/(ASCE)IS.1943-555X.0000681.** 

**Author keywords:** Railway network; Optimization; Maintenance; Intervention program.

## Introduction

Railway infrastructure managers have to decide when, where, and which type of interventions are to be executed on their infrastructure to provide the required service. Asset managers determine the optimal asset intervention strategies. This means they determine how to maintain their assets in the long term and the optimal point in time to execute interventions. The information about the type of intervention, its location, the costs, and the required track possession is then provided to the program manager, who has an overview over all interventions from all types of assets on the network. Program managers determine a cohesive networkwide intervention program for a specific upcoming planning period. They determine the interventions to be executed in the medium term, e.g., 4–12 years. Interventions in the short term, e.g., less than four years, have most often already been handed off to project managers and can no longer be changed without considerable expense. Interventions in the long term, e.g., beyond 12 years, are coupled with a large amount of uncertainty related to the entire transport system, so they are not of particular interest for program managers. For the medium term, program managers have to take into consideration the interactions between the different assets and interventions, the topological characteristics of the network, network level constraints such as budget, and how to ensure that all stakeholders receive the most for their money.

Currently, intervention programs are determined in a qualitative process based on experience, manual grouping of interventions, and simple decision rules. For example, the prioritization of interventions if insufficient resources are available to execute all necessary interventions and the grouping of interventions with a focus on minimizing traffic disturbances are considered in separate steps. Due to the manual work, the qualitative process limits the potential of digitalization to a centralized database, a digital technology that is not yet common in all railway infrastructure organizations. It limits the ability to ensure the optimality of the intervention programs. It can only consider a small number of different things at a detailed level or all things at a highly abstract level within a limited amount of time. Computers, however, can consider a large number of things at a detailed level. Furthermore, the predominant use of a qualitative process prevents the inclusion of all criteria in a way that makes them directly comparable. This is useful in making consistent and transparent decisions (Adey et al. 2019). The field of digitalization has, therefore, a much larger potential than is currently used in infrastructure management. The digitalization of intervention planning enables the use of operation research–based decision models that support program managers in the development of optimal intervention programs. It improves the use of information existing in different departments within a railway infrastructure organization.

Over the last two decades, an increasing number of decision models have been developed in research that allow the optimization of intervention programs from different perspectives, e.g., Budai-Balke (2009), Pargar (2015), Burkhalter and Adey (2018), and Dao et al. (2019). The application of such models requires quantification of the intervention costs and the effects on service related to the interventions and how they change when interventions are moved in time, either due to constraint limitations or due to synergies in grouping the interventions. This quantification, however, is especially

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challenging given the limited information flow that normally exists between asset and program managers. Current processes greatly restrict the use of existing models in decision-making.

In this paper, a network flow optimization model is presented that enables the digitalized determination of the optimal intervention program considering all of the relevant aspects. The artificial network model comprises an object level that enables the selection of the interventions and a network level that enables the correct estimation of the effect on the service provided. It allows the determination of the intervention program with the highest net benefit consisting of the costs and benefits of the interventions. The costs refer to the intervention costs and the effects on service during the execution of the interventions. The benefits refer to the difference in the risk and the interventions beyond the planning period due to the execution of the intervention program. The model is based on the one developed in Burkhalter and Adey (2018) for a small network and a single time period. Within this paper, the underlying assumption about the possibility of executing interventions in parallel is improved to consider the full potential of grouping interventions on a larger railway network. The modeling is further extended to be able to model multiple periods within the entire planning problem.

To demonstrate the potential of a digitalized determination of intervention programs, the model is used to determine the optimal intervention program for a 17-km railway line over a 12-year planning period, divided into three four-year periods. The results of the model are compared with the actual interventions chosen by the infrastructure managers using an existing qualitative process. The example demonstrates that the model can be used to determine optimal intervention programs on real-world rail networks, taking into consideration the intervention costs and all relevant measures of service, the interrelationships between the different assets, and multiple time periods, in ways that are not possible qualitatively. It also demonstrates the usefulness of computer-based optimization models in the digitalization of railway infrastructure management.

The remainder of the paper is structured as follows. First, a summary of the models to develop intervention programs in literature is provided. Second, the methodology to determine optimal intervention programs is introduced, including the formulations of the optimization model. Third, the case study is presented. Forth, the paper is discussed. Last, a conclusion and an outlook are provided.

## Literature

The development of intervention programs on railway infrastructure, as one of many other types of networks (Adey 2019; Lethanh et al. 2018), has received an increasing amount of attention over the last two decades. The developed models vary as a function of the specific problems addressed, including the specific assets and interventions considered and the selected optimization methods. Table 1 summarizes previous research indicating the considered type of assets, the decisions optimized, the optimization objective, the intervention dependencies considered, and the information required as input in the optimization model.

As can be seen in Table 1, there has been considerable research on determining optimal intervention programs for railway infrastructure focused on a single type of asset, e.g., tracks or bridges. The decisions modeled are, therefore, dependent on the type of assets considered. Models for tracks focus on the scheduling and grouping of a set of defined interventions within a limited planning period considering work team constraints (Budai-Balke 2009; Higgins et al. 1999; Peng 2011; Pouryousef et al. 2010). They consider the dependencies in the intervention costs when grouping neighboring interventions. Models considering the different track components optimize the grouping of a set of candidate interventions on the individual components and consider the dependencies in their intervention costs (Caetano and Teixeira 2015; Pargar 2015; Zhao et al. 2009). Models for bridges mostly focus on the prioritization of interventions with given budget limitations, i.e., selecting the interventions to be executed. Due to the characteristic of bridges being individual assets spread across the network, the models do not include dependencies in the intervention costs, but consider the bridges' location within the network topology when considering the network reliability (Frangopol and Liu 2007) or the traffic costs during the execution of interventions (Zhang and Alipour 2020).

The consideration of multiple asset types, and the potential synergies between the interventions on their assets, has only recently become the focus of research efforts (Burkhalter and Adey 2018; Burkhalter et al. 2018; Dao et al. 2019). These efforts consider the interdependent intervention costs between interventions on assets of the same type, and the potential synergies for the traffic disruption when grouping interventions on assets of different types on the same line of the railway network. While Dao et al. (2019) developed a model that allows the optimal grouping of a set of defined interventions within a single time period, Burkhalter and Adey (2018) included additionally the optimal selection of interventions to be executed in a single time period.

In addition to information on the physical aspects of the interventions, e.g., type and location, the models developed in research predominately consider the costs for the infrastructure owner and the effects on service during the execution of the interventions. They neglect the effects of moving interventions in time, e.g., referring to the models that group a set of defined interventions, and the effect of executing an intervention or not, e.g., referring to the models that prioritize and select interventions. This is only justifiable when the move in time is small enough to not affect the asset condition. Budai-Balke (2009) requires, therefore, the earliest and latest point in time that interventions need to be executed, which is defined by the asset managers beforehand. Only a limited number of research studies considered these effects either by considering the life-cycle losses (Zhao et al. 2009), the network reliability based on the assets condition (Frangopol and Liu 2007), or the risk reduced by interventions (Burkhalter and Adey 2018; Burkhalter et al. 2018).

The model proposed in Burkhalter and Adey (2018) enables the consideration of different types of assets, the dependencies between interventions regarding the intervention and traffic state costs, and network-level constraints such as a budget limitation. It maximizes the net benefit of the intervention program, considering the benefit achieved in terms of the risk reduced by the interventions. This model, however, considers only one time period, where the definition of the right period length depends on the differences in asset characteristics and stakeholder requirements. A rather short time period limits the possible interventions to be considered for grouping, and therefore for reducing the impacts related to the execution of the interventions. A rather long time period leads to difficulties in considering assets that deteriorate faster, due to the neglected differences in the assets' condition during the longer time period. Furthermore, this model was applied on a relatively small network, where the assumption that certain interventions cannot be executed simultaneously due to interference on the track clearance may be valid. On a larger network, however, interventions could be executed simultaneously when they are at different locations.

It can be seen from the review of literature that no one has yet proposed an operations research model that can be used on realistically sized networks over multiple time periods to plan maintenance interventions while considering dependencies between

**Table 1.** Literature on the optimization of intervention programs

| Author | Asset types | Decision-making context | Objective | Intervention dependencies | Input information required |
|---|---|---|---|---|---|
| Higgins et al. (1999) | Track | Scheduling a set of defined interventions | Minimal intervention costs and traffic delay | Intervention costs between neighboring interventions<br>Resource limitations | Asset location<br>Intervention costs<br>Intervention duration |
| Zhao et al. (2009) | Track components | Scheduling and grouping a set of defined interventions | Minimal intervention costs and life-cycle cost losses | Intervention costs between neighboring interventions | Asset location<br>Intervention costs<br>The optimal and latest point in time to execute the interventions<br>Life-cycle costs of the asset |
| Budai-Balke (2009) and Pouryousef et al. (2010) | Track | Scheduling and grouping a set of defined interventions and large individual projects | Minimal intervention costs and traffic delay | Intervention costs between neighboring interventions<br>Resource limitations | Asset location<br>Duration of projects<br>Earliest and latest point in time to execute the projects<br>Maximal periodicity of routine maintenance |
| Peng (2011) | Track | Scheduling and grouping a set of defined interventions | Minimal intervention costs and traffic delay | Intervention costs between neighboring interventions<br>Resource limitations | Asset location<br>Intervention costs<br>Intervention duration |
| Pargar (2015) | Track components | Scheduling and grouping of a set of candidate interventions | Minimal intervention and traffic costs | Intervention costs between neighboring interventions<br>Topological consideration for traffic costs | Asset location<br>Intervention costs<br>Intervention duration |
| Caetano and Teixeira (2015) | Track components | Scheduling and grouping of a set of candidate interventions | Minimal intervention costs | Intervention costs between neighboring interventions<br>Budget limitation | Asset location<br>Intervention costs |
| Frangopol and Liu (2007) | Bridges | Prioritizing interventions over multiple time periods | Minimal intervention costs and maximal reliability | Network reliability<br>Budget limitation | Asset location<br>Intervention costs<br>Condition improvement of interventions |
| Zhang and Alipour (2020) | Bridges | Prioritizing interventions for a single time period | Minimal intervention costs and minimal traffic disturbance | Topological consideration for traffic costs<br>Budget limitation | Asset location<br>Intervention costs<br>Intervention duration |
| Burkhalter et al. (2018) and Burkhalter and Adey (2018) | Track, switches, bridges | Selecting and grouping interventions for a single time period | Maximal net benefit considering intervention, traffic costs, and intervention benefit | Intervention costs between neighboring interventions<br>Topological consideration for traffic costs Budget limitation | Asset location<br>Intervention costs<br>Intervention duration<br>Risk reduction of interventions |
| Dao et al. (2019) | Track, switches, level crossing | Grouping a set of defined interventions within a single time period | Minimal intervention and traffic costs | Intervention costs between neighboring interventions<br>Topological consideration for traffic costs | Asset location<br>Intervention costs<br>Intervention duration |

assets of different types. This gap is an essential but missing step in enabling the full potential of digitalization, and the model presented in this paper aims to bridge it.

