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Assessing the Effects of Closure-Free Periods on Railway Intervention Costs and Service

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Abstract: Ensuring that railways provide excellent service requires the execution of maintenance interventions. As railway use intensifies, this becomes increasingly difficult due to the conflict between track possession used for train operation and the execution of interventions. One way to improve the consistency of train schedules, and thus user comfort, is to impose closure-free periods, in which no interventions are planned. The imposition of closure-free periods forces asset managers to group their interventions either before or after the closure-free periods. This encourages asset managers to exploit synergies between interventions which can reduce costs and the negative effects on users. However, it also means that maintenance interventions may need to be executed earlier or later than the times suggested when considering only their optimal life cycles. To deal with this issue, this paper investigated the effect of imposing closure-free periods on the development of intervention programs in terms of intervention costs and disruptions to service. We used a network-flow optimization model to determine the optimal intervention programs for a 5-year planning period without and with the imposition of a minimal 2-year closure-free period on a railway line in Switzerland. The effects of the closure-free period on intervention costs and service were discussed, along with the losses of executing interventions at different points in time from those suggested using optimal asset life cycles. **DOI: 10.1061/(ASCE)IS.1943-555X.0000692.**

Author keywords: Railway network; Maintenance; Intervention program; Interval planning; Closure-free period.

Introduction

Railway infrastructure managers ensure that their infrastructure provides adequate service over time. This requires the regular planning and execution of maintenance interventions on all assets, as well as the definition of the intervals in which the interventions are to be executed. Intervals define when and where topological elements are removed from the operable network, and thereby the network topology available for train operation. Obviously, the service provided by the railway infrastructure is greatly affected by the selection of intervals.

To ensure excellent service, there recently has been an increase in interest in the use of closure-free periods in the development of intervention programs that minimize disturbances to users. A closure-free period defines a period of time, e.g., 2 years, within the planning period during which no intervals are required because no interventions requiring track possession are allowed. The maintenance interventions then are grouped in intervals within the remaining periods. In addition to ensuring large periods with no service disturbances, the use of closure-free periods has the potential to reduce intervention costs due to the grouping of interventions. However, this positive effect has to be traded-off with the increase in asset-level life-cycle costs incurred by moving interventions away from their individual optimal point in time.

In recent decades, an increasing amount of research has focused on the optimization of intervention programs (Burkhalter and Adey 2018; Caetano and Teixeira 2015; Pargar et al. 2017) and the integration of routine maintenance windows in the train schedule (D'Ariano et al. 2019; Lidén 2020; Lidén and Joborn 2016, 2017; Luan et al. 2017; Van Zante-De Fokkert et al. 2007). The former focus on the optimal selection and scheduling of interventions. They consider synergies that reduce the intervention costs and effect on service when interventions are grouped together. The latter focus on how routine maintenance can be integrated into the optimization of train schedules. No research has focused on the effect of imposing closure-free periods on the development of intervention programs for maintenance interventions.

To deal with this issue, this paper investigated the effect of imposing closure-free periods on the development of intervention programs in terms of intervention costs and disruptions to service. We used a network-flow optimization model to determine the optimal intervention programs for a 5-year planning period without and with the imposition of a minimal 2-year closure-free period on a railway line in Switzerland. The interventions considered were partial and complete renewal interventions on tracks, switches, bridges, catenary, and interlocks. The intervals considered were short night breaks, complete night shifts, day shifts, weekends, and continuous closures, which could be implemented on different sections of the line with either a single-track closure or a complete closure. The effect of the closure-free period on intervention costs and service are discussed, along with the losses of executing interventions at different points in time from those suggested using optimal asset life cycles.

The remainder of the paper is structured as follows. First, the existing literature on optimizing intervention programs and interval scheduling is summarized. Second, the methodology used is presented. Third, the example is presented. Last, the paper is discussed and concluded.

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Literature

Intervention Programs

An increasing amount of research has focused on the determination of optimal intervention programs for railway infrastructure since the turn of the millennium. The majority of this research has considered individual asset types, i.e., tracks (Andrade and Teixeira 2012; Budai et al. 2006; Pargar 2015; Pouryousef et al. 2010; Zhao et al. 2009, 2006), bridges (Lounis 2006; O'Connor et al. 2013; Orcesi and Cremona 2011), signaling systems (Morant et al. 2016), and power supply systems (Chen et al. 2013, 2014). Much of this work focused on the determination of the optimal point in time that individual interventions need to be executed and the scheduling of these interventions taking into consideration limited resources. Some, especially the track-related work, considered the synergies in the intervention costs when grouping interventions on neighboring assets.

Recent research has considered assets of different types when optimizing intervention programs. Burkhalter and Adey (2018), Pargar et al. (2017), and Caetano and Teixeira (2015) considered railway infrastructure assets of different types. They included the consideration of network-level constraints and synergies in the intervention costs and in the effects on the service when grouping interventions. The problem of determining optimal intervention programs for infrastructure composed of assets of different types also has been the topic of research on other types of infrastructures, such as waterway networks (Kielhauser et al. 2018), water distribution networks (Kerwin and Adey 2020), and road networks (Lethanh and Adey 2012; Lethanh et al. 2018).

All the research mentioned so far focused on the determination of intervention programs and the scheduling of interventions. Most considered the effect on the service to some degree, e.g., the delays experienced by the user due to maintenance-related traffic disruptions. However, the research did not explicitly include the intervals required to execute the interventions, meaning that the intervals would have to be planned further downstream in the planning process, resulting in deviations from the theoretically optimal intervention program in terms of intervention costs and potentially effects on service.

Intervals

In recent years, an increasing number of studies considered the problem of determining optimal intervals to execute routine maintenance interventions. Some considered an existing train schedule and determined the optimal integration of a required interval (Albrecht et al. 2013; D'Ariano et al. 2019; Lidén and Joborn 2016; Luan et al. 2017). They used state-of-the-art train scheduling models and integrated either virtual maintenance trains (Albrecht et al. 2013; Luan et al. 2017) or track possessions to model the operation disruption due to an interval (D'Ariano et al. 2019).

Train scheduling models are built in such a way that they model only a representative and repetitive period, i.e., 1 h or at most 1 day. Even though routine maintenance requires relatively short, regular, and periodical interval pattern, their patterns still require more time than the periods considered in train scheduling models. Therefore, specific models for a joint train traffic and intervals schedule have been developed in research (Lidén 2020; Lidén and Joborn 2017; Lidén et al. 2018; Van Aken et al. 2017). They are able to model longer, cyclic periods, such as multiple days to an entire week. The allow the integration of periodical intervals rather than only short routine maintenance. They reduce the complex and computational expensive train scheduling optimization to a simplified train schedule representation.

All the aforementioned research considers either short, individual intervals or cyclical periodic intervals. The execution of larger renewal interventions cannot be integrated into these intervals. They occur only once within a few years, and often require intervals that stretch over multiple days or weeks. Specifically, the former means that the train schedule is not even known when the intervention is being planned. The model of Burkhalter and Adey (2018), although it focuses on the development of an intervention program, allows the definition of intervals required for the execution of such larger renewal interventions. It determines the optimal intervals within which interventions can be executed. The intervals are selected based on a set of interval types that are predefined and the effect of which on the service are estimated before running the optimization model.

Closure-Free Periods

Van Zante-De Fokkert et al. (2007) developed a track maintenance model that schedules one interval per location per 4 weeks during which all the maintenance work has to be executed. Even though the reason for its implementation was to increase track workers safety, it led to greater train schedule consistency due to the closure-free period between the defined intervals. A similar periodic interval pattern also resulted from the model of Jenema (2011). These models consider closure-free periods. However, their focus is the scheduling of periodic interval patterns for routine maintenance. Their closure-free periods therefore are relatively short, e.g., weeks or months. No specific research could be found that investigated the implementation of closure-free periods that span multiple years, increase the time schedule consistency, and decrease inconvenience for the users.

Methodology

Optimal Intervention Program

In this paper, the optimal intervention program is the one with the maximal net benefit [Eq. (1)]. The net benefit consists of the costs related with the execution of the interventions and the benefits of the interventions due to the condition improvement obtained (Burkhalter and Adey 2021a). The benefits describe the reduction in the expected future costs due to the condition improvement obtained when executing the interventions compared with when they are not executed during the planning period [Eq. (2)]. The expected future costs consist of the risk of asset failure including the costs of corrective interventions, the associated traffic disruption and possible material damage, injuries, and fatalities due to accidents. The expected future costs further consist of the costs of future predictive maintenance and renewal interventions, including their traffic disruption. The costs include the intervention costs, the traffic management costs, and the travel time costs during the execution of preventive intervention in the program [Eq. (3)]

$$\begin{aligned}\text{Max net benefit} &= \text{benefits of interventions}\\ &\quad - \text{costs related to the interventions}\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Benefits} &= \text{reduction in expected future costs}\\ &= \text{reduction in risk of failures}\\ &\quad + \text{reduction in future intervention costs}\end{aligned} \tag{2}$$

$$\text{Costs} = (\text{intervention costs} + \text{traffic management costs}) + \text{travel time costs} \tag{3}$$

Both the risk of failure and the costs of future preventive interventions are condition-related. Their quantification enables the determination of the effect of moving interventions away from their individual optimal point in time. For example, the probability of a failure, and with it the risk of failure, increases when an intervention is executed after the optimal point in time, e.g., when it is delayed. When an intervention is executed before its optimal point in time, the risk of failures is reduced and the net present value of future interventions is increased because future interventions will be required sooner.

Optimization Model

The optimization model proposed by Burkhalter and Adey (2018) was used to develop the intervention program. It was extended to consider multiple periods and closure-free periods.

The artificial network $G = (V, E)$ represents the decision problem. The set of nodes $v \in V$ is divided into the source node $s \in V$ and the two subsets. The intervention nodes $V^I \subseteq V$ represent specific interventions on specific assets in specific periods $p \in P$. The interval nodes $V^K \subseteq V$ represent specific groups of interventions executed within specific intervals $k \in K$ in specific periods.

