Issue 22(2), 2022, pp. 108-131
https://doi.org/10.18757/ejtir.2022.22.2.6130

TU Delft OPEN

EJTIR
ISSN: 1567-7141
http://ejtir.tudelft.nl/

Minimal utilization rate for railway maintenance windows: a cost-benefit approach

Abderrahman Ait-Ali[1]
Swedish National Road and Transport Research Institute (VTI), Stockholm, Sweden
Department of Science and Technology, Linköping University, Norrköping, Sweden

Tomas Lidén[2]
Swedish National Road and Transport Research Institute (VTI), Stockholm, Sweden
Department of Science and Technology, Linköping University, Norrköping, Sweden

Methods for economic assessment are often used in the rail sector to evaluate large infrastructure investments such as new high-speed lines. With larger networks and ageing infrastructure, these methods can also be used for planning maintenance. In this paper, we focus on the newly introduced concept of maintenance windows in Sweden. These are pre-allocated slots in the train timetable dedicated to performing, among others, periodic/frequent maintenance activities. To justify the pre-allocation of such windows, this study presents a method to find minimal utilization rates depending on window designs and traffic situations. Using a cost-benefit approach, the windows are assessed using a total social cost including work costs, loss in traffic production and reliability gains in future traffic. Based on a case study from the Southern main line in Sweden, we study the minimal utilization rate in different test scenarios, i.e., night or day shifts, asset degradation functions and designs of maintenance windows. The results show that lower utilization rates (4-42%) can be accepted during low-volume traffic or for partial closures, while higher utilization rates (47-83%) are required for full closures during high-volume traffic. Whether the rates are measured as the share of used window time or the share of utilized windows is less important, especially when higher utilization is required. Sensitivity analyses of asset knowledge indicate that parameters such as asset degradation function and minimum asset quality (and to a lesser extent traffic volume, discount rate and failure likelihood) can have a substantial effect on the minimum required utilization rates.

Keywords: *maintenance windows, rail infrastructure; cost-benefit analysis.*

Publishing history

Submitted: 08 November 2021
Accepted: 20 April 2022
Published: 22 April 2022

Cite as

Ait-Ali, A., & Lidén T. (2022). Minimal utilization rate for railway maintenance windows: a cost-benefit approach. European Journal of Transport and Infrastructure Research, 22(2), 108-131.

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[1] A: Malvinas väg 6, 114 28 Stockholm, Sweden T: +46 8 555 367 81 E: abderrahman.ait.ali@vti.se
[2] A: Malvinas väg 6, 114 28 Stockholm, Sweden T: +46 8 555 367 78 E: tomas.liden@vti.se

1. Introduction

With larger railway networks and increasing traffic, ageing infrastructure requires more maintenance investments. For instance, Swedish railway infrastructure expenditures have been steadily increasing since 2018, see Figure 1. The total costs are expected to reach 11 billion SEK in the coming few years according to the recent maintenance plans (Honauer and Ödeen, 2020). Maintenance activities have a major share of the total expenditures partly due to the maintenance debt accumulating over several years.

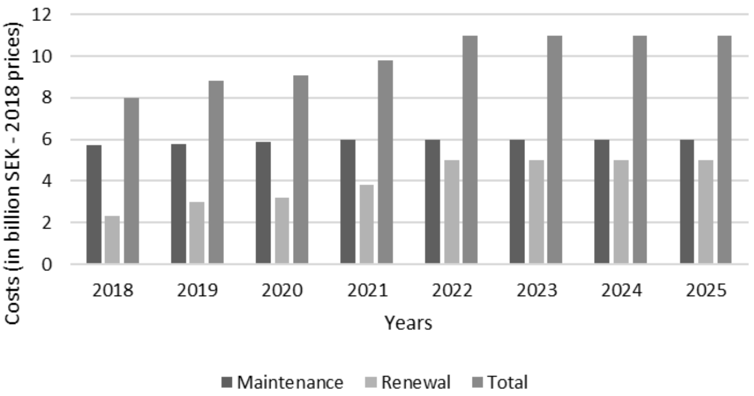

Figure 1. Expenditures on railway infrastructure in Sweden between 2018 and 2025 (Olauson, 2020).

In addition to direct costs such as material and labour, maintenance activities also have social costs, e.g., loss in traffic production (cancelled train paths), service delays and environmental externalities (noise and pollution). In the UK for instance, Sasidharan et al. (2020) indicate that the total social costs of track maintenance are often 30-40% of the total railway transport expenditures. Furthermore, maintenance activities can benefit future traffic production by increasing reliability, availability and safety. In their study of maintenance in Swedish railways, Stenström et al. (2016) show that such activities can decrease delay-related social costs by up to 30%.

The infrastructure manager (IM) is responsible for maintaining and renewing the different assets or infrastructure components, and hence the overall rail infrastructure system (Zoeteman, 2001). In particular, the IMs often decide when assets should be inspected, maintained, or renewed. Such decisions are often a trade-off between costs (e.g., risk of disruptions, safety) and benefits (e.g., increased reliability and punctuality). Consequently, well-founded methods for measuring costs as well as benefits are needed, both from a social and an economic perspective.

Economic assessment approaches, such as cost-benefit analysis (CBA), are often used to evaluate large infrastructure investments, e.g., building new high-speed railway lines. To a lesser extent, such methods have been used when considering maintenance expenditures in the rail sector. In Europe, EC (2018) states that social value should be used as an important prioritization criterion. For instance, Swedish railway legislation states that the IM or Trafikverket must prioritize infrastructure investments according to their socio-economic effects, and competing proposals are evaluated based on strategic governmental directions, e.g., for safety, punctuality, and environment (Ekström, 2015). To help quantify the different effects, Trafikverket publishes regular updates to its CBA guidelines (Trafikverket, 2016). Thus, CBA is an important and commonly used tool to study the social value of investments. As shown later in the literature review, knowledge about the planning of maintenance is however still weak and the support for analysing and comparing maintenance activities/alternatives in the CBA guidelines is less developed.