## Determining Optimal Intervention Programs

### *Methodology*

The optimal intervention program is defined as the one that maximizes the net benefit [Eq. (1)]. The costs and benefits of an intervention program are quantified as the difference in the costs and benefits when the interventions are executed and when they are postponed beyond the planning period of the intervention program. The costs equal the costs of the intervention program, as the costs during the planning period would be zero when all interventions are postponed. The benefits are quantified as (1) the reduction in risk related with an assets failure, and (2) the reduction in costs related to the execution of maintenance and preventive interventions in the future. The costs of the intervention program, the risk related to an asset failure, and the costs related to interventions in the future consist of (1) the preventive or corrective intervention costs for the owner, e.g., costs for material, labor, and logistics; and (2) the additional travel time costs for the user due the traffic disturbance [Eqs. (2) and (3)]. The risk additionally includes the costs for accidents happening due to an assets failure [Eq. (3)].

For example, interventions on assets improve the condition of the assets and therefore reduce the risk related to asset failures, while not executing interventions increases the risks, increases the need for routine maintenance until the next renewal, and makes other interventions required sooner beyond the planning period. More detailed information on how to estimate the net benefit of an intervention can be found in Burkhalter and Adey (2021)

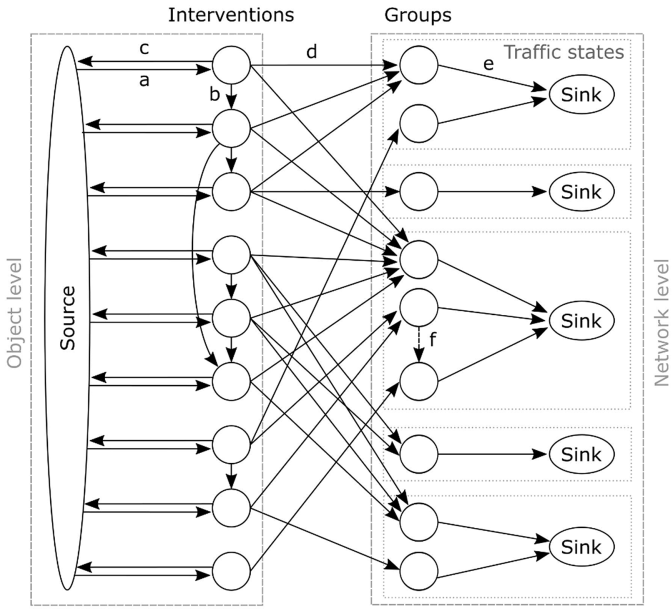


**Fig. 1.** Network flow optimization model.

$$\text{Max net benefit} = \text{Benefit} - \text{Costs} = \text{Reduction in (risk + costs related to future interventions)} - \text{Costs related to the intervention program} \quad (1)$$

$$\text{Costs related to interventions} = \text{Intervention costs} + \text{Travel time costs} \quad (2)$$

$$\text{Risk} = \text{Probability of an asset failure} \cdot (\text{Preventive intervention costs} + \text{Travel time costs} + \text{Accident costs}) \quad (3)$$

To optimize the intervention program, the list of candidate interventions needs to be defined, including the cost and duration of the intervention, the minimal required network closure to execute the intervention, and the benefit of the intervention based on the assets condition and the point in time of the intervention execution. The benefit quantification needs thereby to include the long-term effect of interventions. This requires the consideration of the assets being maintained and renewed according to their individual strategies beyond the planning period. Only a benefit quantification considering the current condition of the asset, the intervention strategies, and the life-cycle costs enables a proper quantification of the effect when an intervention is moved out of its optimal point in time. This requires program managers to have access to more detailed information about the decisions made by asset managers regarding the intervention strategies and the defined interventions. A digitalized determination of intervention program thereby supports the information transfer compared to a manual and qualitative process.

## Network Flow Model

The network flow model developed in this paper is an extension of the one presented in Burkhalter and Adey (2018). The problem is modeled with an artificial network using the type of system model presented in Burkhalter and Adey (2020). It consists of an object level and a network level (Fig. 1). The object level pertains to the selection of the interventions. Its nodes represent specific interventions on specific assets in specific time periods The edges consider the dependencies between different interventions on different assets, e.g., shared logistic and human labor costs. The network level pertains to the estimation of effects on users, taking into consideration the duration of the different traffic states required to execute the interventions. The nodes represent specific groups of interventions executed with specific traffic states in specific time periods. The definition of a traffic state consists of the specific location of a closure and the time window in which it is to be used, i.e., night or day shift. The edges consider the dependencies between different groups of interventions, i.e., their requirement for serial execution or the possibility for a parallel execution. Compared to the model in Burkhalter and Adey (2018), the model formulated here allows for the consideration of multiple time periods $p$ within the entire planning period. Both intervention and group nodes assign a specific intervention or a group of interventions to a specific time period $p$. The structure of the network flow model remains, therefore, the same as in the previous model, but it allows the consideration of multiple time periods.

The model consists of three type of edges, i.e., intervention selection edges $\delta$, execution duration edges $\gamma$, and topological edges $\varepsilon$. Table 2 provides the edge information regarding the

**Table 2.** Edges of the artificial network

| Edges | The flow on edges represent: | Edge in Fig. 1 | The benefit associated with the edge $(u,v)$ equals: | The cost associated with the edge $(u,v)$ equals: |
|---|---|---|---|---|
| $\delta$ | The selected interventions | $a$ | The benefit of executing the intervention represented by Node $v$ $b_{u,v} = b_v$ | The fix and variable cost of executing the intervention represented by Node $v$ $c_{u,v} = c_v^{fix} + c_v^{\text{var}}$ |
| | | $b$ | The benefit of executing the intervention represented by Node $v$ $b_{u,v} = b_v$ | The variable cost of executing the intervention represented by Node $v$ $c_{u,v} = c_v^{\text{var}}$ |
| | | $c$ | 0 $b_{u,v} = 0$ | 0 $c_{u,v} = 0$ |
| $\gamma$ | The duration a traffic state is required | $d$ | 0 $b_{u,v} = 0$ | 0 $c_{u,v} = 0$ |
| | | $e$ | 0 $b_{u,v} = 0$ | The cost per time unit of the traffic state Node $u$ relates to $c_{u,v} = c_v^{\text{time}}$ |
| $\varepsilon$ | The duration of the parallel execution of groups of interventions | $f$ | 0 $b_{u,v} = 0$ | 0 $c_{u,v} = 0$ |



J. Infrastruct. Syst., 2022, 28(2): 04022012

representation of the flow, and the benefit and cost associated with each edge. Topological edges $\varepsilon$ exist between groups of interventions that can be executed parallel in time, which they can if they fulfill all three criteria:

- The group of interventions are executed with the same traffic state;
- The interventions of one group are neither economically nor structurally dependent on the interventions of the other group, which would require a sequential execution of the interventions; and
- The interventions of one group are not at the exact same location in the network as the interventions of the other group, or do not prevent other interventions to be executed at the same location.

The net benefit of each edge $NB_{u,v}$ is estimated by subtracting the costs associated with edge $c_{u,v}$ from the benefit associated with edge $b_{u,v}$ [Eq. (4)]. The costs and benefit associated with each edge vary depending on the edge type (Table 2)

$$NB_{u,v} = b_{u,v} - c_{u,v} \tag{4}$$

Compared to the model in Burkhalter and Adey (2018), the model formulated here allows for the consideration of multiple time periods $p$ within the entire planning period. Therefore, the intervention nodes represent specific interventions on specific assets in specific time periods, and the group nodes represent specific groups of interventions executed under specific traffic states in specific time periods. The budget constraint is modified to ensure that the interventions within one period $V_p$ do not exceed the budget limitation of the period.

### Mathematical Formulation

The objective of the model is to maximize the net benefit of an intervention program by multiplying the flow on the edges of the artificial network with the net benefit values associated with each edge [Eq. (5)]

$$\text{Max } Z = \sum_{u\in V}\sum_{v\in V}\delta_{u,v}\cdot NB_{u,v} + \sum_{u\in V}\sum_{v\in V}\gamma_{u,v}\cdot NB_{u,v} \tag{5}$$

where $\delta_{u,v}$ = binary variables that are 1 if the edge $(u,v)$ between Nodes $u$ and $v$ is part of the optimal path and 0 otherwise; $\gamma_{u,v}$ = nonnegative variables that represent the time flow on the edge $(u,v)$ between Nodes $u$ and $v$; and $NB_{u,v}$ = net benefit associated with the edge between Nodes $u$ and $v$

$$\sum_{v\in V}\delta_{v,u} = \sum_{v\in V}\delta_{u,v}, \quad \forall\ u\in V \tag{6}$$

$$\sum_{v\in V}\delta_{v,u}\cdot d_{v,u} + \sum_{v\in V}\gamma_{v,u} = \sum_{v\in V}\gamma_{u,v} + \sum_{v\in V}\varepsilon_{u,v}, \quad \forall\ u\in V \tag{7}$$

$$\varepsilon_{v,u} \le \sum_{w\in V}\gamma_{u,w}, \quad \forall\ u\in V \tag{8}$$

$$\sum_{u\in V}\sum_{v\in V_n}\delta_{u,v} \le 1, \quad \forall\ n \tag{9}$$

$$\sum_{u\in V}\delta_{u,v} - \sum_{u\in V}\delta_{u,w} \le 0, \quad \forall\ (v,w)\in SD \tag{10}$$

$$\sum_{u\in V^p}\sum_{v\in V^p}\delta_{u,v} * c_{u,v} \le \Omega^p_{\max}, \quad \forall\ p \tag{11}$$