The set of edges $e \in E$ is divided into three subsets. The selection edges $E^S \subseteq E$ model the relationships between different interventions on different assets. They exist between the source and intervention nodes $(s, v \in V^I)$, between the intervention nodes and the source node $(v \in V^I, s)$, and between the nodes of interdependent interventions $(u \in V^I, v \in V^I)$. Their flow is represented by binary variables $\delta_{u,v}$. The execution edges $E^E \subseteq E$ and the topology edges $E^T \subseteq E$ model together the relationships between different groups of interventions, e.g., whether interventions need to be executed in series or can be executed in parallel. Execution edge $e \in E^E$ exists between intervention nodes and related interval nodes $(u \in V^I, v \in V^K)$. The flow through these edges represents the interval duration, and is described with real-valued variable $\gamma_{u,v}$. Topology edge $e \in E^T$ exists between groups of interventions that can be executed in parallel in time $(u \in V^K, v \in V^K)$, and between interval nodes and the source node $(u \in V^K, s)$. Their flow represents the duration of parallel intervention execution, and is described with real-valued variable $\varepsilon_{u,v}$.

The benefit of an intervention represented by $v \in V^I$ is assigned to all selection edges that reach node v, i.e., (s, v) and $(u \in V^I, v)$. The intervention costs are assigned to the same edges. The costs assigned to (s, v) contain the entire costs, i.e., fixed plus variable costs, of the intervention represented by node v. The costs assigned to (u, v) consist only of the variable costs of intervention v considering the fixed costs already included in the intervention represented by node u. The traffic management and travel time costs are assigned to nodes $(u \in V^K, s)$ as the unit costs for applying a specific interval.

The mathematical formulation of the optimization problem is

$$\text{MaxZ} = \sum_{u \in V} \sum_{v \in V} \delta_{u,v} \cdot \text{NB}_{u,v} + \sum_{u \in V} \sum_{v \in V} \gamma_{u,v} \cdot \text{NB}_{u,v} \tag{4}$$

$$\sum_{v \in V} \delta_{v,u} = \sum_{v \in V} \delta_{u,v}, \quad \forall\ u \in V \tag{5}$$

$$\sum_{v \in V} \delta_{v,u} \cdot d_{v,u} + \sum_{v \in V} \gamma_{v,u} = \sum_{v \in V} \gamma_{u,v} + \sum_{v \in V} \varepsilon_{u,v}, \quad \forall\ u \in V \tag{6}$$

$$\varepsilon_{v,u} \leq \sum_{w \in V} \gamma_{u,w}, \quad \forall\ u \in V \tag{7}$$

$$\sum_{u \in V} \sum_{v \in V_n} \delta_{u,v} \leq 1, \quad \forall\ n \tag{8}$$

$$\sum_{u \in V} \delta_{u,v} - \sum_{u \in V} \delta_{u,w} \leq 0, \quad \forall\ (v, w) \in SD \tag{9}$$

$$\sum_{u \in V^p} \sum_{v \in V^p} \delta_{u,v} * c_{u,v} \leq \Omega^p_{\max}, \quad \forall\ p \tag{10}$$

$$\sum_{u \in V^p} \sum_{v \in V^{k,p}} \gamma_{u,v} \leq \Lambda^{k,p}_{\max}, \quad \forall\ k, p \tag{11}$$

Eq. (4) contains the net-benefit objective multiplying the flow on each edge with the net benefit assigned to each edge, where $\text{NB}_{u,v}$ is the net benefit associated with the edge (u, v). Eqs. (5)–11)) formulate the model's constraints. Eqs. (5) and (6) contain the flow conservation constraints on the object and network level, where $d_{u,v}$ represents the durations associated with edge (u, v). Eq. (7) 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. (8) 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. (9) contains the structural constraints ensuring that the mandatory intervention w of a structural pair $(v, w) \in SD$ is selected if the initial intervention v is selected. Eq. (10) formulates the budget constraint with a budget limitation $\Omega^p_{\max}$ for each time period p. Eq. (11) formulates the interval constraints ensuring that the required duration of each interval $k \in K$ per each time period $p \in P$ does not exceed its maximal duration $\Lambda^{i,p}_{\max}$.

Closure-Free Period Consideration

The preceding optimization model is a mixed-integer linear program (MILP) that can be solved to the global optimum using branch-and-bound (Dakin 1965). The closure-free period is not included in the mathematical model shown. This would require further variables and constraints, increasing the complexity and computational effort to solve the optimization. Instead, the problem is solved with a scenario-based optimization. This is a well-known approach in stochastic optimization (Consilvio et al. 2016). Here, the overall problem is divided into subproblems each representing a potential closure-free scenario. Fig. 1 illustrates the concept with a 5-year planning period and a minimal 2-year closure-free period. The overall problem is separated into four subproblems representing the four possible combinations for the implementation of closure-free periods. The optimal intervention program, and subsequent intervals, for each subproblem is determined, and the program with the highest net benefit is the optimal program of the overall problem.

Example

Situation

The model was used to determine the optimal intervention program and subsequent intervals for a railway line in Switzerland. The double-track line passes through seven stations between the

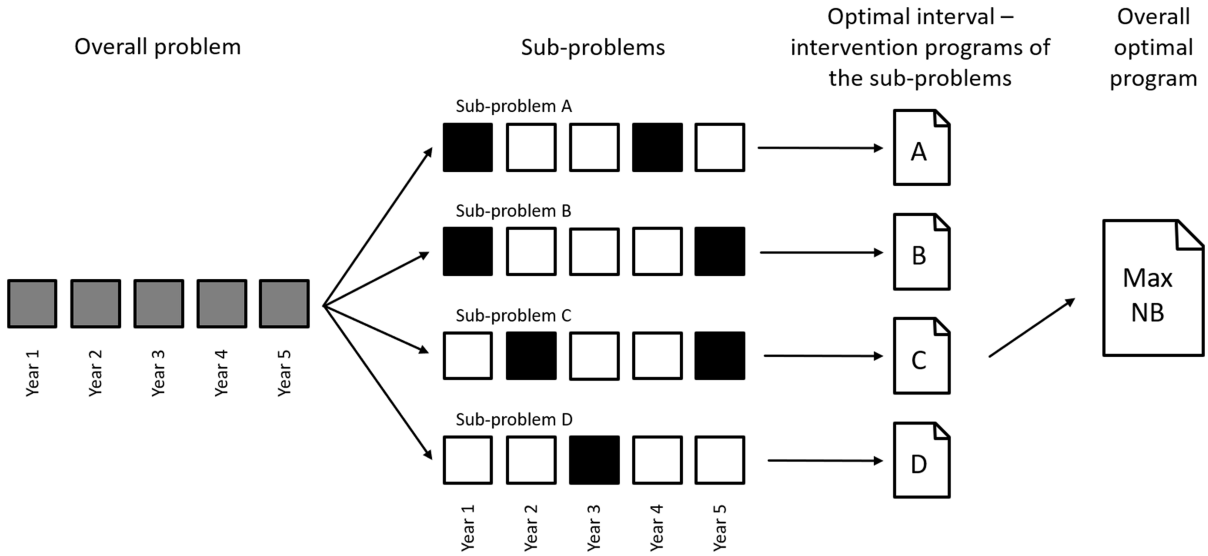

Fig. 1. Concept of determining the optimal intervention program with the consideration of a closure-free period.

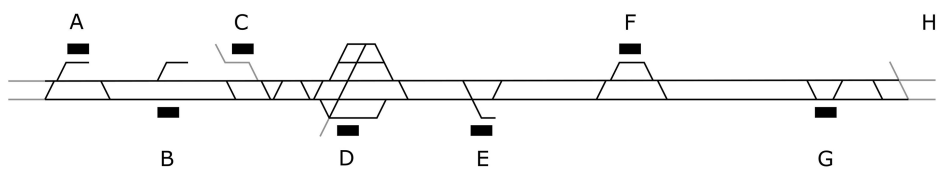

Fig. 2. Example railway line.

junctions connecting it to the rest of the network (Fig. 2). The assets considered were the tracks, the switches, the bridges, the catenaries, and the interlocks along the line. All considered assets are presented in the Appendix.

The condition of the assets was described using the condition classification in RTE 29900 (VöV 2018), in which the condition of an asset is classified with a number between 1 and 5. State 1 refers to a like-new condition. State 5 describes an insufficient condition. The current condition of each asset is presented in the Appendix. Table 1 presents the percentage distribution of the current condition of the assets per asset type. Tracks were in rather poor condition, with 76% in condition State 3 or worse and 39% in State 4 or worse. Most assets of other types were in rather good condition. A total of 10% of all assets were in State 5.

Condition Deterioration

Deterioration was modeled using the minimal requirements suggested in RTE 29900, in which the condition evolution is assumed to be a function of the lifetime of the assets. Table 2 provides the expected points in the lifetime at which an asset reaches a certain state. For example, a track asset is expected to reach condition State 3 after 50% of its expected lifetime.

Intervals

The execution of an intervention requires an interval in the traffic operation during which safe execution is possible. The intervals considered in the examples are listed in Table 3. An interval is described by

- The interval type, describing the time within the week when the interval is placed (Table 4).
- The closure type, describing the local impact of the closure implemented within the interval. It differentiates between a single-track closure, which ensures the operation of the train traffic with reduced capacity and a complete closure of the line section, which prohibits train operation at the location of the interval.

Table 1. Distribution of current condition per asset type

	Condition state (%)				
Asset type	1	2	3	4	5
Track	11	12	37	22	17
Switch	53	22	3	1	0
Bridges	15	73	8	4	0
Catenary	67	33	0	0	0
Interlocks	40	40	20	0	0
All assets	26	23	24	16	10

Table 2. Expected condition states as function of lifetime of each asset type

		Condition states (%)				
Asset type	Lifetime	1	2	3	4	5
Track	38	0	25	50	75	100
Switch	37	0	25	50	75	100
Bridge	97	0	40	80	90	100
Catenary	76	0	25	65	84	100
Interlocks	47	0	25	65	84	100

Table 3. Considered intervals

Closure location	Interval type	Closure type
A, A–C, C, C–D, D, D–E, E, E–F, F, F–G, G, G–H	Night break	Complete closure
	Night shift	Complete closure
	Day shift	Single-track closure
	Weekend	Single-track closure
	Weekend	Complete closure
	Continuous	Single-track closure
	Continuous	Complete closure
A–D, D–H	Nigh break	Complete closure
	Night shift	Complete closure
	Day shift	Single-track closure
	Weekend	Single-track closure
	Weekend	Complete closure
	Continuous	Single-track closure
	Continuous	Complete closure
A–H	Nigh break	Complete closure
	Night shift	Complete closure
	Weekend	Complete closure
	Continuous	Complete closure

- The closure location, describing the spatial extent of the interval, i.e., the track routes that are affected by the interval.