In the context of basic maintenance planning, we focus on the assessment of maintenance windows (MWs) and their utilization rate. MWs are pre-allocated slots or reserved capacity in the annual train timetable (Göransdotter and Dyrssen, 2017). Other equivalent terms3 are also found in the literature (Kalinowski et al., 2020). Such capacity guarantees access to the track for maintenance contractors to perform regular inspection and maintenance activities. Unlike unplanned maintenance activities, pre-allocated MWs reduce the traffic losses to train passengers and operators since they have enough time to choose alternative travel choices, e.g., new routes for passengers and new services for operators. Moreover, such pre-allocation reduces uncertainty for maintenance contractors as they can make more reliable work plans and cost estimates. However, the actual usage of MWs may vary and to justify the pre-allocation (and subsequent reduction in traffic capacity) a certain minimal utilization rate will be required – which is the main question we address here.

This paper presents a method using a cost-benefit approach to find the minimal utilization rate (or MUR) for a given schedule of MWs and train traffic so that the total net social value is positive. The method is demonstrated in a case study that includes a sensitivity analysis.

The MUR accounts for the negative effects of the windows, i.e., opportunity costs of the train traffic that could otherwise have taken place. Establishing such MURs forms the basis for setting contractual requirements and when evaluating the performance of maintenance contractors (MCs). Furthermore, the model considers the capacity planning process and the uncertainties in scheduling maintenance activities. In addition to filling the gap when it comes to using CBA for planning MWs, this study also contributes to the design of cost-effective performance-based contracts between IMs and MCs. Moreover, by estimating the social costs of a given schedule of MWs, the method allows to identify MWs with high social value.

The case study concerns the Southern main line in Sweden, which has been chosen since it connects important centres for passenger and freight traffic. Maintenance costs and benefits are modelled, costs include short- and long-term components, e.g., work and material costs, reduced available capacity and disturbances whereas benefits include the increased availability of future traffic production. The model is applied to several test scenarios with different characteristics such as time period, asset degradation function and design of MWs. Based on the different scenarios, the numerical results indicate which MURs should be required for different designs of MWs and traffic situations. The analysis, in the case study, is limited to one type of asset, namely switches and crossings (S&C). However, it is possible to include more assets given available additional data.

The paper starts with this introductory section. Section 2 reviews the existing related literature. The model is described in section 3. The case study is presented in section 4 including test scenarios, results, and discussions. Section 5 ends the paper with concluding remarks.

2. Literature overview

Train operations in railway systems require the existence of a solid infrastructure that consists of various assets that need continuous inspections, maintenance, corrections/repairs, and renewal. These assets are generally maintained by different activities such as cleaning, lubrication, straightening, calibration, reparation, renovation, and replacement. There are generally two categories of maintenance activities. One is the renewal after the maximum lifetime is reached whereas the second category is basic maintenance which is often frequently performed before failures occur. Given prediction tools, a proactive approach (also called preventive maintenance) is more efficient than the reactive or corrective one (Ran et al., 2019).

To choose the correct time and place to perform activities on the infrastructure, some assets are periodically inspected. These inspections improve the asset knowledge so that maintenance

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[3] ”Maintenance access windows” is an alternative and more precise term, it indicates that the windows may not always be used but only provide capacity to access the tracks for maintenance if needed. For brevity, we adopt instead the term ”maintenance windows” or MWs for short throughout this paper.

activities can be planned more efficiently. In case of an accident or infrastructure failure(s), corrective maintenance is performed either immediately or scheduled for later, usually combined with some operative restrictions, e.g., lowered speeds, until the repair(s) have been completed. Other examples include urgent interventions due to accidents, crime or failures as well as winter maintenance, e.g., snow removal (Göransdotter and Dyrssen, 2017).

Although not discussed in this paper, the choice of whether to renew or otherwise maintain the infrastructure is important and is often based on the balance between several elements, e.g., safety, costs/economy, and type of the infrastructure/asset(s). Interested readers are referred to a more detailed recent analysis by Nilsson and Odolinski (2020).

In this section, we first describe and summarize literature concerning maintenance planning (subsection 2.1) and maintenance windows (subsection 2.2), followed by a review of literature and approaches used for assessing maintenance plans (subsection 2.3).

2.1 Planning for maintenance

National IMs, such as Trafikverket in Sweden, are generally responsible for the different assets and their maintenance. However, differences exist between countries depending on the market organization (Alexandersson, 2015). In addition to the IM, often the main owner of the infrastructure assets, there are several stakeholders which are involved in the different levels of planning for maintenance such as government regulator(s), representatives for passengers and freight customers, and train operators (Kobbacy and Murthy, 2008).

Moreover, there are different maintenance planning levels with planning problems, see Figure 2. Strategic questions are treated several years in advance to set overall maintenance goals and large investments. However, most activities are considered at the tactical level. Urgent activities are often planned during operations.