The model constraints are shown in Eqs. (6)–(11). Eqs. (6) and (7) contain the flow conservation constraints on the object and network level. They ensure that the incoming flow of a node equals the outgoing flow. $d_{v,u}$ represents the durations associated with the edge between Nodes $u$ and $v$. Edge $\varepsilon_{u,v}$ is a sink edge that is only part of the flow conservation constraint in its original node $u$, but not in its destination node $v$. $\varepsilon_{u,v}$ is constrained by the flow in the destination node $v$, which is shown formulated in Eq. (8). Eq. (8) contains the topological dependency constraints ensuring that not more of the time in Node $u$ is considered as parallel to Node $v$, represented by $\varepsilon_{u,v}$, than the actual used time in Node $v$. Eq. (9) contains the exclusivity constraint ensuring that at most one intervention per asset is selected, where $V_n$ refers to the set of intervention nodes representing an intervention on Asset $n$. Eq. (10) contains the structural constraints ensuring that the mandatory intervention $w$ of a structural pair $SD$ is selected if the initial intervention is selected $v$. A structural pair $(v,w)\in SD$ of interventions exist when Intervention $v$ requires the execution of Intervention $w$, e.g., a track on a bridge needs to be renewed when the bridge is renewed. Finally, Eq. (11) formulates the budget constraint with a budget limitation $\Omega^p_{\max}$ for each time period $p$.

## Case Study

How the model is used to determine optimal intervention programs, and how it improves the intervention program with respect to one developed qualitatively, is demonstrated by determining the intervention program for a railway line in Switzerland for a 12-year planning period, i.e., 2019–2030. The entire planning period is divided into three four-year periods for which the interventions to be executed are selected and grouped. The developed program is compared with the one developed by the railway managers using their qualitative process.

The different intervention programs are determined with and without considering a budget constraint. All intervention programs are compared with respect to their selected interventions, their grouping of the interventions, their costs related to the execution of the interventions, and the benefit achieved by the execution of their interventions. The intervention program developed qualitatively represents the process currently used in practice, where the interventions required are provided by asset managers and manually converted into intervention programs by program managers. This manual development of intervention programs is mainly based on discussions between the program managers and the asset managers about the possibilities and effects of moving interventions in time and grouping interventions together. In this qualitative process, the intervention program is determined based on rather limited information about the interventions required, i.e., the point in time to execute the intervention, the location of the asset within the network, and the required network closure to execute the interventions. Determining the optimal intervention program using the optimization model, however, uses more detailed information, including that provided by the asset manager, i.e., the asset's condition and deterioration, intervention strategies, the condition-related risk of failure, and costs related to routine maintenance. To enable this comparison, all missing information that was not available was estimated using reliable sources.

First, the considered situation is introduced with all required information, i.e., infrastructure, deterioration models, the interventions and intervention strategies, traffic states, and risk. Second, the complexity of the network flow model for this situation is provided. The last two subsections provide and discuss the results without and with a budget limitation.

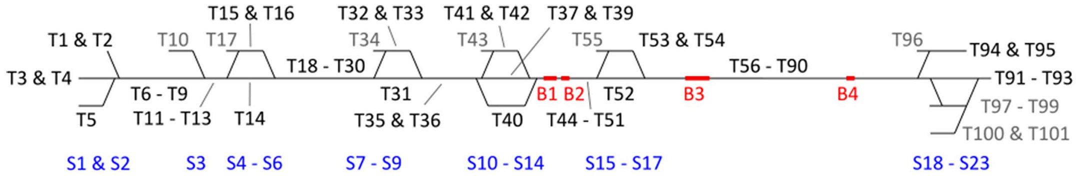


**Fig. 2.** Case study network.

### *Situation*

#### Infrastructure

The railway network is a 17-km-long single-track line in Switzerland consisting of 10 stations, labeled A–J, 101 track segments, 23 switches, and four bridges (Fig. 2). Station A is connected to the rest of the network and Station J is a terminal station. The location, extent in meters, and condition of each track segment are given in Table 3. The location is described by the section or station to which the track belongs, and the numbered track segment within the section or station. For example, Track T2 is the second track segment on Track 1 of Station *A*. *Siding* refers to a track next to the main track not used for the operation of the scheduled passenger service. The location and condition of each switch is given in Table 4. The location is described with the station name and the switch number within the station. The track segments connected to each switch are also given. For example, Switch S2 is the second switch in Station A connecting Track segments T5 straight with T2 and by a turnout to T4. The locations and conditions of the bridges are given in Table 5. The location is described by the section. For example, Bridge B1 is located within F–J. The track segments on top of each bridge are also noted.

#### Condition Classification

Asset conditions in Tables 3–5 are described according to the classification scheme of the R RTE 29900 (VöV 2018) (Table 6). This classification uses a generalized condition description of the functional state of the assets, which is applicable for all type of assets. A generalized condition scale based on the function state is preferable in this situation, as it simplifies the consistency between the asset's condition, the intervention strategies, and the impacts related to the asset's condition, i.e., risk of failure and required routine maintenance. It requires asset managers, however, to aggregate and transform the physical condition of the asset or its individual component to a generalized condition.

#### Deterioration Models

Deterioration models are required to predict the future asset condition, which in turn is required to identify candidate interventions and estimate their costs and benefits. Although there is extensive research in this area that has resulted in sophisticated and detailed deterioration models for different types of infrastructure assets, only simple approximate deterioration models (Table 7) were used in this case study. This helps keep the focus of the paper on the model to be used to determine intervention programs. More sophisticated models can be used if desired. The deterioration rates used were developed using the lifetimes suggested in the R RTE 29900 (VöV 2018). Using partial linear functions to model the deterioration, the asset conditions are modeled in continuous form. An asset is in one of the conditions described in Table 6 when its continuous condition description reaches the integer values. For example, an asset with a condition of 2.3 is in a good state.

**Table 3.** Track segments

| ID | Location (section/track/segment) | Length (m) | Current condition |
|---|---|---|---|
| T1 | A/1/1 | 155 | 1.5 |
| T2 | A/1/2 | 60 | 2.4 |
| T3 | A/2/1 | 239 | 1.4 |
| T4 | A/2/2 | 31 | 2.0 |
| T5 | A/3 | 197 | 1.2 |
| T6 | A–B/1/1 | 235 | 2.2 |
| T7 | A–B/1/2 | 468 | 1.0 |
| T8 | A–B/1/3 | 104 | 1.8 |
| T9 | A–B/1/4 | 758 | 2.0 |
| T10 | B/siding | 192 | 2.0 |
| T11 | B–C/1/1 | 306 | 1.5 |
| T12 | B–C/1/2 | 37 | 2.8 |
| T13 | B–C/1/3 | 46 | 1.0 |
| T14 | C/1 | 209 | 1.0 |
| T15 | C/2/1 | 47 | 1.3 |
| T16 | C/2/2 | 163 | 2.0 |
| T17 | C/siding | 121 | 1.1 |
| T18 | C–D/1/1 | 126 | 3.8 |
| T19 | C–D/1/2 | 295 | 2.2 |
| T20 | C–D/1/3 | 38 | 2.0 |
| T21 | C–D/1/4 | 268 | 2.8 |
| T22 | C–D/1/5 | 76 | 2.0 |
| T23 | C–D/1/6 | 194 | 2.8 |
| T24 | C–D/1/7 | 296 | 2.8 |
| T25 | C–D/1/8 | 181 | 2.2 |
| T26 | C–D/1/9 | 787 | 2.0 |
| T27 | D–E/1/1 | 120 | 2.3 |
| T28 | D–E/1/2 | 135 | 1.4 |
| T29 | D–E/1/3 | 394 | 3.8 |
| T30 | D–E/1/4 | 72 | 1.2 |
| T31 | E/1 | 193 | 2.5 |
| T32 | E/2/1 | 57 | 2.7 |
| T33 | E/2/2 | 136 | 2.0 |
| T34 | E/siding | 180 | 1.0 |
| T35 | E–F/1/1 | 264 | 3.1 |
| T36 | E–F/1/2 | 1,494 | 2.0 |
| T37 | F/1/1 | 43 | 2.0 |
| T38 | F/1/2 | 161 | 1.1 |
| T39 | F/1/3 | 24 | 2.0 |
| T40 | F/2 | 229 | 2.0 |
| T41 | F/3/1 | 37 | 2.0 |
| T42 | F/3/2 | 124 | 2.0 |
| T43 | F/siding | 113 | 2.7 |
| T44 | F–G/1/1 | 21 | 2.0 |
| T45 | F–G/1/2 | 97 | 2.7 |
| T46 | F–G/1/3 | 160 | 2.7 |
| T47 | F–G/1/4 | 57 | 2.7 |
| T48 | F–G/1/5 | 11 | 2.7 |
| T49 | F–G/1/6 | 7 | 2.7 |
| T50 | F–G/1/7 | 176 | 2.7 |
| T51 | F–G/1/8 | 1,233 | 1.1 |
| T52 | G/1 | 239 | 2.0 |
| T53 | G/1/1 | 186 | 2.0 |
| T54 | G/1/2 | 54 | 2.0 |
| T55 | G/siding | 106 | 1.5 |
| T56 | G–H/1/1 | 102 | 1.4 |