The closure duration and the work duration are equal for all interval types except the continuous interval type. For the continuous interval type, it is assumed that the work is executed in two 8-h shifts per day, and that the network remains closed the entire time.

The implementation of an interval leads to traffic management costs for the infrastructure manager and to additional travel time costs for the users (Table 4). Both costs were estimated per hour and multiplied by the duration of each interval. The traffic management costs were simplified estimates provided by the infrastructure manager. Traffic management costs CHF 5,200/night shift, CHF 7,800/day shift, CHF 18,000/weekend, and CHF 14,800/complete day closure. These costs are independent of the location and type of the closure and depend only on the interval type.

The total length of possible intervals per year was limited to three-quarters of a year, i.e., 273 days, to take into consideration that there are periods during which interventions are not possible, i.e., during winter. Additionally, the type of interval imposed constraints on when the interval can occur, e.g., there can be no more than 273 day shifts and no more than 39 weekends per year (Table 4).

The travel time costs per hour of an interval were defined as the product of the number of passengers per hour, the additional travel time per passenger, and the value of time

$$\text{Unit travel time costs} = \text{traffic volume} \cdot \text{additional travel time per passenger} \cdot \text{value of time} \tag{12}$$

The traffic volume, i.e., number of passengers per hour, was considered to be constant over the line; 4,588 passengers/weekday and 9,000 passenger/weekend use the railway line (SBB Infrastruktur 2018). The traffic volume affected by a night shift was considered to be 5% of the number of passengers per weekday (Weidmann 2013), i.e., 5% of 4,588, or 17 passengers/h. A day shift was considered to be between the morning and evening peak traffic, and affected 38% of the passengers on weekdays (Weidmann 2013), i.e., 218 passengers per hour. Table 4 presents the considered passenger volume per hour for each interval type.

The additional travel time per passenger was estimated based on the train schedule and a travel time comparison between the train service and a train replacing bus service. A local closure at a single station or between two neighboring stations led to additional travel time of 4 min when a single-track closure was implemented, and of 12 min when a complete closure was implemented. A single-track closure and a complete closure on one part of the line, i.e., A–D or D–H, led to an additional 13 and 20 min/passenger, respectively. A complete closure of the entire line A–H led to an additional travel time per passenger of 45 min.

The value of time was defined as CHF 14.4/h based on the value for public transportation in the cost–benefit analysis guidelines of VSS (2009).

Interventions

Table 5 presents an overview of all considered interventions and their associated characteristics. The closure duration was considered instead of the intervention duration because the required intervals depend on the closure duration.

The unit costs for renewal interventions were estimated using the values provided by the infrastructure manager and a reference project (Burkhalter et al. 2020). For each intervention, a percentage of the total costs was assumed to be independent of the size of the intervention. It was assumed that this fixed cost (Table 5) can be shared among interventions when interventions of the same type are executed on neighboring assets. For example, 16% of the costs of a switch replacement can be saved when combined with a switch replacement of a neighboring switch. This percentage was estimated based on the results of Dao et al. (2019). For track and catenary interventions, it was assumed that 50% of the engineering and logistic costs can be shared when neighboring track assets have intervention simultaneously; engineering and logistic costs compose 40% of the total costs (Caetano and Teixeira 2016). These values are rough estimates and may vary significantly. Further research is required to identify the actual cost percentage that can be saved when combining interventions on neighboring assets if more-accurate estimates are required. The assumptions regarding the unit closure duration were based on information provided by the infrastructure manager. Some interventions require continuous closure of the track, whereas others can be divided into separate shifts, and trains can operate between the work shifts.

Table 4. Costs related to interval type

Interval type	Duration (h)	Traffic management costs (CHF/h)	Passenger volume (PAX/h)	Max number of intervals/year
Night break	6	0	0	273
Night shift	8	650	17	273
Day shift	8	975	218	273
Weekend	54	333	167	39
Continuous	Infinite for closure duration; 16/day for the work time	925	287	273

Note: PAX = passenger.

Table 5. Interventions

Asset type	Intervention	Unit	Unit costs (CHF/unit)	Fix cost (%)	Unit closure duration (h/unit)	Improved condition state
Track	Renewal	m	2,360	0.20	0.10	1
	Partial renewal	m	1,180	0.20	0.05	2
Switch	Replacement	Asset	300,000	0.16	8.00	1
	Partial renewal	Asset	150,000	0.16	4.00	2
Bridges	Renewal	m^2	11,000	0	0.50	1
	Partial renewal	m^2	5,720	0	0.26	2
Catenary	Renewal	m	683	0.20	0.05	1
	Partial renewal	m	410	0.20	0.03	2
Interlocks	Renewal	Asset	10,000,000	0	8.00	1
	Partial renewal	Asset	5,500,000	0	4.40	2

Interventions on the track and the catenary can be divided into shifts.

The partial renewal intervention represents a typical intervention on the assets that improves the condition of the asset by either renewing or rehabilitating single components of the asset. The assets are improved to condition State 2 by a partial renewal. The costs and duration of the partial renewal interventions, which contain a wide range of possible specific activities, are considered as a percentage of the complete renewal. These partial renewals do not include routine maintenance work. Routine maintenance is planned on the operational level. This is considered in the next section.

The costs of intervention vary as a function of the intervention execution situation (Galli 2020). Continuous and weekend closures do not require clearing the track for train operation between two shifts. They lead to an increase in productivity due to the omission of unproductive times at the beginning and end of individual shifts. Therefore a 1.02 productivity factor was considered for the continuous and weekend interval types.

Night breaks with shifts shorter than 8 h reduce the productivity of the intervention. They reduce the effective working hours, but not the required set-up and clean-up time. A 6-h shift has a productivity of roughly 0.91 compared with that of the usual 8-h shift (Galli 2020).

In addition to the productivity change based on the interval duration, a 5% cost increase was considered for night work.

Routine Maintenance

Routine maintenance is not part of the optimized maintenance interventions, but does have to be considered in the determination of optimal intervention programs because it does affect costs. The costs for routine maintenance are a function of asset condition (Table 6) (SBB Infrastruktur 2020). Here, a linear increase in the routine maintenance costs as a function of the condition was assumed.

Risk

The risk of asset failure corresponds to the product of the probability of asset failure and the consequences related to asset failure

$$\text{Risk of failure} = \text{probability of failure} \cdot \text{consequences of failure} \tag{13}$$

The probabilities of failures assumed in the present situation were based on reliability theory (Mahboob and Zio 2018; Sykora et al. 2017). The reliability indexes for new structures, which correspond to condition State 1, and the minimal accepted reliability index, corresponding to condition State 4, were estimated and transformed into probabilities of failure. The considered probabilities of failure are summarized in Table 7, and represent an average failure (Papathanasiou and Adey 2021). These probabilities must be considered together with the definition of condition states and deterioration rates. Changes in the definition of condition states lead to changes in the probabilities of failures. The comparison of the probabilities of failures for different asset types must be considered together with the deterioration rate. For example, switches and tracks have the same probabilities of failure. Switches deteriorate faster than tracks, and therefore lead to more failures than of tracks over the same period.

The consequences of failures are summarized in Table 8 for each asset type. Corrective interventions were considered to be renewal interventions that are 10% more expensive than preventive renewal interventions (Table 5). Their duration was considered to be equal to that required for preventive renewal. Additional traffic disruption exists due to the reaction time between a failure occurrence and the start of the corrective intervention. In addition to costs related to interventions and traffic disruption, the consequences of a failure include accident costs. The probabilities of an accident due to an asset failure and the probabilities of injuries and fatalities due to an accident were based on the Swiss (BFS 2019a, b) and European (European Union Agency For Railways

Table 6. Routine maintenance costs as function of condition (CHF/year · unit)

			Condition state				
Asset type	Unit	Average costs	1	2	3	4	5
Track	m	34	17	26	34	43	51
Switches	Asset	9,650	4,825	7,238	9,650	12,063	14,475
Bridges	Asset	1,000	61	76	91	106	121
Catenary	m	4.0	2.7	3.3	4.0	4.7	5.3
Interlocks	Asset	137,000	109,600	123,300	137,000	150,700	164,400

Table 7. Probability of failures

Asset type	Condition state 1	2	3	4	5
Track	1.2×10^{-4}	4.0×10^{-4}	1.4×10^{-3}	4.8×10^{-3}	6.7×10^{-2}
Switches	1.2×10^{-4}	4.0×10^{-4}	1.4×10^{-3}	4.8×10^{-3}	6.7×10^{-2}
Bridges	1.4×10^{-7}	7.3×10^{-7}	4.0×10^{-6}	2.2×10^{-5}	9.4×10^{-4}
Catenary	2.5×10^{-4}	6.8×10^{-4}	1.8×10^{-3}	4.8×10^{-3}	5.0×10^{-2}
Interlocks	1.2×10^{-4}	4.0×10^{-4}	1.4×10^{-3}	4.8×10^{-3}	6.7×10^{-2}

Table 8. Consequences of failures

Asset type	Unit	Costs corrective intervention (CHF/unit)	Duration corrective intervention (h/unit)	Reaction time (h)	Probability of accident in case of asset failure	Probability of injury/passenger in case of accident	Probability of fatality/passenger in case of accident
Track	m	2,596	0.20	4	1.2×10^{-3}	1.8×10^{-1}	3.5×10^{-2}
Switches	Asset	330,000	8.00	2	2.0×10^{-4}	1.8×10^{-1}	3.5×10^{-2}
Bridges	m^2	12,100	0.50	24	1.0×10^{-1}	7.0×10^{-1}	2.0×10^{-1}
Catenary	m	751	0.05	4	1.0×10^{-5}	1.8×10^{-1}	3.5×10^{-2}
Interlocks	Asset	11,000,000	8.00	12	1.0×10^{-5}	1.8×10^{-1}	3.5×10^{-2}

2019; EUROSTAT 2018) databases for accidents and failure data provided by the infrastructure manager. The costs of property damage due to an accident, for an injured passenger, and for a passenger fatality were assumed to be CHF 84,000, 89,900, and 3,191,400, respectively (VSS 2013).