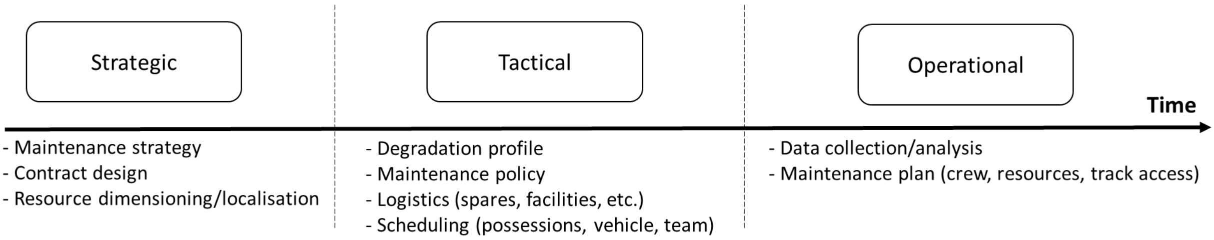

Figure 2. Maintenance planning levels and problems, inspired by Kobbacy and Murthy (2008) and Lidén (2014).

More specific plans are made during the tactical planning level, e.g., traffic and maintenance schedules based on maintenance policies and other information such as asset degradation profiles. Data is collected/analysed during the operational level where detailed maintenance plans are performed including possessions guaranteeing access to the track for maintenance and the corresponding crew/resource allocation. In a book about the maintenance of complex systems, Kobbacy and Murthy (2008) present an application in the rail industry for grouping and prioritizing maintenance activities.

Based on the outcomes (at the operational level) of these maintenance activities, IMs can evaluate the performances of MCs and hence redesign the corresponding contracts (at the strategic level). Famurewa et al. (2011) describe how this can be used to achieve maintenance objectives by identifying important considerations in the implementation of a performance-based framework.

At the tactical level, the allocation of railway capacity for track access is generally part of an annual process described in the national network statement, see for instance the Swedish network statement by Trafikverket (2020d). At the beginning of the annual process, the statement lists the main maintenance activities that are planned to be included in the annual timetable including MWs, see (Hedström, 2020) for examples of activities that are typically performed within MWs.

2.2 *Maintenance windows (MWs)*

Inspired by other countries such as France and the Netherlands, Sweden has since 2016 adopted MWs as a new planning policy during the capacity allocation process. Scheduling slots for maintenance activities within allocated MWs have therefore no direct effects on train traffic. Another advantage is that they guarantee access to the track for the contractors and thus allow them to estimate their costs more accurately (Honauer and Ödeen, 2018).

MWs were initially introduced to secure enough capacity or track access time in the annual train timetable that can be used to perform, among others, essential recurrent maintenance activities including inspections, schedule/status-based maintenance, and repairs. One of the purposes for these pre-allocated slots is to make these maintenance activities have as few disturbances to train traffic as possible. As illustrated in Figure 3, several inspection and maintenance activities can be planned within MWs. In practice, the contractors apply for possessions before being allowed to access the tracks within the pre-defined MWs (Alexandersson, 2015).

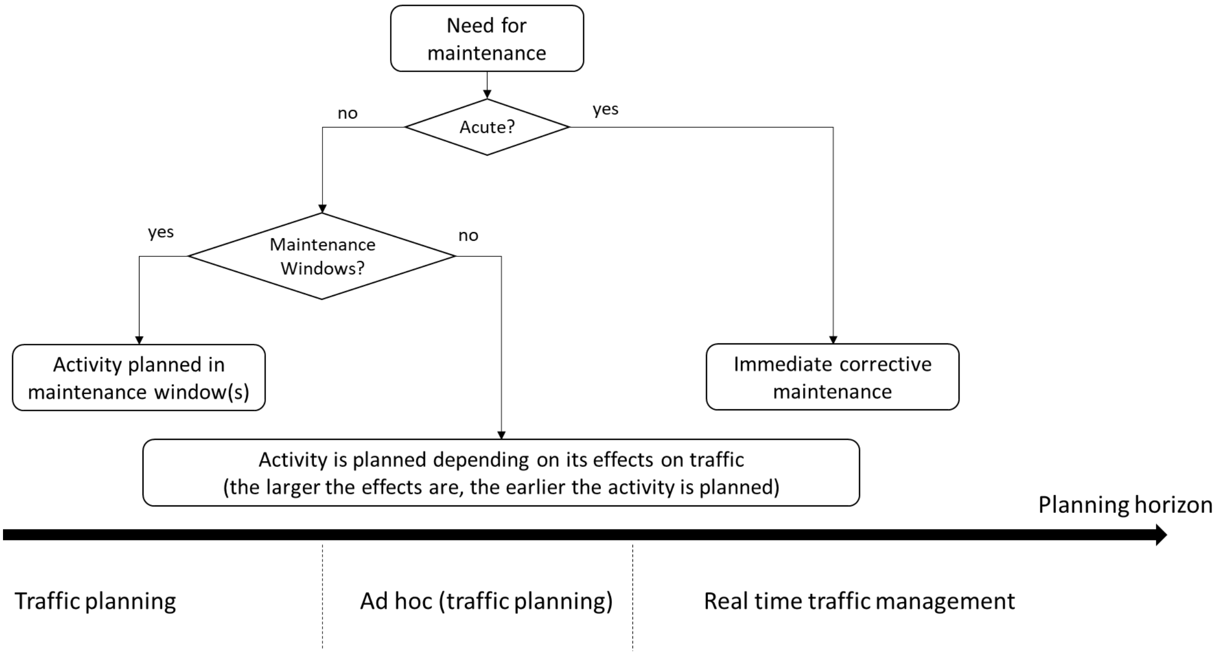

Figure 3. Different scenarios to allocate capacity for maintenance activities in Sweden, inspired by Hedström (2020).