**Table 3.** (*Continued.*)

| ID | Location (section/track/segment) | Length (m) | Current condition |
|---|---|---|---|
| T57 | G–H/1/2 | 273 | 3.3 |
| T58 | G–H/1/3 | 299 | 2.3 |
| T59 | G–H/1/4 | 299 | 2.3 |
| T60 | G–H/1/5 | 120 | 2.3 |
| T61 | G–H/1/6 | 115 | 2.2 |
| T62 | G–H/1/7 | 272 | 2.5 |
| T63 | G–H/1/8 | 177 | 2.0 |
| T64 | G–H/1/9 | 92 | 1.3 |
| T65 | H–I/1/1 | 112 | 2.3 |
| T66 | H–I/1/2 | 305 | 3.1 |
| T67 | H–I/1/3 | 673 | 4.0 |
| T68 | H–I/1/4 | 164 | 2.2 |
| T69 | H–I/1/5 | 60 | 2.4 |
| T70 | H–I/1/6 | 281 | 2.2 |
| T71 | H–I/1/7 | 396 | 2.2 |
| T72 | H–I/1/8 | 266 | 1.0 |
| T73 | H–I/1/9 | 566 | 4.0 |
| T74 | H–I/1/10 | 102 | 4.0 |
| T75 | H–I/1/11 | 111 | 3.6 |
| T76 | H–I/1/12 | 182 | 2.0 |
| T77 | I–J/1/1 | 90 | 3.1 |
| T78 | I–J/1/2 | 397 | 1.0 |
| T79 | I–J/1/3 | 150 | 2.3 |
| T80 | I–J/1/4 | 161 | 2.3 |
| T81 | I–J/1/5 | 199 | 2.5 |
| T82 | I–J/1/6 | 136 | 2.2 |
| T83 | I–J/1/7 | 6 | 2.2 |
| T84 | I–J/1/8 | 61 | 2.2 |
| T85 | I–J/1/9 | 77 | 2.2 |
| T86 | I–J/1/10 | 174 | 2.0 |
| T87 | I–J/1/11 | 601 | 1.5 |
| T88 | I–J/1/12 | 226 | 2.0 |
| T89 | I–J/1/13 | 431 | 1.1 |
| T90 | I–J/1/14 | 16 | 4.0 |
| T91 | J/1/1 | 82 | 2.0 |
| T92 | J/1/2 | 181 | 4.0 |
| T93 | J/siding 1 | 58 | 4.0 |
| T94 | J/2/1 | 57 | 1.4 |
| T95 | J/2/2 | 182 | 1.2 |
| T96 | J/siding 2 | 76 | 2.4 |
| T97 | J/3/1 | 55 | 2.0 |
| T98 | J/3/2 | 90 | 2.2 |
| T99 | J/siding 3 | 78 | 4.2 |
| T100 | J/3/3 | 36 | 2.0 |
| T101 | J/siding 4 | 169 | 4.1 |

## Interventions and Intervention Strategy

The types of interventions considered were track renewal and rail replacement, switch replacement, and bridge renewal. The interventions are given in Table 8 along with the condition expected following the intervention, their unit costs, their shared cost factors, and the required duration of track possession. The shared cost factors indicate thereby the percentage of the costs that can be shared when interventions are combined on neighboring assets. The intervention program to be determined consists only of these types of interventions. Minor interventions, such as tamping and grinding, are omitted from the intervention program as they are planned less ahead of time and because they can mostly be executed without traffic disruption. They are, though, considered in the route maintenance costs as a function of the asset condition.

The unit cost and track possession per unit were assumed based on the information provided by the infrastructure manager.

**Table 4.** Switches

| ID | Location | Adjoined track segments | Current condition |
|---|---|---|---|
| S1 | A 1 | T4, T3, T5 | 1.2 |
| S2 | A 2 | T6, T4, T2 | 1.2 |
| S3 | B 1 | T11, T9, T10 | 3.5 |
| S4 | C 1 | T13, T14, T15 | 1.3 |
| S5 | C 2 | T16, T17, T15 | 1.3 |
| S6 | C 3 | T18, T14, T16 | 1.0 |
| S7 | E 1 | T30, T31, T32 | 3.4 |
| S8 | E 2 | T33, T34, T32 | 2.0 |
| S9 | E 3 | T35, T31, T33 | 3.4 |
| S10 | F 1 | T36, T37, T40 | 3.4 |
| S11 | F 2 | T37, T38, T41 | 1.6 |
| S12 | F 3 | T42, T43, T42 | 1.0 |
| S13 | F 4 | T39, T38, T42 | 1.8 |
| S14 | F 5 | T44, T39, T40 | 3.4 |
| S15 | G 1 | T51, T52, T53 | 1.5 |
| S16 | G 2 | T54, T55, T53 | 1.9 |
| S17 | G 3 | T56, T52, T54 | 1.3 |
| S18 | J 1 | T90, T91, T94 | 4.1 |
| S19 | J 2 | T95, T96, T94 | 4.1 |
| S20 | J 3 | T91, T92, T97 | 1.9 |
| S21 | J 4 | T98, T99, T97 | 4.1 |
| S22 | J 5 | T100, T98, T101 | 1.1 |
| S23 | J 6 | T93, T92, T100 | 4.1 |

**Table 5.** Bridges

| ID | Location | Related track | Extent ($m^2$) | Current condition |
|---|---|---|---|---|
| B1 | F–G | T47 | 285 | 2.0 |
| B2 | F–G | T49 | 33 | 1.6 |
| B3 | G–H | T63 | 883 | 3.0 |
| B4 | I–J | T83 | 30 | 3.1 |

**Table 6.** Conditions according to the R RTE 29900 (VöV 2018) (translated to English)

| Condition | Description |
|---|---|
| 1—New | There are no discernible differences between the actual and design characteristics; the probability that the design traffic flow capacity will be affected in the next year is negligible |
| 2—Good | There are discernible differences between actual and design characteristics; the probability that the design traffic flow capacity will be affected in the next year is nonnegligible |
| 3—Sufficient | There are small differences between the actual and design characteristics; the probability that the design traffic flow capacity will be affected in the next year is small |
| 4—Bad | There are medium differences between the actual and design characteristics; the probability that the design traffic flow capacity will be affected in the next year is medium |
| 5—Insufficient | There are large differences between the actual and design characteristics; the probability that the design traffic flow capacity will be affected in the next year is high |

**Table 7.** Deterioration considered

| Asset category | Condition range | Deterioration rate |
|---|---|---|
| Main tracks | 1–5 | 0.16 |
| Siding tracks | 1–5 | 0.075 |
| Switches | 1–5 | 0.12 |
| Bridges | 1–3 | 0.025 |
| | 3–5 | 0.1 |

For example, the infrastructure manager executes 100 m of rail replacement in a 4-h night shift, and the renewal of a bridge of 880 $m^2$ requires a track possession for three weeks. These numbers are, of course, approximate averages varying widely depending on the specific asset (MAINLINE Consortium 2013).

The shared cost factor was based on values shown in literature. For tracks, it was assumed that 20% of the total costs for interventions on tracks could be shared when combining interventions on neighboring assets. This estimate was made assuming that 50% of the engineering and logistic costs, which were shown by Caetano and Teixeira (2016) to be 40% of the total costs of track interventions, were independent of the assets' extent. For switches, a 16% cost reduction was considered for grouping switch interventions, as found by Dao et al. (2019).

The intervention strategies for tracks, switches, and bridges were to renew the assets if they were in State 4. The track intervention strategy additionally included the replacement of the rails if the track was in State 3. Rail replacement was a partial renewal intervention and replaced only the rail. It improved the overall asset condition by one state relative to the current condition. Track renewal included the replacement of sleepers, ballast, and the rail. This improvement, however, decreased with each additional rail replacement between two track renewals, and therefore it was only used once between two track renewals.

## Routine Maintenance

The interventions considered for the intervention program consist only of renewal and partial renewal. Nevertheless, routine interventions were considered to be executed over time to ensure the assets reach their intended lifetime, e.g., grinding and tamping. This routine maintenance is considered here as maintenance costs dependant on the asset condition. The values in Table 9 are derived from the average spending for maintenance in Switzerland (SBB Infrastruktur 2020).

## Traffic States

The traffic states specify which section of the network is closed (*closure*) during which time of the day or week (*time window*), and have their own costs per hour. The cost of a traffic state $k$ per hour $C_k$ is estimated by multiplying the number of passengers affected per hour, the additional travel time per passenger, and the value of time [Eq. (12)]

**Table 9.** Maintenance costs per CS and asset category in CHF per unit

| Asset category | Unit | Maintenance costs $C_m^{cs}$ | | | | |
|---|---|---|---|---|---|---|
| | | CS 1 | CS 2 | CS 3 | CS 4 | CS 5 |
| Track | m | 17 | 26 | 34 | 43 | 51 |
| Switch | Asset | 4,825 | 7,238 | 9,650 | 12,063 | 14,475 |
| Bridge | $m^2$ | 61 | 76 | 91 | 106 | 121 |

**Table 10.** Cost for traffic states in CHF per hour

| Closures | Night break | Night closure | Day closure | Weekend closure | 24-h closure |
|---|---|---|---|---|---|
| A–J | 0 | 130 | 1,303 | 521 | 1,086 |
| A–C | 0 | 84 | 842 | 228 | 702 |
| C–J | 0 | 36 | 363 | 176 | 302 |
| E–J | 0 | 16 | 156 | 75 | 130 |
| F–J | 0 | 12 | 118 | 57 | 98 |
| I–J | 0 | 8 | 83 | 40 | 69 |
| Main track in C | 0 | 50 | 501 | 200 | 418 |
| Main track in G | 0 | 20 | 196 | 95 | 164 |

$$C_k = \frac{\text{Passengers}}{\text{Hours}} \cdot \frac{\text{Additional travel time}}{\text{Passenger}} \cdot \text{Value of time} \tag{12}$$

The traffic states considered, i.e., all possible combination of closures and time windows, are listed in Table 10, where the cost of having each traffic state per hour is shown based on the passenger volume and the value of time, taken as 14.43 Swiss francs per hour (CHF/h) (VSS 2009). For example, the day closure on A–J has an effect of 1,303 CHF/h, which is the multiplication of the passenger volume of 8,338 passengers/day divided by the operation hours of 20 h/day, the additional travel time per passenger on this closure of 13 min/passenger, and the value of 14.43 CHF/h [Eq. (13)]

$$C_{\text{A-J}}^{24\,\text{h}} = \frac{8{,}338\ \text{P/day}}{20\ \text{h/day}} \cdot \frac{13\ \text{min/P}}{60\ \text{min/h}} \cdot 14.43\ \text{CHF/h} = 1{,}303\ \text{CHF/h} \tag{13}$$

A closure on the track between two stations led to a complete closure of the line section between these stations. A closure of one track in a station did not. When closing a line section, train replacement bus services must be operated. Closures were therefore only considered possible between stations that were easily accessible with buses, had enough space for buses to operate, and were deemed reasonable. An example of the latter is that it was not considered reasonable to have a train run between the last and second