Intervention Strategies

Based on current practice, assets are renewed if they are in condition State 4 and they are given partial renewal if they are in condition State 3. This strategy was assumed to be the same for assets of all types.

Discounting

All future costs were discounted with a 0.5% discount value.

Results

Intervention Program without Closure-Free Period

The intervention program for the 5-year planning period without a closure-free period is illustrated in Figs. 3–5. All assets that are to have an intervention are colored, and the colors represent groups of interventions executed within the same interval. Fig. 3 shows a long list of interventions, mostly renewal interventions, to be executed in Year 1. This is because many of the assets are currently in condition States 3 and 4, and interventions are required according to the intervention strategies when the assets are in these states. Rather few interventions are planned in the second, third, and fourth years (Fig. 4). Year 5 has a considerable number of interventions (Fig. 5). Most interventions in Year 5 are partial renewals.

The intervals required to execute all interventions in the 5-year planning period are illustrated in Figs. 6–8. For each year, all intervals are shown with the extent of their closure, the closure type (i.e., single track or complete closure), the temporal aspect of the interval type, and its required duration. For example, in Year 1, the interval type of a continuous closure of a single track in Station A is required for 167 h (approximately 11 days). This includes the sequential closure of both tracks in Station A to execute the interventions on both tracks.

The optimal intervention program consists of mostly local closures, meaning that the interventions are executed with a closure implemented at a local station or on the line between two neighboring stations. The execution of the renewal on Bridge 14 and the replacements of all switches in Station E (both illustrated in dark blue) are the exception. They are executed with a continuous closure of D–H (Fig. 6). It is only with this closure that the underpass and the switches in Station Sub can be combined.

A standard laptop (Windows 10 64-bit operating system, 1.90 GHz, and 16 GB RAM) required 47 s to determine the optimal interval–intervention program in the situation without a closure free period, solving an optimization problem with 34,288 decision variables and 20,576 constraints.

Intervention Program with Minimal 2-Year Closure-Free Period

Figs. 9 and 10 show the intervention program with a minimal 2-year closure-free period. Interestingly, the imposition of the 2-year closure-free period resulted in a 3-year closure-free period with interventions in Year 1 (Fig. 9) and Year 5 (Fig. 10). The model also imposed the 2-year closure-free period in the subsequent years. Therefore interventions that are not executed within the 5-year planning period also are not executed in Years 6 and 7.

This intervention program included interventions on the same assets as in the program determined without a closure-free period. The interventions previously planned for Years 2, 3, and 4 are either moved forward to Year 1 or postponed to Year 5. Most are moved forward to Year 1 (Fig. 9, bold). The renewal interventions on Track A 6,126.2–7,013.1 and Track D 18.2–42.2 are included in existing weekend intervals on A and D. The other interventions moved forward in time are either grouped in night shifts in Station D or executed during an additional weekend interval in Station C.

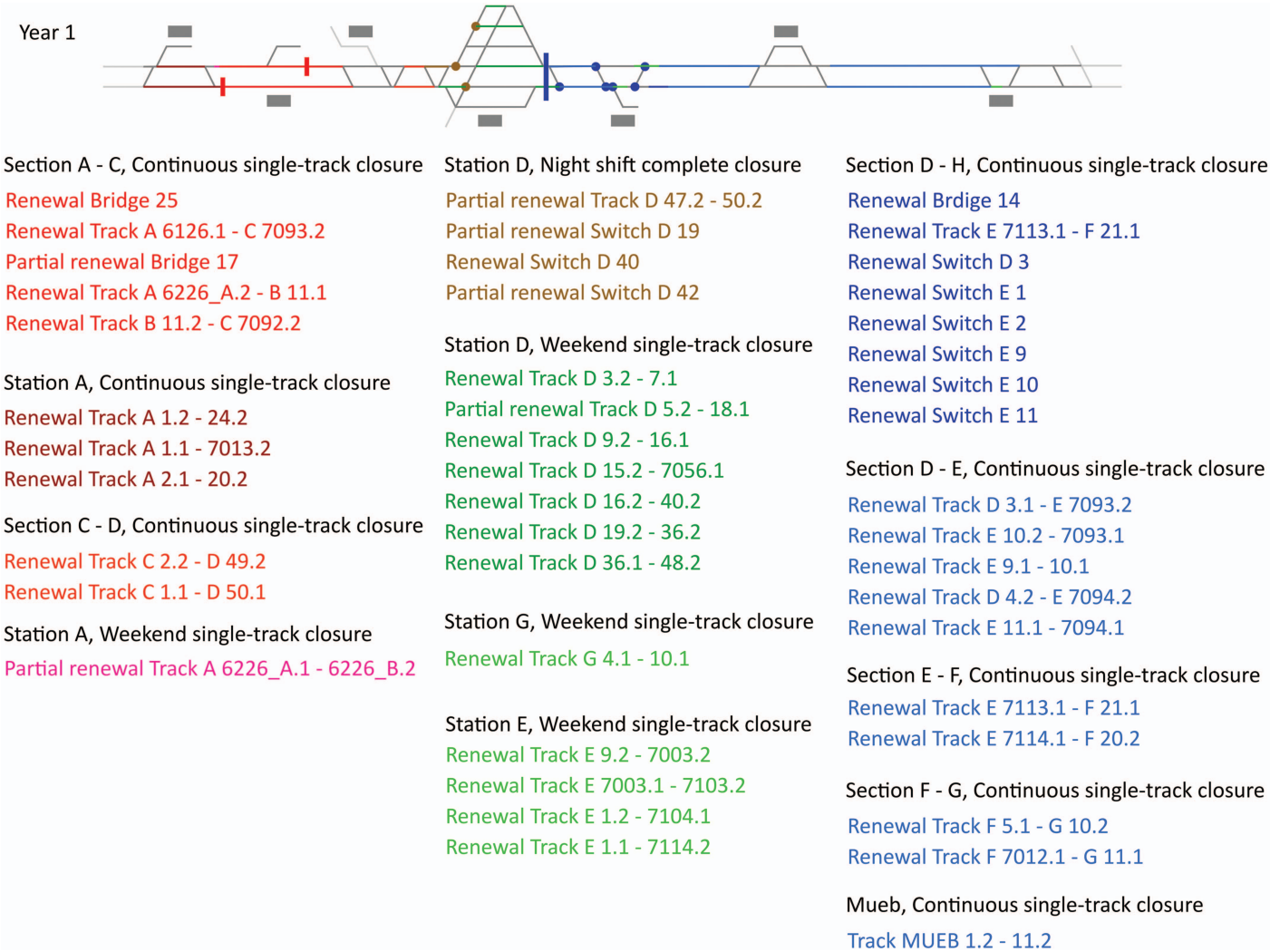

Fig. 3. (Color) Year 1 of the intervention program without a closure-free period.

Some interventions are postponed (Fig. 10, bold). The replacement of Switch D 39 and the partial renewal of Interlock A are postponed from Year 4 to Year 5. The partial renewal of Switches C 10 and D 20 planned for Years 2 and 3, respectively, are changed to switch replacements in Year 5. A replacement of these switches in Year 5 is more beneficial than executing a partial renewal in Year 1.

Figs. 11 and 12 illustrate the intervals required to execute all interventions in Year 1 and Year 5. Due to the large number of interventions required to be executed in Year 1, the interval program for Years 1 and 5 with a closure-free period is similar to the interval program without the consideration of a closure-free period. The additional interventions in Year 1 and Year 5 increase slightly the required duration of the intervals, and lead to additional intervals in Station C in Year 1 and Year 5, and on Section A–C in Year 5.

A standard laptop (Windows 10 64-bit operating system, 1.90 GHz, and 16 GB RAM) required 20 h to determine the optimal interval–intervention program in the situation with a minimal 2-year closure-free period, solving an optimization problem with 34,288 decision variables and 20,577 constraints.

Net Benefit

The net benefits of the two programs are presented in Table 9. The benefit is divided into the reduction in risk and maintenance costs during the 5-year planning period, and the reduction in risk, maintenance costs, and future renewal costs beyond the planning period. The first two provide information about how the provided service is affected in the short term during the planning period. The latter three indicate the long-term impact of moving interventions away from their individual optimal point of execution as determined in the asset-level intervention strategies. The costs are divided into intervention costs, traffic management costs and additional travel time costs during the execution of the interventions. Given the approximations made in the underlying data, more weight should be placed on the comparison of the programs than on the absolute values.

The program with a closure-free period leads to a lower net benefit. This is to be expected because the optimal program with a closure-free period is also a possible candidate program in the situation without a closure-free period. This means that the program developed without a closure-free period is at least as good in terms of the net benefit as the program developed with the consideration of a closure-free period. The unrestricted situation enables the consideration of further programs that disregard the 2-year closure period and have a higher net benefit.