MWs can have different designs. It is important to mention that there is generally a trade-off in the size of the slots in MWs. Although preferred by entrepreneurs, longer slots have more effects on traffic production and risk having lower overall utilization rates. However, shorter slots have a lower effect on traffic but are often not long enough for entrepreneurs to perform certain activities and thus may also tend to not be fully utilized (Olauson, 2020). Thus, finding the most efficient configuration depends on elements such as utilization rates of the MWs, track access frequency (type of maintenance activity), and tolerance for negative effects on traffic production (Lidén et al., 2020).

Since its introduction, the new concept has not been efficiently used in Sweden. Alexandersson (2015) mentions that there may be many reasons for this, e.g., not including all stakeholders in the planning and not enough information about the maintenance needs, in addition to the IM lacking enough knowledge about the infrastructure assets. Trafikverket (2020b) has therefore been working on different projects and several actions to improve the utilization rates of MWs. Some of these actions are:

- Possibility to cancel slots for maintenance activities for alternative use, e.g., train traffic
- Earlier schedule of maintenance plans at key operation sites where all tracks are used

- Improved coordination between stakeholders and activity areas
- Segmentation of sites into so-called islands for efficient maintenance plans

In a recent follow-up study on the Swedish southern main line, Granberg and Rehn (2020) report that 51-52% of the pre-allocated MWs are used compared to 78-93% on the Värmland single-track line. Trafikverket (2015) aimed at 80% (or more) of all windows being effectively used for maintenance, recent goals are even higher at 85% (Trafikverket, 2019). This study already shows that MWs may differ in space and time depending on the traffic conditions.

2.3 *Approaches to assessing maintenance plans*

Cost-benefit analysis or CBA is commonly used to assess investment proposals even if the methodology has certain limitations (Van Wee, 2007). Although such analysis has been mainly used to assess large infrastructure investments, an increasing number of studies look at the use of CBA for planning infrastructure maintenance.

Several studies suggest that the maintenance costs in railways are driven by various factors, UIC (2015) short-listed aspects such as asset density, electrification, tonnage, speed, maintenance strategy and service quality. Traffic density is one aspect that attracted substantial attention in the literature (Andersson, 2006). An early literature review by Hedström (1996) has also shown that the effects of traffic volumes are significant.

Many studies attempted to quantify the marginal costs of railway maintenance. Odolinski and Boysen (2019) estimate the marginal costs from capacity utilization which is useful for planning maintenance activities for parts of the infrastructure with different traffic volumes. Such estimates are also useful for track access charging (Odolinski and Wheat, 2018) and/or planning the renewal of assets (Nilsson and Odolinski, 2020). Moreover, additional costs can be incurred when scheduling maintenance activities on infrastructure sections with high-volume traffic because of the loss in traffic production. MWs are therefore in competition with potential train services, Lidén (2018) investigated how such windows can be designed in a cost-efficient way.

Most activities in MWs have pre-planned/expected and continuous effects on train traffic. Infrastructure-related delays are due to corrective maintenance or repair activities that have unexpected effects on traffic. In this study, the former is included as a social cost whereas the latter is used as a proxy for the benefit of increased punctuality or reduced risk of delays.

The literature includes a few other CBA studies of maintenance, Stenström et al. (2016) consider that maintenance activities have both direct and indirect costs. In their CBA model, the authors include different cost components, e.g., material and labour costs (direct costs), maintenance times (logistic time and active repair time), production or service losses (delays), and failure costs for corrective maintenance. Moreover, the same authors state that for planning maintenance activities, the following characteristics should also be considered: cost of downtime, redundancy of the infrastructure (network connectivity), and reliability characteristics. Andersson et al. (2011) studied the relation between the costs of maintenance activities and their socio-economic effects including benefits. Train operations together with maintenance or renewal activities define several characteristics in the system, e.g., speed, reliability, level of comfort, tonnage/load, safety and emissions. These in turn lead to different effects that include, among others, travel/transport time or cost, delay, crowding and accidents.

Based on this previous framework, Eliasson and Börjesson (2014) highlight the importance of the assumptions that are used to construct train timetables for train services in the resulting total socio-economic effects. Using a similar methodology, Lidén and Joborn (2016) compared the costs of infrastructure maintenance activities with the socio-economic effects of train traffic by optimizing the train timetable using mathematical programming. In CBA frameworks, the resulting benefit/cost ratio often called the net present value ratio is used to rank the different possible alternatives in comparison to the do-nothing scenario (also called comparison alternative), indicating for instance the most economically efficient maintenance plan (Bångman, 2012).

To assess infrastructure maintenance and lower the operations costs, it is also important to know the costs throughout the life cycle of the assets, also called life cycle cost/costing or LCC for short (Zoeteman, 2001). Quantitative LCC studies aim at assessing the total cost of acquiring, owning and disposing of assets. This can serve in decision-making tools, e.g., to improve maintenance strategies such as finding the optimal trade-off between investment and maintenance for assets such as rail tracks (Patra, 2007), and S&C (Nissen, 2009). LCC analysis can also be used in combination with other approaches such as CBA to find which asset and when to replace it. It can also be used at an earlier stage to choose between different types and/or combinations of assets (Nissen, 2009). LCC has even been recently used in a KPI model to study the potential of different innovations of Shift2Rail projects, e.g., in railway infrastructure and rolling stock (Perreal et al., 2019).

There are 6 phases in an LCC analysis, i.e., concept and definition, design and development, manufacturing, installation, operation and maintenance, and disposal. The simpler alternative analysis includes only 3 main phases, i.e., development, operation, and phase-out. We focus in this study on the performances of the assets during operations, i.e., asset degradation. There are different types of degradation curves/functions, see some illustrative examples in Figure 4 from a study of S&C in Switzerland by Zwanenburg (2007). Similar examples exist in survival analysis and are often called survival functions (Rayhusthwaite, 2009).