**Table 8.** Interventions

| Asset type | Intervention | Applied condition | Condition following intervention | Unit | Unit cost (CHF/unit) | Shared cost factor (%) | Track possession (h/unit) |
|---|---|---|---|---|---|---|---|
| Track | Rail replacement | 3 | 2 | m | 200 | 20 | 0.04 |
| Track | Track renewal | 4 | 1 | m | 2,350 | 20 | 0.1 |
| Switch | Switch replacement | 4 | 1 | Asset | 255,000 | 16 | 8 |
| Bridge | Bridge renewal | 4 | 1 | $m^2$ | 4,000 | 0 | 0.5 |

**Table 11.** Additional travel time per passenger (min/p) of possible closures and passenger volume (P/day)

| ID | Closures | Additional travel time (min/p) | Passenger volume (P/day) | | | |
|---|---|---|---|---|---|---|
| | | | Monday–Friday | Saturday | Sunday | Night[a] |
| 1 | A–J | 13 | 8,338 | 4,921 | 3,743 | 334 |
| 2 | A–C | 10 | 7,004 | 2,774 | 2,164 | 280 |
| 3 | C–J | 6 | 5,026 | 3,609 | 2,720 | 201 |
| 4 | E–J | 3 | 4,318 | 3,101 | 2,337 | 173 |
| 5 | F–J | 3 | 3,268 | 2,347 | 1,769 | 131 |
| 6 | I–J | 3 | 2,288 | 1,643 | 1,238 | 92 |
| 7 | Main track in C | 5 | 8,338 | 4,921 | 3,743 | 334 |
| 8 | Main track in G | 5 | 3,268 | 2,347 | 1,769 | 131 |
| 9 | A, E, F, J, and all sidings | 0 | — | — | — | — |

[a]Night passengers refer to passengers between 22:00 and 6:00.



last station of the line if a bus was used up to the second last station, because a replacement bus could simply be extended to the last station. The additional travel time due to closures at different locations is given in Table 11. It included a 5-min transfer time, which was considered the time to physically move between the train and the bus and some additional buffer for congestion. In stations with multiple tracks, both sidings and main tracks in stations where trains do not cross each other according to the schedule could be closed without impacting operation. Trains crossed only in Stations C and G. The additional travel time required if trains had to cross to other stations was 5 min (Table 11, IDs 7 and 8). Closures of sidings and single tracks in Stations A, E, F, and J did not lead to additional travel time because they did not affect the train schedule (Table 11, ID 9).

Table 11 additionally shows the passenger volume for weekdays, Saturdays, and Sundays in passengers per day for each possible closure. The passengers per night were assumed to be 4% of the average daily traffic (BFS 2012).

Five different time windows were used for execution interventions (Table 12). The night break refers to the time window during the night when no trains are operating, while the night closure is an extension of this time window to 8 h by replacing the last trains in the evening and the first train in the morning with buses. The day closure refers to a closure during a weekday for the duration of one shift, i.e., 8 h. For the weekend closure, it is assumed that it is applied after finishing the operation on Friday and ending before the operation starts again on Monday morning, resulting in a total time of 52 h. The 24-h closure refers to the closure for an entire day during the week, when the work is executed in multiple shifts. Unlike all other time windows, the 24-h closure is not restricted in length.

## Risk

The risk was defined as the probability of an unplanned interruption to service multiplied by the consequences of this interruption [Eq. (14)], taking into consideration the different ways the assets could fail, the probable restoration interventions, and the impact on stakeholders until the infrastructure was restored (Papathanasiou and Adey 2020; Papathanasiou and Adey 2021)

$$R = P_f \cdot C_f \tag{14}$$

The probabilities of failure (Table 13) were estimated using reliability indexes from literature (Mahboob and Zio 2018; Sykora et al. 2017), and they were assumed to increase exponentially as a function of condition state (CS) [Eq. (15)], which is an often-used simplification (Fendrich and Fengler 2013). More sophisticated models could be used if desired

$$p_{CS} = p_1 \cdot e^{b\cdot(CS-1)} \tag{15}$$

The consequences of a failure were comprised of the corrective intervention cost $C_{f,CI}$, the additional travel time from traffic disturbances $C_{f,tt}$, and accident costs $C_{f,A}$ [Eq. (16)]

$$C_f = C_{f,CI} + C_{f,tt} + C_{f,A} \tag{16}$$

Corrective intervention costs (Table 14) were estimated assuming that a failed object was restored as quickly as possible. They were assumed to be 10% higher than the cost of preventive renewal interventions.

The additional travel time costs due to failure are those that occur between the points in time when the failure occurs until when the infrastructure is restored by the corrective intervention. The duration of the corrective intervention itself is assumed to be equal to the preventive renewal intervention, while additional 4, 2, and 24 h are assumed for the reaction time between a failure and the start of the corrective intervention for track, switches, and bridges

**Table 12.** Time windows

| Time window | Start time | End time | Duration (h) |
|---|---|---|---|
| Night break | 01:00 | 05:10 | 4 |
| Night closure | 22:00 | 06:00 | 8 |
| Day closure | Sometime during the day | | 8 |
| Weekend closure | Saturday 01:00 | Monday 05:10 | 52 |
| 24-h closure | 00:00 | 24:00 | 24 |

**Table 13.** Probability of failure per CS and asset category

| Asset category | Probability of failure $P_f^{cs}$ | | | | |
|---|---|---|---|---|---|
| | CS 1 | CS 2 | CS 3 | CS 4 | CS 5 |
| Track | $5.0\times10^{-4}$ | $1.3\times10^{-3}$ | $3.2\times10^{-3}$ | $8.0\times10^{-3}$ | $4.0\times10^{-2}$ |
| Switch | $4.0\times10^{-3}$ | $7.1\times10^{-3}$ | $1.6\times10^{-2}$ | $2.2\times10^{-2}$ | $4.0\times10^{-2}$ |
| Bridge | $2.7\times10^{-5}$ | $7.8\times10^{-5}$ | $2.3\times10^{-4}$ | $6.8\times10^{-4}$ | $4.0\times10^{-3}$ |

**Table 14.** Corrective interventions

| ID | Category | Unit | Unit cost (CHF/unit) | Track possession (h/unit) | Reaction time (h) |
|---|---|---|---|---|---|
| $CI^T$ | Track | m | 2,585 | 0.1 | 8 |
| $CI^S$ | Switches | Asset | 280,500 | 8 | 2 |
| $CI^B$ | Bridge | $m^2$ | 4,400 | 0.5 | 24 |

**Table 15.** Probabilities related to accidents

| Category | Probability of an accident in case of a failure | Probability of injury per passenger in case of an accident | Probability of fatality per passenger in case of an accident |
|---|---|---|---|
| Track | 0.0023 | 0.18 | 0.035 |
| Switches | 0.0002 | 0.18 | 0.035 |
| Bridge | 0.01 | 0.7 | 0.2 |

(Table 14). The duration of traffic disturbance ($d_{\text{reaction}} + d_{CI}$) is multiplied by the cost incurred for the user per hour of track closure $c_u$ [Eq. (17)]

$$C_{f,tt} = (d_{\text{reaction}} + d_{CI}) \cdot c_u \tag{17}$$

The accident costs [Eq. (18)] consisted of the property damage, injuries, and fatalities that might occur due to a failure. They were estimated taking into consideration the number of passengers that might be using the infrastructure at the time of failure, as well as the probabilities of each passenger being injured or losing their life. The values used are given in Table 15 and were based on the available information provided in BFS (2019b, a), European Union Agency for Railways (2019), and EUROSTAT (2018). The cost for property damage $C_{pd}$ was assumed to be 84,000 per accident, while the cost per injury $c_{\text{inf}}$ and fatality $c_{\text{fat}}$ were assumed to be 89,900 and 3,191,400 CHF (VSS 2013)

$$C_{f,A} = p_{f,A} \cdot (C_{pd} + (p_{\text{inf}} \cdot c_{\text{inf}} + p_{\text{fat}} \cdot c_{\text{fat}}) \cdot n_{\text{passengers}}) \tag{18}$$

**Discount Rate**

All costs in the future are discounted with a discount rate of 0.5%.

### *Model Complexity*

The network flow model for this case study consists of 5,637 decision variables and 5,650 constrains excluding the variable bounds. The model was created using R (R Core Team 2016) and solved using the branch-and-bound algorithm. A standard laptop computer (Windows 10, 16 GB RAM, 2.70 GHz) required 18 s to solve the situation with no budget constraint and 985 s to solve the situation with a budget constraint.

## Intervention Programs with No Budget Constraints

### *Results*

The intervention program for the 12-year planning period, divided into three four-year periods, using the proposed network model and the intervention program developed qualitatively are shown in Figs. 3 and 4. The types of closures are noted with colors, e.g., the violet group in Period 2019–2020 (Fig. 3) indicates that the interventions are executed during a weekend closure between Stations I and J. The costs for both programs are given in Table 16. Table 16 additionally shows the percentage of optimum, which indicates the ratio between the result developed qualitatively and the result developed using the model.