It also is to be expected that the benefit is reduced when implementing a closure-free period. The closure-free period makes it necessary to move some interventions away from their

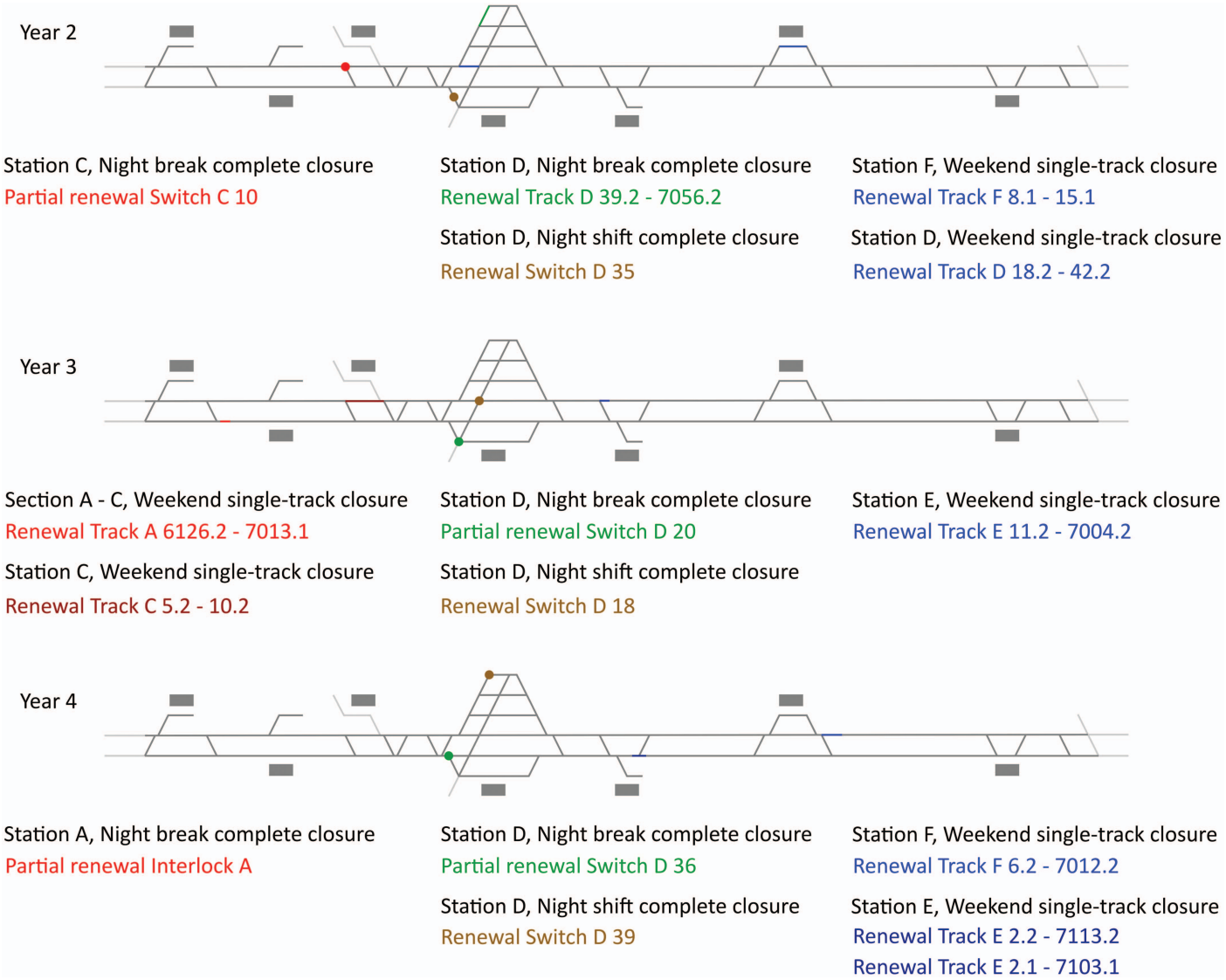

Fig. 4. (Color) Years 2–4 of the intervention program without a closure-free period.

individual optimal points in time. This increases the intervention costs over the lifetime of the assets and therefore leads to a reduced benefit of the interventions in the net-benefit consideration. The different benefit components show that moving interventions in time is beneficial for some aspects, but worse for others. For example, the postponement of some interventions decreases the potential short-term risk reduction—meaning that there is higher failure risk. However, the maintenance required in the short-term is decreased due to the earlier execution of some interventions.

The program with a closure-free period leads to higher costs, in which all cost types increase (Table 9). This is not a direct result of implementing a closure-free period. It can be assumed that the costs would be equal or even reduced because of the clustering of more interventions within a single year. Nevertheless, all costs increase in the considered situation because the partial renewals on Switches C 10 and D 20 are changed to complete switch replacements. For these switches, the execution of a switch replacement in Year 5 is more beneficial than the execution of an earlier partial renewal in Year 1. To illustrate the effect of the closure-free period, the last column of Table 9 presents the differences in the costs and benefits of the programs, neglecting the interventions on these two switches. With the remaining interventions, the closure-free period reduces all costs. The intervention costs are reduced mostly due to the possibility of combining the execution of the partial renewal of Switch D 36 with other switch interventions in Station D. The traffic management and the additional travel time costs are reduced because the interventions moved in time are assigned to already-required intervals in Years 1 and 5.

In general, the comparison of the two programs indicates that the implementation of closure-free periods reduces net benefit. The net benefit is reduced as long as the potential reduction of the costs related to the execution of the interventions is not higher than the loss of benefit. This means that as long as the optimal program without considering a closure-free period as a constraint does not result in such a closure-free period, the implementation of a closure-free period brings a loss of net benefit.

Although the net benefit does not have a beneficial aspect of the closure-free period, infrastructure managers may have other reasons that make the implementation of closure-free periods worthwhile, and therefore may be willing to accept the slight decrease of net benefit. Some aspects are discussed in the following section.

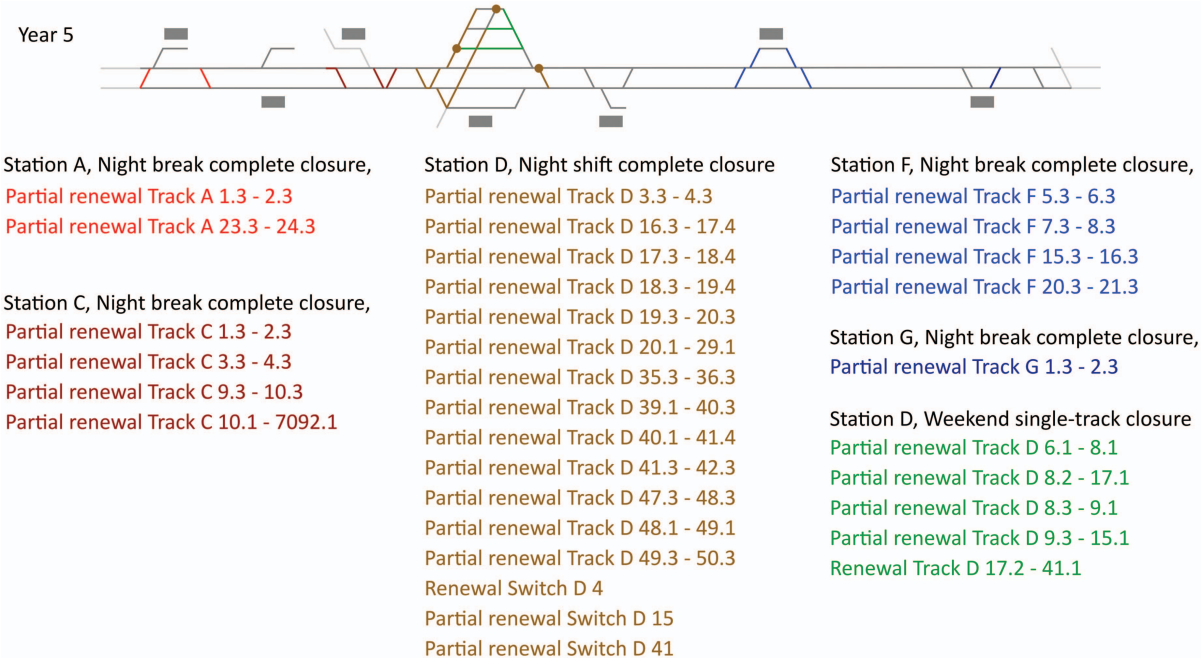

Fig. 5. (Color) Year 5 of the intervention program without a closure-free period.

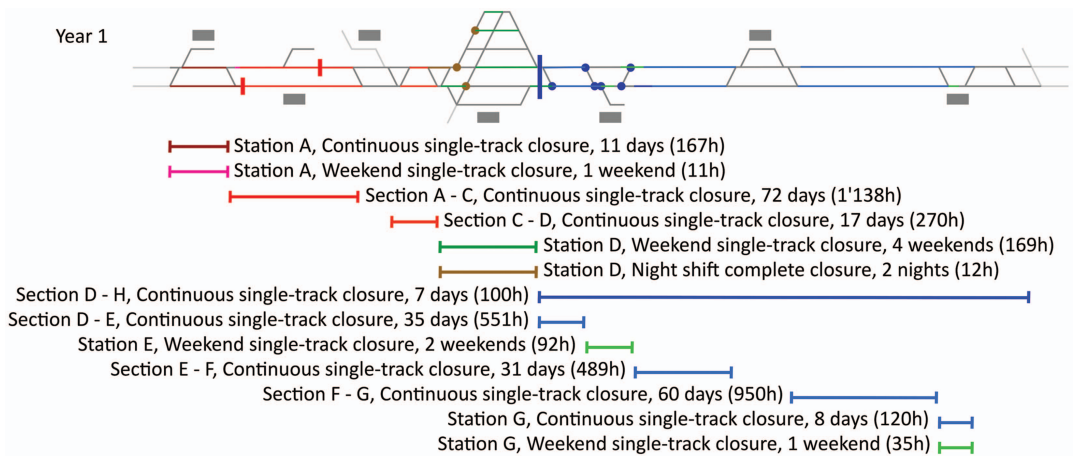

Fig. 6. (Color) Intervals in Year 1 without a closure-free period.

Required Intervals

An integral part of the net-benefit estimation in the previous section is the durations of the intervals, which are considered to be variable. Although this makes sense from an optimization point of view, it may be better from an organization point of view to have fixed interval durations in practice. Therefore, Table 10 presents the required intervals of the two programs, with the intervals considered with fixed durations. For example, a weekend is always a weekend with 54 h whether the interventions require the entire 54 h or only a part of it.

Table 10 presents only the required intervals, i.e., the night break with double-track closure, the night shift with double-track closure, the weekend single-track closure, and the continuous single-track closure. The first two are provided in terms of the nights required, the weekend single-track closure is provided in terms of the weekends required, and the continuous single-track closure is provided in terms of the days required. The required nights, weekends, and days of a specific interval type are independent of the location, because the exact location does not influence the costs of the considered inputs. This means that the eight weekends required in Year 1 of the unrestricted situation consist of the required weekend closures in Stations A, D, E, and G.