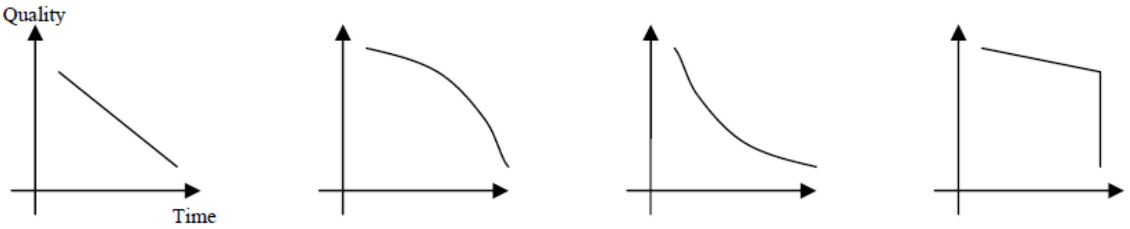

Figure 4. Illustration of different types of degradation curves (Zwanenburg, 2007).

In LCC analysis, the total costs of the phases (and components) are evaluated at the time of the analysis. It is therefore important to use the so-called total present value (TPV) where all the costs and benefits, including the ones in the future, are all converted/discounted to an equivalent present value using a discounting factor. Interested readers are referred to the paper by van der Weide et al. (2010) for more details on the importance of such discounting in maintenance planning. Other metrics are used to present the costs in LCC studies such as internal rate of return and/or annuity. The resulting values are often validated using sensitivity or uncertainty analysis (Zoeteman, 2001).

For rail infrastructure assets, there is a trade-off between the maintenance period and the risk of failure or disruptions. It is ideally preferable to schedule maintenance just before the failure of the asset, e.g., when the degradation curve, as illustrated in Figure 5, goes below a certain minimal quality. Thus, the loss from maintaining an already functional asset is reduced/absent. In general, e.g., due to varying conditions (increased traffic volume and/or harsher weather), some assets can fail before the usual period and such uncertainties risk provoking costly disruptions, e.g., delays and discomfort. Another advantage of perfectly scheduled maintenance, guaranteeing a minimal accepted quality, is the reduction in the loss due to early excessive maintenance activities. Considering these uncertainties, Sasidharan et al. (2020) present a new approach based on LCC analysis to assess track maintenance strategies. Based on a case study from the UK, the authors identified more economically beneficial strategies compared to the ones currently in use.

Decision support systems use LCC to analyse the long-term impacts of design and maintenance activities on the total cost but also on other aspects such as reliability, traffic performance or punctuality, availability and safety (Zoeteman, 2001). However, the degradation function is often not known or uncertain even if traffic conditions, e.g., weather, trainloads, are not highly variable.

Maintenance assessment is not restricted to analysing the costs and benefits over the life cycle of assets. It is therefore important to also consider other aspects, one more general approach is the so-called RAMS analysis which stands for Reliability, Availability, Maintainability and Safety. These four are all used as indicators of the quality and performance of the infrastructure assets (Patra, 2007). RAMS aims to predict the specific functionalities of a product over its complete life cycle (Ghodrati et al., 2017).

Table 1. Comparative overview of main literature, assessment approaches and the studied maintenance plans.

Reference (chronologically)	Approach(es)			Main topic(s)
	CBA	LCC	RAMS	
Zoeteman (2001)		X		Decision support for infrastructure management
Patra (2007)		X	X	Rail track maintenance
Zwanenburg (2007)		X		Wear and tear of S&Cs
Nissen (2009)		X		Life-cycle cost of S&Cs
Andersson et al. (2011)	X			Socio-economic effects of maintenance activities
Eliasson and Börjesson (2014)	X			Effects of investments and timetable assumptions
Stenström et al. (2016)	X			Preventive and corrective maintenance planning
Ghodrati et al. (2017)			X	Reliability of S&Cs
Odolinski and Wheat (2018)	X			Track access charging based on maintenance costs
Lidén (2018)	X			Planning MWs with train traffic
Odolinski and Boysen (2019)	X			The marginal social cost of maintenance capacity
Perreal et al. (2019)		X		LCC benefits from infrastructure innovations
Nilsson and Odolinski (2020)	X			Asset renewal plans
Sasidharan et al. (2020)		X		Life cycle approach for ballasted track maintenance
Elena (2021)	X	X		Life cycle perspective for infrastructure management
This paper	**X**	**X**	**X**	**MURs of MWs of S&Cs**

Table 1 provides a comparative overview of some of the main references that are mentioned in this section of the literature review. The table indicates that earlier research, about maintenance plan assessment, focused particularly on LCC methods whereas CBA is increasingly adopted in the more recent literature. However, RAMS or a combination of the different approaches is less common.

Although some recent studies adopted a combination of different approaches such as LCC and CBA (Elena, 2021), no previous work, to our knowledge, has applied it to the assessment of pre-reserved MWs and their utilization rate. Reviewed published works do not distinguish between reserved and used time slots, and the difference in traffic impact. Hence, they do not consider the actual capacity planning process – assuming perfect correspondence between planning and execution. With a focus on MWs, this paper attempts to fill this gap using a cost-benefit approach over a life-cycle period between consecutive maintenance activities of S&Cs. The model also includes certain RAMS aspects such as reliability and availability when calculating future traffic benefits.