The total cost of the intervention program developed using the optimization model is 14.79 million CHF consisting of 14.74 million CHF of intervention costs and 48,000 CHF of additional travel time costs (Table 16). The benefits due to the risk reduction and the reduction of costs related to maintenance and future preventive interventions are 5.6 million and 11.7 million CHF, which sum to a total benefit of 17.3 million CHF. The net benefit of the intervention program is equal to 2.5 million CHF. The intervention costs are distributed inhomogeneously over the periods with higher costs in the first and last period. Besides individual executions of interventions, the intervention program contains eight groups. In the first period, i.e., 2019–2022, the switch replacements in Station J are grouped within a weekend closure, while the track renewals in Station J are grouped within single-track closures during the day. Two further groups executed during night closures include the rail replacements on Track segments T21–T24 and the track renewal on T73–T75. In the second period, i.e., 2023–2026, the switch replacements in Stations E and F and the rail replacements on Track segment T62 are executed in parallel during a weekend closure between C and J. The groups of rail replacements on Track segments

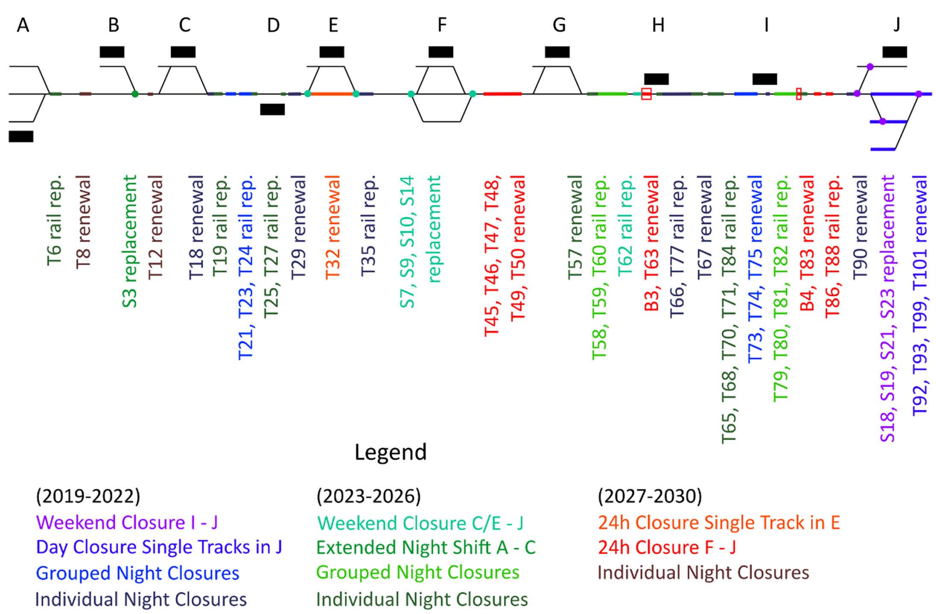


**Fig. 3.** Intervention program developed using the optimization model.

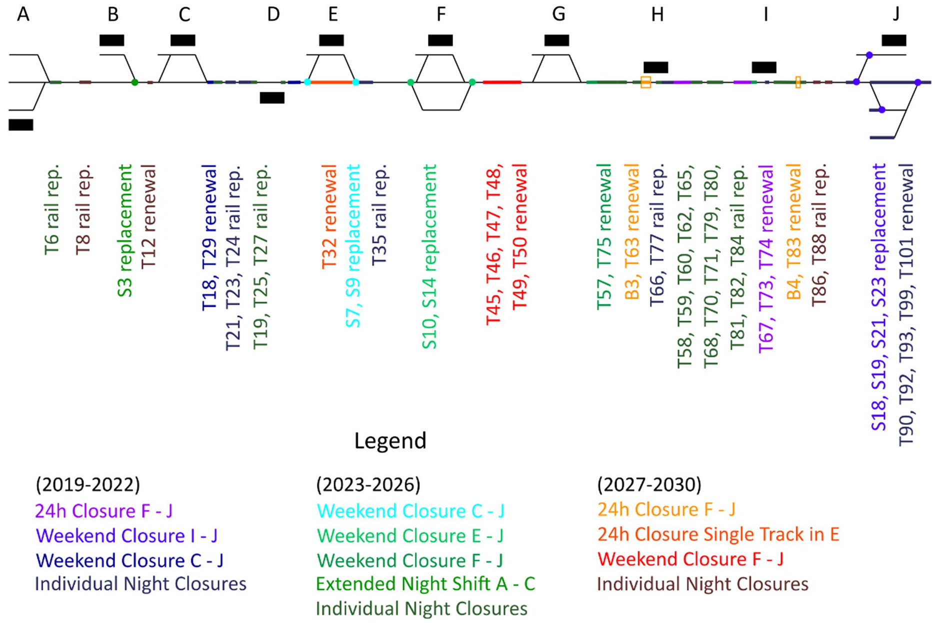


**Fig. 4.** Intervention program developed qualitatively.

T58–T60 and on Track segments T79–T82 are executed during local night closures. In the third period, i.e., 2027–2030, the renewal of Track segments T45–T50 and the rail replacements of T86 and T88 are grouped parallel to the execution of the bridge renewals of B3 and B4.

The total cost of the reference intervention program developed qualitatively is 15.00 million CHF consisting of 14.88 million CHF of intervention costs and 113,000 CHF of additional travel time costs (Table 16). The benefits due to the risk reduction and the reduction of costs related to maintenance and future preventive interventions are 5.6 million and 11.7 million CHF, which sum to a total benefit of 17.3 million CHF. The intervention program results in a net benefit of 2.3 million. As in the intervention program developed using the optimization model, the intervention costs are distributed inhomogeneously over the periods with higher costs in the first and last period. In the intervention programs, interventions are grouped together on a qualitative process that focuses on grouping interventions within asset types and within sections of the network. For example, switch replacements are grouped together within stations, i.e., E, F and J. The two bridge renewals on B3 and B4 are executed in parallel during a closure of F–J. Beside the cost values, Table 16 gives the percentage difference of the total cost values of the intervention program developed qualitatively to the intervention program developed with the optimization model considered as the optimal intervention program. The net benefit of the intervention program developed qualitatively reaches 92% of the net benefit of the intervention program developed using the optimization model.

### Discussion

When considering the cost values in Table 16, it is obvious that the additional travel time costs in the case study situation are significantly lower than the intervention costs and the benefits, roughly in the range of 1:200. The reason for the large difference between intervention costs and additional travel time costs are the rather high intervention costs on this particular line due to the difficult topography, and the relatively low traffic on the line. When considering an urban main line, the ratio between intervention and additional

**Table 16.** Cost values in CHF of the intervention programs without a budget limitation

| Intervention program | Cost category | Period 2019–2022 | Period 2023–2026 | Period 2027–2030 | Total | Percentage of optimum (%) |
|---|---|---|---|---|---|---|
| Developed using the model | Intervention costs | 6,855,690 | 2,478,710 | 5,404,380 | 14,738,780 | 100 |
| | Additional travel time cost | 320 | 2,680 | 45,002 | 48,002 | 100 |
| | Total costs | 6,856,010 | 2,481,390 | 5,449,382 | 14,786,782 | 100 |
| | Risk reduction | 3,629,281 | 1,891,983 | 121,669 | 5,642,933 | 100 |
| | Future cost reduction | 4,606,811 | 1,116,532 | 5,939,557 | 11,662,900 | 100 |
| | Benefit | 8,236,093 | 3,008,515 | 6,061,225 | 17,305,833 | 100 |
| | Net benefit | 1,380,083 | 527,125 | 611,844 | 2,519,052 | 100 |
| Developed qualitatively | Intervention costs | 6,686,110 | 2,792,000 | 5,404,380 | 14,882,490 | 101 |
| | Additional travel time cost | 50,905 | 6,244 | 56,027 | 113,176 | 236 |
| | Total costs | 6,737,015 | 2,798,244 | 5,460,407 | 14,995,666 | 101 |
| | Risk reduction | 3,555,337 | 1,948,552 | 121,669 | 5,625,558 | 100 |
| | Future cost reduction | 4,419,353 | 1,337,797 | 5,939,557 | 11,696,707 | 100 |
| | Benefit | 7,974,689 | 3,286,350 | 6,061,225 | 17,322,264 | 100 |
| | Net benefit | 1,237,675 | 488,106 | 600,818 | 2,326,598 | 92 |

travel time costs would be more balanced, if not even, flipped the other way around.

The intervention program developed using the optimization model (Fig. 3) shows how the model considers the grouping of interventions in terms of reduced intervention costs and additional travel time costs. For example, by grouping the renewals of Tracks T45–T50, their intervention costs can be reduced. It can also be seen that the model considers the synergies between interventions regarding the required closures. For example, the execution of the renewal on Bridge B3 requires F–J to be closed for 440 h, during which the interventions on Bridge B4 and Tracks T45–T50, T86, and *T88* can also be executed. The execution of these track renewals parallel to the bridge renewal is only considered by the model due to the improved consideration of parallel execution of interventions compared to the model in Burkhalter and Adey (2018).

Comparing the two developed intervention programs indicates that the qualitative process may lead to an intervention program that is close to the optimal intervention program. The qualitative process, however, lacks the capability to consider all possible combinations and the comparability of different possibilities, which may lead to a nonoptimal intervention program. This can be seen in the developed intervention programs. For example, the intervention program developed using the optimization model quantifies the costs and benefits of the interventions systematically and realizes that the track renewal on Track segment T75 is more beneficial to execute in the first period (2019–2022) instead of the second period (2023–2026). Period two is the proposed period based on the assets' condition. In the first period, however, it can be grouped with the renewals on Track segments T73 and T74. This decreases the benefit of the renewal on T75 by 16,000 CHF, while enabling a savings of 52,000 CHF in intervention costs. This slight improvement is missed in the intervention program developed qualitatively because it is not detectable without a proper quantification of the impacts of an intervention program and a complete investigation of all possible combinations when using a qualitative process.

Further, the intervention program developed using the optimization model considers the combination of the bridge renewals on B3 and B4 together with the track renewals on Segments T45–T50. This is more beneficial than executing the track renewals with an additional weekend closure. It requires a spatial extension of the local closure required to execute the bridge renewals. To find the optimal grouping of interventions, all possible combinations of grouping assets of different types and the spatial and temporal aspects of closures need to be considered, something of which the qualitative process is not capable.

## Intervention Programs with Budget Constraint

### *Results*

The budget limit considered is four million CHF per four-year period. This limitation to four million CHF requires (1) that interventions optimally executed in the first period are postponed to later periods as the intervention costs in period one exceed the four million in the unlimited situation, i.e., seven million CHF (Table 16), and (2) that not all interventions can be executed within the 12-year planning period, i.e., $3 \times 4$ million CHF is smaller than 15 million CHF (Table 16). The intervention programs for the situation with a budget limitation developed using the optimization model and developed qualitatively are shown in Figs. 5 and 6. The interventions whose executions are moved from one four-year period into another four-year period compared to the unlimited situation are framed in a box. For example, the renewal of Track T29 is executed in Period 2023–2026, while it has been allocated to the earlier Period 2019–2022 in the situation without a budget limitation. Table 17 provides the cost values of the intervention programs, including the percentage of the total values compared to the optimal intervention program, i.e., the intervention program developed using the optimization model in the unlimited situation (Table 16).