The comparison of the required intervals of the situation without a closure-free period and with a closure-free period shows the difference in the required intervals. Due to the movement of interventions from Years 2, 3 and 4 to Years 1 or 5, the optimal grouping of interventions and the optimal intervals to execute the interventions change. The requirement for night breaks decreases by 4 nights. However, 3 additional nights are required for a night shift. This results in 1 night less in total. The required weekends can be reduced by five due to the possibility of combining more interventions within intervals of a single year. The largest requirement, the

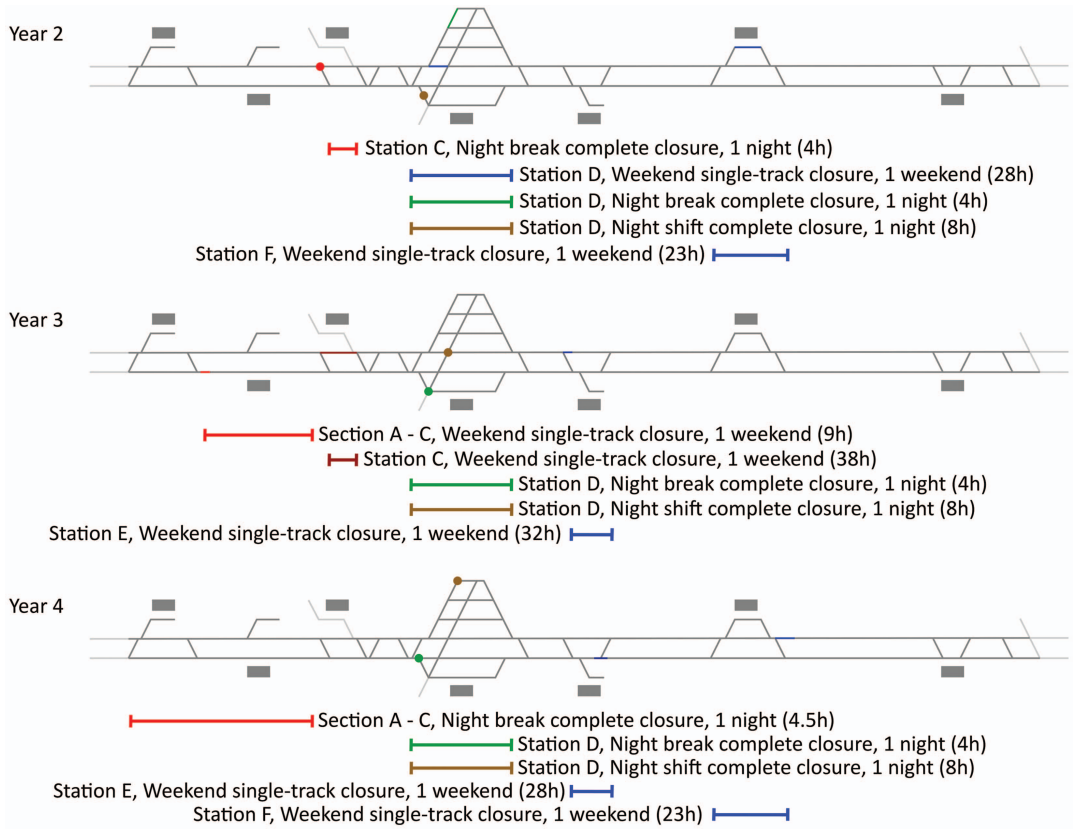

Fig. 7. (Color) Intervals in Years 2–4 without a closure-free period.

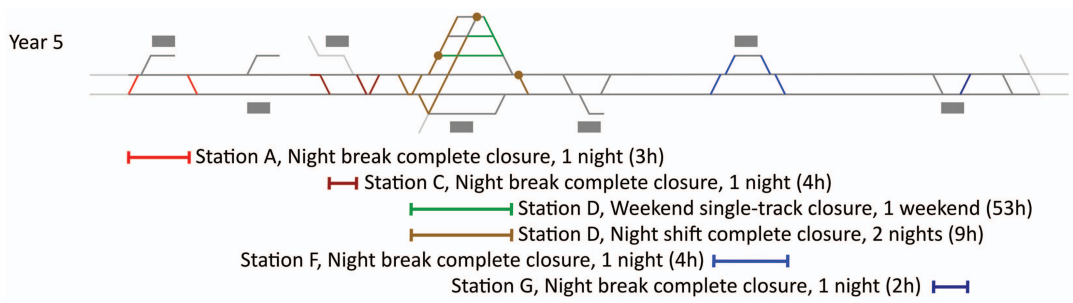

Fig. 8. (Color) Intervals in Year 5 without a closure-free period.

241 days of continuous single-track closures, remains unchanged. The requirement to execute such a large number of interventions within the first year is independent of the imposition of closure-free period. It is due to the initial situation in which many assets are in rather poor condition and require interventions according to the asset-level intervention strategies. When considering the intervals with fixed durations, the consideration of a closure-free period produces a benefit by requiring fewer weekends to execute all interventions within the 5 years.

Discussion

Example Situation

The input information in the example is based on the information provided by the infrastructure manager and by literature values. To keep the focus of the article on the optimization model and on the assessing the effects of closure-free periods, simplified information was used. A partial linear deterioration model, static traffic volume, and average failure events are examples of such simplified information. All these could be replaced with more-detailed information, e.g., nonlinear deterioration, traffic volumes changing over time, and more-detailed failure analysis. Such higher complexity in the input information does not affect the optimization model. The proposed model does cope with it as long as all information can be estimated before the optimization.

Sensitivity of Results

The optimal intervention program depends on the situation and on the parameters considered. Variations and uncertainties in the parameters may affect the optimal intervention program. Infrastructure managers must be aware of the accuracy of the parameters and

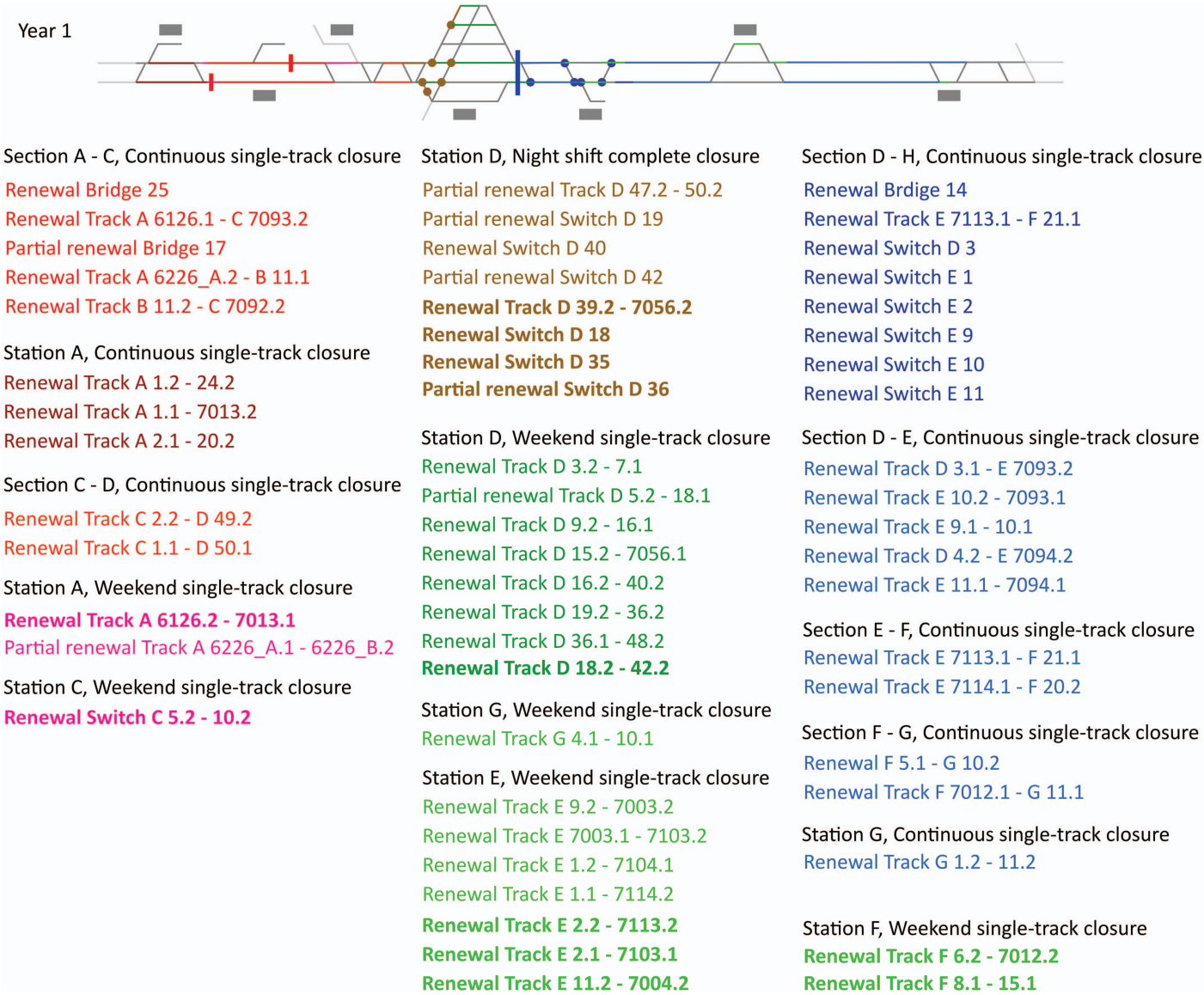

Fig. 9. (Color) Year 1 of the intervention program with a minimal 2-year closure-free period.

the uncertainties of the results when making decisions based on the results. Because this paper focuses on the optimization model, the example does not include a sensitivity analysis. Further information about determining whether an intervention program actually is optimal was presented by Burkhalter and Adey (2021b).

Modeling Complexity

The example network used in this paper contains a single line, which is part of a larger network. The double-track line can be considered a network by itself because it is a set of interconnected assets that offer a service when considered together. However, this example also is relatively small compared with entire networks of a railway infrastructure manager and all possible type of assets and interventions. Therefore, it is necessary to place the example in the context of size, mathematical complexity, and computational effort.