3. Modelling

Based on the review of existing literature as well as the main components of a possible model, to assess the effects of MWs, this section describes the developed model. It combines different assessment approaches which are presented in the literature overview. Before modelling the utilization rate of MWs, we make the following assumptions:

- The studied schedules for MWs are assumed to be periodic, i.e., activities are taking (on average) the same number of hours every weekend/weekday over several weeks. Alternatively, the schedule can be characterized by the total number of working hours.
- When different MWs are utilized at the same time in two or more sites on the same line, we assume that the total access time corresponds to the longest MW.
- The total social cost is assumed to include: the cost of maintenance work, the loss in traffic production, and the gain in improved traffic reliability.
- The modelling is assumed to focus on one type of asset (e.g., S&Cs as in the case study).
- When modelling the gain in future production, maintenance activities are assumed to take place as soon as the quality of the asset reaches a certain minimum.

For the sake of simplicity and/or limited data availability, several externalities (e.g., taxes, track access charges, noise, and pollution) are not included in the model.

3.1 Utilization rates of MWs

As described in the literature, MWs are pre-allocated slots in the annual timetable that guarantee access to the tracks for entrepreneurs to perform various maintenance activities. The slots are generally reserved for a few hours (typically 2-6 hours) per day over several weeks.

Let $W = (n_{weeks}, n_{days}, n_{hours})$ denote the main characteristics of the MW that is performed on a section of the rail infrastructure, i.e., the number of weeks, days and hours. The total access time (in hours) is then $T(W) = n_{weeks} \times n_{days} \times n_{hours}$. The utilization rate of these MWs can be defined as $u = \frac{T_{eff}}{T(W)}$ where T_{eff} is the effective average time spent on track.

The previous definition of u corresponds to the share of utilized access time which can be useful to assess if MWs are too long. However, there are several alternative characterizations, Granberg and Rehn (2020) state that a useful definition to assess the costs in traffic production is to use u as the share of utilized slots. This definition is also tested in this study. Another definition, proposed by the same authors, is to use the share of cancelled or performed activities which can be useful to assess short-term planning. The same authors also conclude that such definitions are only useful to study and follow up on a few important parts of the infrastructure, referred to as "hot" MWs. Moreover, large complex parts of the infrastructure should use adapted characterization to study the utilization rates of MWs in these regions, referred to as "islands".

Given a particular definition of u, the total social costs TC can be formulated as the sum of the work cost CC and the loss in (current traffic) production LP minus the gain in future traffic production GP, i.e., $TC(u) = CC(u) + LP - GP(u)$. Since MWs are pre-allocated during capacity planning, the loss in production LP is independent of u whereas the work costs and future benefits are not. Note that, although omitted, all the terms of the total social costs are dependent on the design W of MWs.

The comparison alternative is the do-nothing scenario, i.e., no utilization of MWs ($u = 0\%$). In this case, the total net social value is negative and includes both the loss in production (costs of cancelled traffic) as well as the total corrective maintenance costs. The latter, as will be explained later, includes both the work/repair and delays costs.

As mentioned in the literature, the net present value ratio is often used to present the resulting profitability of the different utilization rates. However, we use the total net social value since MWs' profitability always increases with higher utilization rates, i.e., full utilization (or $u = 100\%$) is always the most profitable policy. We are therefore interested in finding the minimal utilization rate (MUR) after which the total net social value becomes positive.

3.2 Cost of maintenance work

The cost of construction work CC depends, among others, on the time spent on the track before finishing the maintenance activity. We consider the direct time needed for the steps to perform the different maintenance activities (Hedström, 2020). Although not included in this study, there are additional indirect costs for maintenance work such as license assessment and project management.

Given u, the cost of work $CC(u)$ can be formulated as in equation (1) where the additional overhead time includes the time for transport (noted $t_{transport}$). K_{fixed} is the average fixed cost of the material needed for work, k_{time} is the cost of work per time unit, and ρ is the compensation factor for night shifts. In general, activities may include additional delays and/or waiting times. However, we do not consider these additional overhead times in this study.

$$CC(u) = (1+\rho)\, k_{time}\left(t_{transport} + u\, T\right) + uK_{fixed} \tag{1}$$

Note that both cost data (K_{fixed} and k_{time}) and effective time on track ($u\,T$) may depend on other parameters such as weather, type and condition of the assets, and working time (night/day, weekdays/weekends). It is also important to distinguish between the primary effect of certain factors. For instance, weather and asset conditions affect the total access time (and hence the costs) whereas factors such as asset type and working time may directly affect the costs. Using available cost data, such general parameterizations are straightforward. See for example Table 4 for a distinction in the case study between cost parameters during the day/night shifts.

The transport time $t_{transport}$ depends on the number of shifts n_{shift} that are performed. If the share of utilized access time is used, such number is $n_{shift} = \left\lceil \frac{T_{eff}}{n_{hours}} \right\rceil = \left\lceil u\, n_{weeks}\, n_{days} \right\rceil$.

A unitary transport time can be used, i.e., for travelling between the site and depot. In the case study, we assume that the average transport or setup time is $t_{transport} = 1$ hour for day-time and 3 hours during night shifts. In reality, this average time depends on, e.g., contract (response time requirement for corrective maintenance), site (remote or dense areas) and labour law (work conditions).

Although the work cost for maintenance activities is relatively similar when performed on highly or rarely used infrastructure, both the frequency/need of maintenance activities and their corresponding loss in potential traffic are considerably higher on lines with higher traffic of passengers/goods.

3.3 Loss in traffic production due to maintenance work

Allocating capacity for MWs can lead to the reduction/removal of potential traffic, i.e., the loss in the potential current production which is also known as the cost of downtime or opportunity cost of train traffic (Kobbacy and Murthy, 2008). This loss $LP = LP(W)$ of traffic production depends only on the characteristics w of the MW, i.e., independent from the utilization rate u of the window.