The intervention program developed using the optimization model consists of 43 of the 59 interventions included in the intervention program developed using the optimization model in the unlimited situation (Fig. 3). The execution of the interventions on T18, T29, T77, and T90 are postponed from the first (2019–2022) to the second period (2023–2026). In the third period (2027–2030), the costs for the renewal of Bridge B3 and Track 163 sum up to

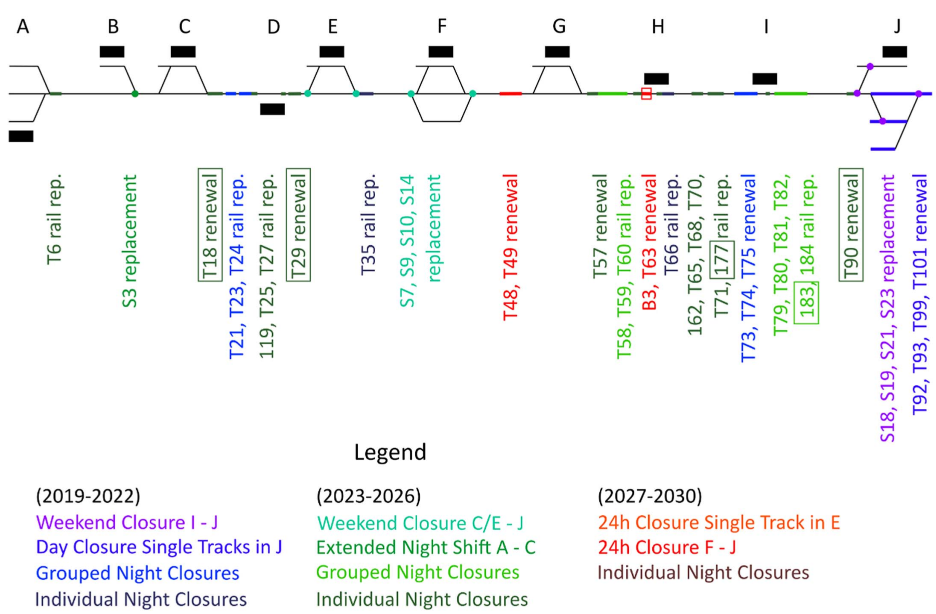


**Fig. 5.** Intervention program developed using the optimization model in case of a budget limitation.



J. Infrastruct. Syst., 2022, 28(2): 04022012

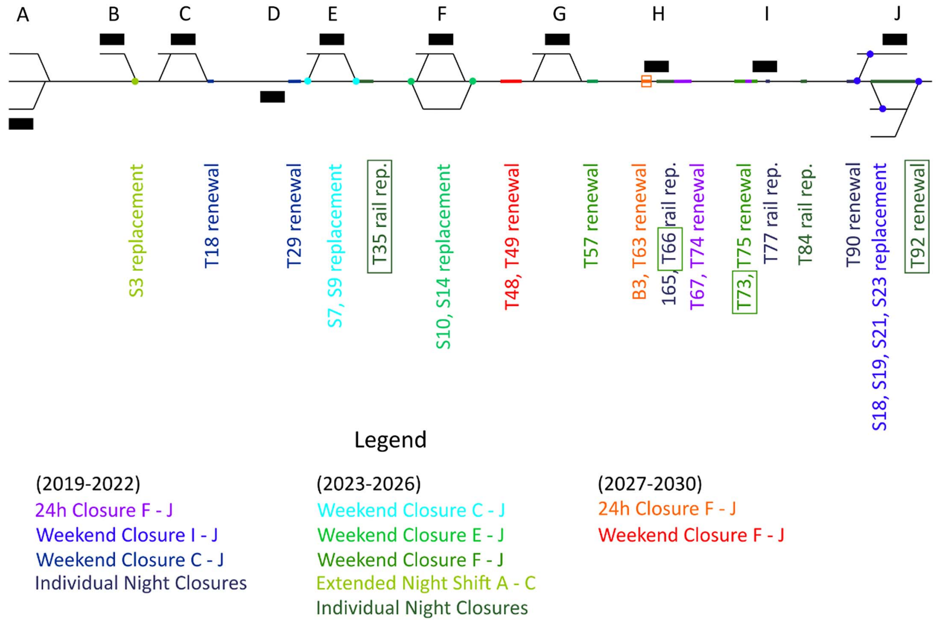


**Fig. 6.** Reference program developed qualitatively in case of a budget limitation.

**Table 17.** Cost values in CHF of the intervention programs in case of a budget limitation

| Intervention program | Cost category | Period 2019–2022 | Period 2023–2026 | Period 2027–2030 | Total | Percentage of optimum (%) |
|---|---|---|---|---|---|---|
| Developed using the model | Intervention costs | 3,996,540 | 3,754,830 | 3,986,750 | 11,738,120 | 80 |
| | Additional travel time cost | 320 | 2,680 | 45,002 | 48,002 | 100 |
| | Total costs | 3,996,860 | 3,757,510 | 4,031,752 | 11,786,122 | 80 |
| | Risk reduction | 2,509,169 | 2,259,175 | 26,120 | 4,794,465 | 85 |
| | Future cost reduction | 2,583,330 | 2,183,681 | 4,394,692 | 9,161,704 | 79 |
| | Benefit | 5,092,500 | 4,442,857 | 4,420,813 | 13,956,169 | 81 |
| | Net benefit | 1,095,640 | 685,347 | 389,061 | 2,170,047 | 86 |
| Developed qualitatively | Intervention costs | 3,996,450 | 3,999,650 | 3,986,960 | 11,983,060 | 81 |
| | Additional travel time cost | 33,823 | 10,099 | 45,100 | 89,022 | 185 |
| | Total costs | 4,030,273 | 4,009,749 | 4,032,060 | 12,072,082 | 82 |
| | Risk reduction | 1,528,582 | 1,089,182 | 8,676 | 2,626,440 | 47 |
| | Future cost reduction | 3,113,454 | 3,307,695 | 4,409,266 | 10,830,414 | 93 |
| | Benefit | 4,642,036 | 4,396,877 | 4,417,942 | 13,456,854 | 78 |
| | Net benefit | 611,762 | 387,128 | 385,882 | 1,384,772 | 55 |

3.95 million CHF, leaving only a limited budget to other interventions, i.e., the track renewals on Track segments T48 and T49. All other interventions included in the intervention program in the unlimited situation are delayed for a later execution. The total cost of the intervention program equals 11.7 million CHF, which mostly consists of the intervention costs, i.e., 11.8 million CHF, and marginal additional travel time costs, i.e., 48,000 CHF (Table 17). The benefit achieved equals 14.0 million CHF consisting of 4.8 million CHF of risk reduction and 9.2 million CHF of future cost reduction. This leads to a net benefit of 2.2 million CHF, which is 86% of the optimal net benefit in the unlimited case.

The intervention program developed qualitatively consists of much fewer interventions, i.e., 27 interventions, due to the inclusion of the track renewal on T67 in the first period, which has intervention costs of 1.6 million CHF. This is almost equal to the combined intervention costs of the 21 interventions that are postponed in the first two periods. The reduced number of included interventions limit the possibility to group interventions, which is mostly focused on grouping switch replacements within stations to reduce the intervention costs, i.e., Stations E, F, and J. The total cost of the intervention program equals 12.1 million CHF consisting of 12.0 million CHF of intervention costs and 89,000 CHF of additional travel time costs (Table 17). The benefit reaches 13.5 million CHF consisting of 2.6 million of risk reduction and 10.8 million of future cost reduction. This equals a net benefit of 1.4 million CHF, which is 55% of the optimal net benefit.

## Discussion

A significant difference can be seen between the intervention program developed using the optimization model and the intervention program developed qualitatively. The qualitative process selects interventions more focused on the perceived importance of assets within the network, e.g., a large bridge is considered to be more important than a small overpass, while the optimization model selects interventions purely based on the quantified costs and benefits. Considering Table 17, a significant difference can be seen in the benefits between the intervention program developed qualitatively and the one developed using the optimization model in the first and second periods, i.e., 500,000 CHF for both periods. Selecting interventions based on perceived importance of assets (e.g., larger compared to others) or in worse condition than others (i.e., Tracks T67 and T73 in the first period) limits the possibility to select additional interventions, which may be smaller but lead to a higher risk reduction when combined. The omission of the renewal on Track T67 in the intervention program developed using the optimization model enables the inclusion of interventions on 21 other assets, which increases the reduction of risk by 2.6 million CHF for an increase of only 2 million CHF in intervention costs. It is clearly visible that the interventions selected in the intervention program developed qualitatively tend toward a higher reduction in intervention costs related to future preventive interventions and a lower reduction in risk than the interventions selected by the optimization model.

The intervention program developed using the optimization model shows how the model considers the synergies between interventions. The improved consideration of parallel execution of interventions compared to the model in Burkhalter and Adey (2018) enables the determination of more realistic and improved intervention programs. Additionally, the application shows that the proposed optimization model allows the consideration of multiple periods within the planning period. What seems like small changes from the model proposed in Burkhalter and Adey (2018) are a tremendous improvement regarding the optimization of intervention programs on real-world railway networks. Railway infrastructure assets of different types vary significantly regarding their deterioration rate, their expected lifetimes, their intervention intervals, and therefore their impacts when moved in time. For example, the intervention program developed using the optimization model for the situation with a budget limitation (Fig. 5) does not postpone any interventions on switches, which have a rather short lifetime. Instead, a bridge intervention is postponed beyond the 12-year planning period. The consideration of multiple time periods within the planning period of the intervention program allows the consideration of a planning period that is large enough to make use of the synergies of grouping the execution of interventions, while the impact of moving interventions in time can be quantified more realistically.

The application shows the potential benefit of using computer-based optimization models to determine optimal intervention programs. The intervention program developed using the mostly manual and qualitative process currently used in practice is relatively near to the one developed using the optimization model in the situation without a budget limitation, i.e., up to 92%. The situation with a budget limitation shows, however, the difficulty in determining optimal intervention programs using a qualitative process due to the limitations in comparing interventions on different assets and considering all possible combinations. Its net benefit is 36% of the one from the intervention program developed using the optimization model.