The example considered 182 assets, 2 possible interventions/asset, and 18 different intervals with which the interventions on an asset can be executed. A total of 6,537 intervention options were possible for the selection in the optimal intervention program. An intervention option describes a specific intervention executed on a specific asset with a specific interval. This resulted in 7×10^{1967} possible intervention programs from which the optimal solution was searched.

In the example situation, the mathematical optimization model considering all synergies and constraint is a mixed-integer linear problem with 34,288 variables and 20,576 constraints. The problem was solved using branch-and-bound in the programming software R version 4.0.2 on a standard laptop computer (Windows 10, 2.70 GHz, and 16 GB RAM). The required solving time was 46 s in the situation with no closure-free period constraint, and 71,567 s (=19.9 h) in the situation with a closure-free period constraint.

The number of possible intervention programs indicates the large complexity of the given problem. This increases exponentially with the network size, i.e., the number of assets, interventions, and intervals. Considering individual lines simplifies the consideration of the dependencies in the services on different lines. It helps to reduce the search space and the complexity of the optimization model. Most interdependencies between interventions, and between interventions and service, are related to the line to which they belong. Therefore, it is worthwhile to consider a single line in a first implementation.

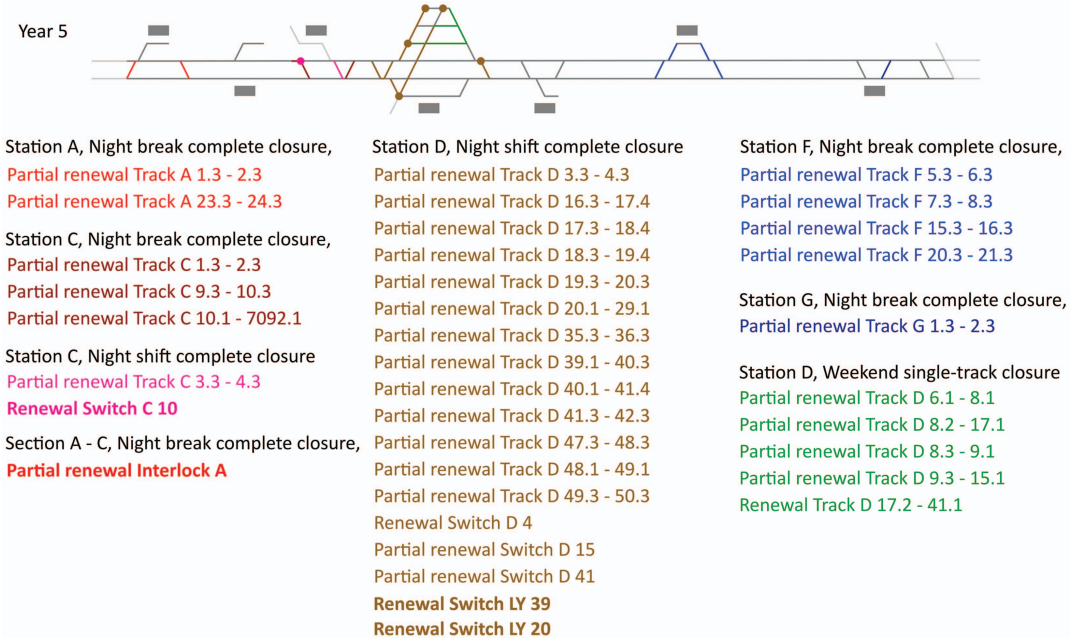

Fig. 10. (Color) Year 5 of the intervention program with a minimal 2-year closure-free period.

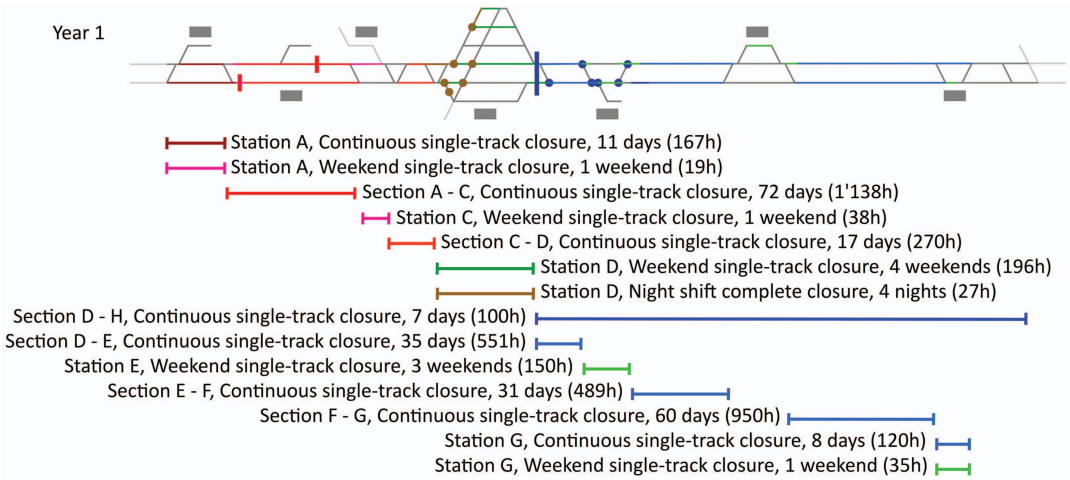

Fig. 11. (Color) Intervals in Year 1 with a minimal 2-year closure-free period.

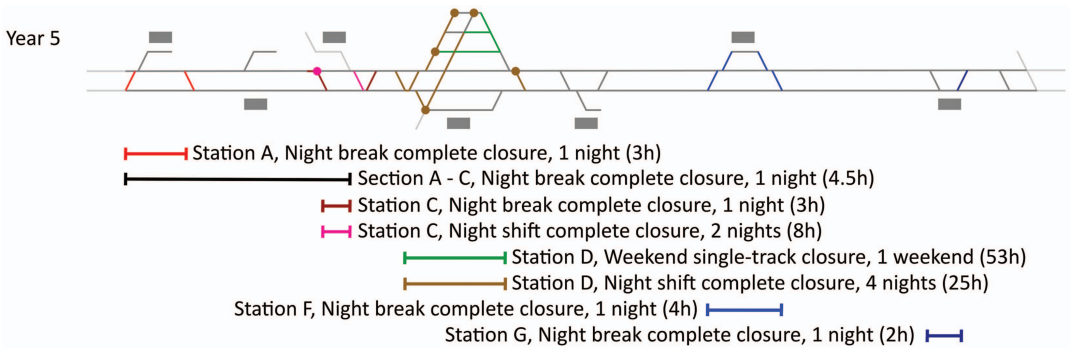

Fig. 12. (Color) Intervals in Year 5 with a minimal 2-year closure-free period.

Table 9. Net-benefit comparison

Parameter	Unrestricted (M CHF)	With closure-free period (M CHF)	Difference (CHF)	Difference without assets with changed interventions (CHF)
Planning period risk reduction	125.8	125.5	−397,000	−387,000
Planning period maintenance costs reduction	10.6	10.7	128,000	135,000
Future risk reduction	−2.5	−2.5	22,000	8,000
Future maintenance costs reduction	−6.4	−6.4	−44,000	−90,000
Future renewal costs reduction	145.8	145.8	−25,000	−300,000
Total benefit	273.4	273.1	−316,000	−634,000
Intervention costs	105.4	105.7	282,000	−7,000
Traffic management costs	3.7	3.7	10,000	−700
Additional travel time costs	70.8	70.9	44,000	−91,000
Total costs	179.9	180.2	336,000	−98,000
Net benefit (benefit–costs)	93.5	92.9	−652,000	−536,000

Note: M = million.

Table 10. Comparison of required intervals

Intervention program	Year	Night break (6 h) double-track closure (nights)	Night shift (8 h) double-track closure (nights)	Weekend single-track closure (weekends)	Continuous single-track closure (days)
Unrestricted	Year 1	—	2	8	241
	Year 2	2	1	2	—
	Year 3	1	1	3	—
	Year 4	2	1	2	—
	Year 5	4	2	1	—
	Total	9	7	16	241
With closure-free period	Year 1	—	4	10	241
	Year 5	5	6	1	—
	Total	5	10	11	241
Difference	Total	−4	+3	−5	0

Regarding the computational performance, the example was solved using a global optimization algorithm. The use of advanced heuristic algorithms has the potential to massively reduce the computational effort at the expenses of nonoptimal solutions. Such heuristic optimization algorithms may be of significance for large-scale applications in the real world. However, their performance is case-based and their development should be part of the implementation process when integrating such an operation research solution in praxis.

Conclusion

This paper investigated the effect of imposing closure-free periods on the development of intervention programs in terms of intervention costs and disruptions to service. Closure-free periods represent periods, i.e., multiple years, when no intervals are scheduled and thus no interventions are executed. The optimal intervention programs are developed using an existing network flow optimization model. Closure-free periods are considered in the network flow optimization model using a scenario-based optimization approach.

In the example, the optimal intervention program and its associated intervals were determined for a real railway line in Switzerland using real data. The example demonstrated the potential effect of implementing closure-free periods. The intervention program was determined for a 5-year planning period, once without considering a closure-free period and once with a minimal 2-year closure-free period. The results showed that a 3-year closure-free period was more beneficial than a 2-year closure-free period in the considered situation. However, the net benefit obtained was lower than when no closure-free period was considered. The potential reduction of costs by grouping interventions in space and time was smaller than the losses of benefit due to moving interventions away from their theoretically optimal execution time. However, having lower net benefit in this situation does not mean that closure-free periods should not be implemented per se. As shown in the example, the total number of intervals, e.g., the number of required weekends, can be reduced. Therefore, the lower net benefit may be worthwhile from an organizational perspective. It also may be worthwhile in terms of something not considered in the net-benefit calculation, e.g., user satisfaction with having no planned disruption on this line for 3 years. When integrating this optimization model in practice, the solution method has to take into consideration the problem size and the desired accuracy.