Trafikverket (2020c) uses priority criteria to estimate the costs of train path cancellation. Given a type of traffic k (e.g., freight, commuter or highspeed), there are $N_k = N_k(W)$ trains paths which are cancelled to pre-allocate capacity for MWs W. Based on such criteria, the loss in traffic production, due to the slots for MWs W, is given in equation (2) where $\mathrm{B_k}$ and $\mathrm{C_k}$ are, respectively, time and distance cost parameters for excluding a path of train type k. The percentage parameters $\mathrm{K_k}$ and $\mathrm{J_k}$ are used to account for the exclusion of train paths of type k. They refer to the correction factor for the base time and the utility threshold of the train path, respectively. For more details on these cost parameters, see (Trafikverket, 2020c).

$$LP = \sum\nolimits_{\mathrm{k}} N_k (\mathrm{Time_k} \times (100\% + \mathrm{K_k}) \times (100\% + \mathrm{J_k}) \times \mathrm{B_k} + \mathrm{Distance_k} \times \mathrm{C_k}) \tag{2}$$

N_k can be assumed to be dependent on the frequency of the train services as well as W. Assuming a frequency F (in number of departures per hour) on a single-track/direction, we have $N(W) = F \times T(W)$ cancelled trains in that direction. The number N of cancelled train paths can also depend on the number of tracks that are closed/unavailable for maintenance. In case both directions/tracks are unavailable, the number of cancelled trains is doubled assuming similar traffic in both directions.

If trip distributions, e.g., origin-destination matrix often for commuter train services using smart cards, are known, there are alternative and more accurate methods to calculate the social costs of certain traffic services. For instance, Ait-Ali et al. (2020) developed a model to compute such loss in traffic production when cancelling/modifying commuter train services.

3.4 The gain in future production

The gain in future production includes both the improvements in service reliability for the customers (Ling, 2005), as well as the reduction in corrective maintenance and/or inspections (for the IM). We first assume that maintenance contractors have enough knowledge about the studied assets so that they can perfectly schedule these activities. This means that the gains in terms of reduced need for future maintenance/inspection activities are negligible.

The total gain in future traffic production $GP(u)$ can be captured by the benefits BR in terms of traffic reliability (thanks to performed activities with utilized windows) minus the costs CR from unreliability risks (due to unperformed activities in non-utilized windows). One possible formulation is $GP(u) = u\,BR - (1-u)\,p\,CR$, where parameter p is the likelihood of a failure that requires immediate corrective maintenance after inspection. This failure risk often depends on the type of assets and can be affected by other factors such as inspection duration/frequency, traffic volume and weather. Although not included here, failure risk costs can also include safety factors using, e.g., the value of a statistical life (VSL) to convert from fatality risk to monetary values.

Note that the benefits from increased reliability BR are projected in the future whereas the previously presented costs, i.e., loss in production and maintenance costs, are in present value. We will therefore use, in what follows, a discounting factor r when calculating the future gains for conversion into a present value.

Several maintenance activities are scheduled to take place periodically, e.g., as recommended by the manufacturer or based on knowledge of the assets, i.e., life-cycle analysis. We assume that maintenance contractors have enough knowledge of the asset to be able to efficiently schedule or select the right time and location for maintenance activities. For instance, maintenance activities are assumed to be carried out as soon as asset quality reaches a certain minimum, see Figure 5. In general, such activities are often not carried out at the ideal time for different reasons, e.g., lack of knowledge about asset quality. Thus, the losses which are due to early or late maintenance are neglected in this study.

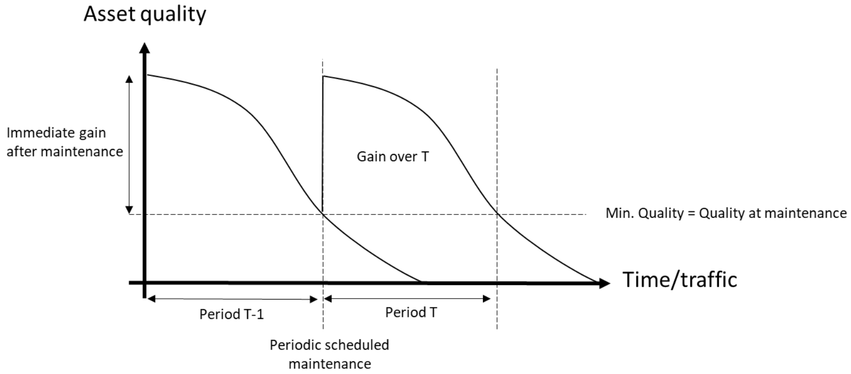

Figure 5. Gain in performance when maintenance is perfectly scheduled.

Let T_{asset} be the period in years between two consecutive scheduled maintenance activities of the asset, e.g., 1 year on average for switches and crossings. Let $Q(t)$ be the production quality function at time $t \in [0, T_{asset}]$, and $Q_{\min}$ be the minimal asset quality/reliability before performing maintenance. The gain in future production can be formulated as in equation (3).

$$BR = \int_0^{T_{asset}} \frac{Q(t) - Q_{\min}}{(1+r)^t} dt \tag{3}$$

In equation (3), we account for the discounted gains of maintenance over the period T_{asset}, we set the discount rate $r = 0.035$ (or 3.5%). A similar value is also adopted in national guidelines for CBA of infrastructure investments (Asplund, 2019).

Since it is difficult to estimate the monetary value of an asset given a certain level of production quality, we use the proxy benefits from avoiding disruption costs such as corrective maintenance costs, delays and/or discomfort. How the degradation function $Q(t)$ varies over time, from $t = 0^+$ (just after maintenance is performed) to $t = T_{asset}$, depends on many factors, e.g., weather conditions, type of asset, the volume of train traffic (Andersson et al., 2016) and axle load (Odolinski, 2019).