The application is used for a one-time situation, where the intervention program for an upcoming 12-year planning period is determined. In practice, the planning process is a dynamic process with a receding horizon. Over time, the intervention programs are updated, e.g., every year, considering the most up-to-date infrastructure information. The presented methodology could be used in such a dynamic process, where the digitalized determination of intervention programs increases efficiency compared to a manual and qualitative process. Its full integration is a topic for further work.

While the digitalized determination of intervention programs using a computer-based optimization model supports infrastructure managers in improving their decisions, it also requires a higher degree of digitalization in the entire infrastructure management process. The consistent and systematic quantification of all impacts for all stakeholders requires a more detailed information flow between asset and program managers, which is hardly possible with the current mostly manual process.

## Conclusion

In this paper, an optimization model based on operation research methods is proposed that allows a digitalized determination of optimal intervention programs on railway infrastructure networks. The model uses an artificial network to generate a network flow optimization model formulated as an integer linear program. It enables the consideration of different asset types, the interrelations between the assets of the railway network and between the interventions executed on the assets, the impacts on different stakeholders (i.e., owner and user), and the benefit of including an intervention in an intervention program. The improvements to former models make it more realistic to consider (1) the possible combinations of interventions to reduce the impact on the travel time during the execution of the interventions; and (2) the difference in the deterioration processes of the assets by allowing the consideration of multiple time periods within the planning period of the intervention program.

The model is used to develop an intervention program for the 12-year planning period 2019–2030 on a real-world railway line in Switzerland. The overall planning period is divided into three four-year periods in respect to three founding periods and to facilitate the deterioration process within the 12-year planning process. The optimization model proposed in this paper, which uses a systematic and consistent quantification of the impacts related to an intervention program to quantify the net benefit of the intervention program, is compared to a qualitative process to develop intervention programs as it is often used in practice. The comparison is done for a situation without a budget limitation and for a situation with a limited budget. The example clearly shows the limitation of developing an intervention program qualitatively and the advantage of using mathematical optimization models using operation research methods.

The example without a budget limitation shows that even though infrastructure managers can develop a near-optimal intervention program using a qualitative process, the optimization model allows the development of even better intervention programs that include even more beneficial combinations of interventions. The huge advantage of using the model is more visible in the situation with a budget limitation, where the qualitative process lacks (1) the quantification of the interventions in order to select the more beneficial interventions between different possible interventions; and (2) the capability to consider all possible combinations.

Mathematical optimization models, such as the one proposed in this paper, cope with the complexity of real-world railway infrastructures and are able to develop optimal intervention programs. Therefore, a systematic and comparable quantification of the impacts is required. Further work must be conducted that focuses on the entire management and intervention planning process, that combines maintenance interventions and extension and development interventions, and that considers the uncertainties in intervention planning due to missing or inaccurate information as well as unknown future development. Overall, the systematic quantification of the impacts and the use of mathematical optimization models can support infrastructure managers in managing their infrastructure more sustainably and are a driving factor in the digitalization of railway infrastructure management.

## Data Availability Statement

The original data used during the study are confidential in nature and may only be provided with restrictions. Anonymized infrastructure data and the code for the optimization model that support the findings of this study are available from the corresponding author upon reasonable request.


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## References


Adey, B. T. 2019. "A road infrastructure asset management process: Gains in efficiency and effectiveness." *Infrastruct. Asset Manage.* 6 (1): 2–14. https://doi.org/10.1680/jinam.17.00018.

Adey, B. T., C. Martani, N. Papathanasiou, and M. Burkhalter. 2019. "Estimating and communicating the risk of neglecting maintenance." *Infrastruct. Asset Manage.* 6 (2): 109–128. https://doi.org/10.1680/jinam.18.00027.

BFS (Bundesamt für Statistik). 2012. *Mobilität in der Schweiz, Ergebnisse des Mikrozensus Mobilität und Verkehr 2010*. Neuchâtel, Switzerland: BFS.

BFS (Bundesamt für Statistik). 2019a. "Öffentlicher Verkehr 2000-2018." Accessed November 2, 2019. https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/unfaelle-umweltauswirkungen/verkehrsunfaelle/eisenbahn.html.

BFS (Bundesamt für Statistik). 2019b. "Unfälle der Eisenbahnen und verunfallte Personen." Accessed November 2, 2019. https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/unfaelle-umweltauswirkungen/verkehrsunfaelle/eisenbahn.html.

Budai-Balke, G. 2009. *Operations research models for scheduling railway infrastructure maintenance*. Rotterdam, Netherlands: Erasmus Univ.

Burkhalter, M., and B. T. Adey. 2018. "A network flow model approach to determining optimal intervention programs for railway infrastructure networks." *Infrastructures* 3 (3): 31. https://doi.org/10.3390/infrastructures3030031.

Burkhalter, M., and B. T. Adey. 2020. "Modelling the complex relationship between interventions, interventions costs and the service provided when evaluating intervention programs on railway infrastructure networks." *Infrastructures* 5 (12): 113. https://doi.org/10.3390/infrastructures5120113.

Burkhalter, M., and B. T. Adey. 2021. "Quantifying net-benefits of intervention programs to enable their digitalized generation [accepted for publication]." *Infrastruct. Asset Manage.* 8 (3): 141–154. https://doi.org/10.1680/jinam.20.00020.

Burkhalter, M., C. Martani, and B. T. Adey. 2018. "Determination of risk-reducing intervention programs for railway lines and the significance of simplifications." *J. Infrastruct. Syst.* 24 (1): 04017038. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000401.

Caetano, L. F., and P. F. Teixeira. 2015. "Optimisation model to schedule railway track renewal operations: A life-cycle cost approach." *Struct. Infrastruct. Eng.* 11 (11): 1524–1536. https://doi.org/10.1080/15732479.2014.982133.

Caetano, L. F., and P. F. Teixeira. 2016. "Strategic model to optimize railway-track renewal operations at a network level." *J. Infrastruct. Syst.* 22 (2): 04016002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000292.

Dao, C. D., A. Hartmann, A. Lamper, and P. Herbert. 2019. "Scheduling infrastructure renewal for railway networks." *J. Infrastruct. Syst.* 25 (4): 04019027. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000515.

European Union Agency for Railways. 2019. "Railway accident and incident investigations." Accessed November 2, 2019. https://erail.era.europa.eu/investigations.aspx.

EUROSTAT. 2018. "Railway transport—Accidents 2010-2017." Accessed November 2, 2019. http://ec.europa.eu/eurostat/web/transport/data/database.

Fendrich, L., and W. Fengler. 2013. *Handbuch Eisenbahninfrastruktur*. Berlin: Springer.

Frangopol, D. M., and M. Liu. 2007. "Maintenance and management of civil infrastructure based on condition, safety, optimization, and life-cycle cost." *Struct. Infrastruct. Eng.* 3 (1): 29–41. https://doi.org/10.1080/15732470500253164.

Higgins, A., L. Ferreira, and M. Lake. 1999. "Scheduling rail track maintenance to minimise overall delays." In *Proc., 14th Int. Symp. on Transportation and Traffic Theory*, edited by C. Avishai, 779–796. Oxford, UK: Elsevier.

Lethanh, N., B. T. Adey, and M. Burkhalter. 2018. "Determining an optimal set of work zones on large infrastructure networks in a GIS framework." *J. Infrastruct. Syst.* 24 (1): 04017048. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000410.

Mahboob, Q., and E. Zio. 2018. *Handbook of RAMS in railway systems, theory and practice*. Boca Raton, FL: Taylor & Francis.

MAINLINE Consortium. 2013. *MAINLINE deliverable 3.1: Benchmark of production and replacement of railway infrastructure*. Paris: MAINLINE Consortium.

Papathanasiou, N., and B. T. Adey. 2020. "Usefulness of quantifying effects on rail service when comparing intervention strategies." *Infrastruct. Asset Manage.* 7 (3): 1–20. https://doi.org/10.1680/jinam.19.00071.

Papathanasiou, N., and B. T. Adey. 2021. "Making comparable risk estimates for railway assets of different types." *Infrastruct. Asset Manage.* 8 (2): 53–74. https://doi.org/10.1680/jinam.20.00009.

Pargar, F. 2015. "A mathematical model for scheduling preventive maintenance and renewal projects of infrastructures." In *Safety and reliability of complex engineered systems*, 993–1000. London: Taylor & Francis.

Peng, F. 2011. *Scheduling of track inspection and maintenance activities in railroad networks*. Urbana, IL: Univ. of Illinois at Urbana-Champaign.

Pouryousef, H., P. F. Teixeira, and J. Sussman. 2010. "Track maintenance scheduling and its interactions with operations: Dedicated and mixed high-speed rail (HSR) scenarios." In Vol. 2 of *Proc., 2010 Joint Rail Conf. (JRC2010)*, 317–326. New York: ASME. https://doi.org/10.1115/JRC2010-36125.

R Core Team. 2016. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

SBB Infrastruktur. 2020. *Netzzustandsbericht 2019*. Bern, Switzerland: SBB Infrastruktur.

Sykora, M., D. Diamantidis, M. Holicky, and K. Jung. 2017. "Target reliability for existing structures considering economic and societal aspects." *Struct. Infrastruct. Eng.* 13 (1): 181–194. https://doi.org/10.1080/15732479.2016.1198394.

VöV (Verband öffentlicher Verkehr). 2018. *R RTE 29900 Netzzustandsbericht: Minimalanforderungen*. Bern, Switzerland: VöV.

VSS (Verband der Strassen- und Verkehrsfachleute). 2009. *SN 641 822a cost benefit analysis for road traffic: Travel time costs for passenger traffic*. Zurich, Switzerland: VSS.

VSS (Verband der Strassen- und Verkehrsfachleute). 2013. *SN 641 824 cost benefit analysis for road traffic: Accidents and accident cost rates*. Zurich, Switzerland: VSS.

Zhang, N., and A. Alipour. 2020. "A two-level mixed-integer programming model for bridge replacement prioritization." *Comput.-Aided Civ. Infrastruct. Eng.* 35 (2): 116–133. https://doi.org/10.1111/mice.12482.

Zhao, J., A. H. C. Chan, and M. P. N. Burrow. 2009. "A genetic-algorithm-based approach for scheduling the renewal of railway track components." *Proc. Inst. Mech. Eng. Part F: J. Rail Rapid Transit* 223 (6): 533–541. https://doi.org/10.1243/09544097JRRT273.