The model used to optimize intervention programs considering closure-free periods can be used in the real world, as shown in the example. However, it has potential for further development. First, the scenario-based optimization has limited scalability and is applicable only when there is a limited number of combinations regarding the closure-free periods. Second, the model can be extended with the consideration of uncertainties of future events, i.e., the uncertainty that interventions actually are required during the determined intervals. Nevertheless, the model used in this paper allows the investigation of implementing closure-free periods in intervention programs and their effects on the costs and service provided.

Appendix. Asset Data

Tables 11–15 provide the information about tracks, switches, bridges, catenaries, and interlockings.

Table 11. Track assets

ID	Name	Condition	Extent (m)	Neighbors
1	A 20.1–23.1	1.42	32.3	2
2	A 23.3–24.3	3.21	12.6	—
3	A 1.2–24.2	5.00	913.3	—
4	A 1.3–2.3	3.21	43.5	6
5	A 2.2–7,012.2	1.96	56.4	6
6	A 2.1–20.2	5.00	716.0	1
7	A 1.1–7,013.2	4.44	36.3	3, 4
8	A 6,126.1–C 7,093.2	5.00	3,869.2	9
9	A 6,126.2–7,013.1	4.44	80.4	7
10	A 6,226_A.2–B 11.1	5.00	2,019.8	11
11	A 6,226_A.1–6,226_B.2	5.00	102.4	12
12	A 6,226_B.1–7,012.1	1.90	25.3	5
13	C 1.2–4.2	1.95	114.0	14
14	C 4.1–5.1	1.95	18.0	24
15	C 2.1–3.1	2.05	6.0	17, 21
16	C 1.3–2.3	3.21	12.6	15
17	C 3.3–4.3	3.21	12.6	14
18	C 2.2–LY 49.2	5.00	1,397.1	15
19	C 1.1–LY 50.1	5.00	1,297.2	13, 16
20	B 11.2–C 7,092.2	5.00	1,777.1	10
21	C 3.2–9.1	2.68	406.8	22, 23
22	C 9.2–7,093.1	1.73	35.6	8
23	C 9.3–10.3	3.21	28.0	25
24	C 5.2–10.2	4.48	378.6	25
25	C 10.1–7,092.1	3.15	8.0	20
26	D 3.3–4.3	3.21	9.7	37
27	D 35.3–36.3	3.17	14.7	51
28	D 42.1–47.1	3.73	270.5	29, 31
29	D 47.2–50.2	3.82	101.6	19
30	D 48.1–49.1	3.09	8.0	18, 32
31	D 47.3–48.3	3.21	4.9	30
32	D 49.3–50.3	3.21	4.9	19
33	D 18.3–19.4	3.21	26.2	35, 36
34	D 18.2–42.2	4.54	271.1	28
35	D 19.2–36.2	4.71	242.3	51
36	D 19.3–20.3	3.21	7.9	46
37	D 4.1–5.1	2.00	12.7	38, 39
38	D 5.2–18.1	3.72	440.1	33, 34
39	D 5.3–6.2	2.01	13.0	40
40	D 6.1–8.1	2.48	27.3	41, 45
41	D 8.2–17.1	3.07	293.2	42, 49
42	D 17.2–41.1	4.16	272.0	53
43	D 3.2–7.1	4.91	173.3	44, 50
44	D 7.2–19.1	4.05	374.5	35, 36
45	D 8.3–9.1	2.48	2.1	48, 54
46	D 20.1–29.1	2.70	12.1	47
47	D 29.2–35.1	1.84	112.6	27
48	D 9.3–15.1	3.21	177.2	52
49	D 17.3–18.4	3.21	7.9	33, 34
50	D 7.3–20.2	2.76	410.5	46
51	D 36.1–48.2	3.83	287.1	30
52	D 15.2–7,056.1	5.00	263.5	58
53	D 41.3–42.3	3.12	9.9	28
54	D 9.2–16.1	5.00	200.4	55, 57
55	D 16.2–40.2	4.71	302.5	56
56	D 40.1–41.4	3.21	8.1	53
57	D 16.3–17.4	3.21	33.1	42, 49
58	D 39.2–7,056.2	4.61	39.7	59
59	D 39.1–40.3	3.05	4.0	56
60	D 3.1–E 7,093.2	4.51	2,440.0	26, 43
61	D 4.2–E 7,094.2	4.99	2,490.8	37
62	G 1.1–H 11.1	3.03	883.5	63, 66
63	G 1.2–11.2	5.00	848.1	69
64	G 2.2–H 12.2	3.97	1,041.9	65
65	G 2.1–4.2	1.58	4.6	68
66	G 1.3–2.3	3.21	21.1	65
67	G 10.3–11.3	3.21	5.0	69
68	G 4.1–10.1	3.75	686.6	67, 70
69	F 7,012.1–G 11.1	5.00	4,670.3	72
70	F 5.1–G 10.2	5.00	4,821.7	76, 79
71	F 15.3–16.3	3.21	21.6	75
72	F 6.2–7,012.2	4.38	163.1	73
73	F 6.1–7.1	1.23	41.4	74, 80
74	F 7.2–16.2	1.80	321.0	75
75	F 16.1–20.1	2.62	218.5	78, 82
76	F 5.2–21.2	2.24	770.9	81
77	F 8.1–15.1	4.62	228.3	71
78	F 20.3–21.3	3.21	10.6	81
79	F 5.3–6.3	3.21	14.7	73
80	F 7.3–8.3	3.21	19.6	77
81	E 7,113.1–F 21.1	5.00	2,908.5	85
82	E 7,114.1–F 20.2	5.00	2,972.0	89
83	E 9.1–10.1	4.17	33.9	84, 93
84	E 10.3–11.3	3.21	7.7	94
85	E 2.2–7,113.2	4.42	169.8	86
86	E 2.1–7,103.1	4.10	100.3	87
87	E 7,003.1–7,103.2	4.34	446.1	88
88	E 9.2–7,003.2	5.00	199.5	83
89	E 1.1–7,114.2	5.00	121.7	90
90	E 1.2–7,104.1	3.99	149.8	91
91	E 7,004.1–7,104.2	4.03	448.0	92
92	E 11.2–7,004.2	4.54	313.5	94
93	E 10.2–7,093.1	4.88	293.9	60
94	E 11.1–7,094.1	4.15	244.6	61

Table 12. Switch assets

Name	Condition	Group
Switch A 1	1.74	1
Switch A 2	1.76	1
Switch A 20	1.77	1
Switch A 23	1.46	1
Switch A 24	1.47	1
Switch A 6126	2.23	1
Switch A 6226_A	1.51	1
Switch A 6226_B	1.48	1
Switch C 1	1.78	2
Switch C 2	1.77	2
Switch C 3	1.99	2
Switch C 4	1.81	2
Switch C 5	1.87	2
Switch C 9	2.09	2
Switch C 10	3.56	2
Switch D 39	4.31	3
Switch D 40	4.80	3
Switch D 41	3.03	3
Switch D 3	4.99	3
Switch D 4	3.97	3
Switch D 35	4.53	3
Switch D 36	3.38	3
Switch D 42	3.71	3
Switch D 49	2.52	3
Switch D 50	2.34	3
Switch D 47	2.42	3
Switch D 48	2.62	3
Switch D 18	4.57	3
Switch D 19	3.59	3
Switch D 20	3.28	3
Switch D 5	1.95	3
Switch D 6	1.61	3
Switch D 8	2.22	3
Switch D 9	2.18	3

Table 12. (*Continued.*)

Name	Condition	Group
Switch D 15	2.72	3
Switch D 16	1.94	3
Switch D 17	2.39	3
Switch D 29	2.20	3
Switch D 3	4.99	3
Switch D 4	3.97	3
Switch D 35	4.53	3
Switch D 36	3.38	3
Switch D 42	3.71	3
Switch D 49	2.52	3
Switch D 50	2.34	3
Switch D 47	2.42	3
Switch D 48	2.62	3
Switch D 18	4.57	3
Switch D 19	3.59	3
Switch D 20	3.28	3
Switch D 5	1.95	3
Switch D 6	1.61	3
Switch D 8	2.22	3
Switch D 9	2.18	3
Switch D 15	2.72	3
Switch D 16	1.94	3
Switch D 17	2.39	3
Switch D 29	2.20	3

Table 13. Bridge assets

Name	Location ID	Condition	Extent (m^2)
Bridge 1	237559_99.893	2.69	81.0
Bridge 2	237562_100.075	2.69	64.3
Bridge 3	238760_10.586	2.62	180.2
Bridge 4	238762_11.085	1.00	26.2
Bridge 5	239405_14.395	2.62	111.0
Bridge 6	239413_16.447	2.62	63.0
Bridge 7	513181_16.796	1.00	40.2
Bridge 8	239649_18.227	2.69	72.0
Bridge 9	1273325_21.039	2.62	71.0
Bridge 10	239654_21.046	2.69	76.0
Bridge 11	237555_22.469	2.69	147.1
Bridge 12	7241920_22.58	2.62	56.4
Bridge 13	238592_22.807	2.69	118.8
Bridge 14	238596_23.136	3.83	198.1
Bridge 15	238602_24.000	2.69	556.2
Bridge 16	228213_26.356	2.69	46.4
Bridge 17	228215_26.897	3.83	252.9
Bridge 18	228216_26.899	1.08	215.0
Bridge 19	228221_27.624	2.69	34.3
Bridge 20	228220_27.625	2.69	41.7
Bridge 21	228225_28.115	2.69	60.8
Bridge 22	228226_28.120	2.69	60.8
Bridge 23	227924_29.687	1.08	40.0
Bridge 24	227927_30.149	2.69	610.0
Bridge 25	227926_30.150	4.62	610.0
Bridge 26	227929_30.305	2.69	143.2

Table 14. Catenary assets

Name	Condition	Extent (m)
Catenary D–H	1.60	36,783
Catenary C–D	1.92	15,649
Catenary A–C	2.19	15,822

Table 15. Interlock assets

Name	Condition
Interlock A	3.38
Interlock D	1.47
Interlock G	2.06
Interlock F	2.06
Interlock E	1.95

Data Availability Statement

The original data used during the study are proprietary or confidential in nature and may be provided only 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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