Let i be the curvature parameter, we formulate the quality function as $Q(t) = Q_0 \sqrt[i]{1 - \left(\frac{t}{T_{asset}}\right)^i}$. The quality value just after the maintenance is defined as $Q_0 = Q(t = 0^+) = C^{corr} + C^{del}$, where C^{corr} is the cost for repair work, and C^{del} is the cost of delays for passenger/freight services. Although omitted, the costs of fatality risks can also be included here using the national VSL values.

The costs C^{corr} for corrective/repair work is calculated in a similar way to that of maintenance work CC but with a higher overhead cost parameter $\rho^{corr} > \rho$. Moreover, the effective access time T_{eff} is assumed to be the average required time to repair the asset, e.g., the average total delay.

To calculate the delay costs C^{del}, we use existing statistics about delays due to asset failure, e.g., reported by Lidén (2019) for assets such as switches and crossings (SC), overhead or contact wires (CW) and track circuits (TC). For instance, SC is the cause of considerable delays which accounts for more than 13% of the maintenance costs in the Swedish railways (Ghodrati et al., 2017).

4. Case study

In this section, we present the data and test scenarios. Results are presented and discussed later in the section.

We focus in this case study on the line section between Mjölby and Malmö, see Figure 6. It is an important section of the Swedish southern main line since it also links two of Sweden's largest marshalling yards, i.e., Hallsberg and Malmö. Thus, the studied line section connects important centres for passenger and freight traffic in Sweden.

Figure 6. The southern main line, the case study focus is between Mjölby and Malmö (Kavelgrisen, 2017).

4.1 Input data

We first present the main characteristics of the studied service lines. For each line, Table 2 lists the distance, speed, and travel time.

Table 2. Characteristics of the main train services that are studied in the chosen line section.

Characteristic	Commuter	Highspeed	Freight	Unit
Line	Norrköping - Mjölby	Stockholm - Malmö	Hallsberg – Malmö (vial Mjölby)	-
Distance (speed)	79 (140)	614 (200)	450 (135)	km (km/h)
Travel time	0:49	4:25	3:20	h:min

Note that other train services (e.g., intercity, night trains, postal services) operate on the studied line but are omitted for the sake of simplicity.

Traffic and delays

In Table 3, we give an overview of the traffic data which is collected mainly from the statistics report by Nelldal et al. (2019) but other sources, e.g., IM and train operators' documents are also used.

The average traffic volumes differ between night and day times. We, therefore, assume that passenger traffic (around 80%, of which half is highspeed) is predominant during the day whereas freight is assumed to be dominant at night.

Based on traffic data (in train-km) from Table 3, we assume that delayed trains, due to failures in the infrastructure, are 80% passenger trains, of which half are regional/local commuting trips

(40%), and the remaining 20% are freight trains. Moreover, statistics from the Ofelia database[4] indicate that failures in S&Cs lead to an average delay of 20 minutes (Ghodrati et al., 2017).

Table 3. Traffic overview of the studied train services nationally and on the studied service lines in 2018.

	Commuter	Highspeed	Freight
Traffic in million person/ton-km	6 521	3 900	21 842
Average train load (pax or ton)	66	138	800
Average traffic share in train-km	48%	30%	22%
Line	Norrköping - Mjölby	Stockholm - Malmö	Hallsberg – Malmö
Departures/frequency	4 trains/h (peak)	15 dep/day & direction	30 dep/24h & direction

Costs

The average cost K_{fixed} for material is estimated based on statistics about the total yearly infrastructure spending, e.g., 1 200 MSEK/year for switches and crossings in Sweden. Additional cost values are based on other sources, e.g., (Lidén and Joborn, 2016) and (Lidén et al., 2020). Table 4 summarizes the different cost parameters that are adopted.

Table 4. Adopted values for maintenance costs, also used by Lidén and Joborn (2016) and Lidén et al. (2020).

Parameter (notation)	Value		Unit
	Day	Night	
$t_{transport}$	1	3	Hour
k_{time}	1 250	10 000	SEK per hour
ρ	0	60	%

Together with the previously presented traffic and delay data, the valuation of delays in Table 5 is used to calculate the total costs of delays. Trafikverket (2020a) provides different values for the passenger (commuter and highspeed) and freight services.

Table 5. Valuation of delays (e.g., after disturbances) in SEK per hour and person or ton, data by Trafikverket (2020a).

Type of traffic	Valuation of delays	Unit
Highspeed	298	SEK/hour
Commuter	282	SEK/hour
Freight	3.85	SEK/ton

The cost parameters for the loss in traffic production depend on the type of traffic that corresponds to the excluded train path. Based on recommended values from Trafikverket (2020c), we adopt the parameters that are provided in Table 6 for the studied train path categories, namely commuter (SP) and intercity passenger trains (FX) and freight services (GS).

Table 6. Parameter values for train path exclusion, also used by Trafikverket (2020c).

Type of train traffic	Category	Cost parameters			
	A	B (SEK/min)	C (SEK/km)	J (%)	K (%)
Commuters in large cities	SP	1238	104	15	20
Intercity (higher speed)	FX	816	71	20	6

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[4] A database used by Trafikverket for infrastructure failures and repairs which are reported on the Swedish railways. It is used by both contractors (to report) and analyst (to study statistics).

Freight (higher speed)	GS	269	61	15	2

4.2 Test scenarios

In this case study, we look at different test scenarios. To study the effect of MWs on the corresponding MUR, we consider various designs for these windows.

On the Swedish southern main line, Trafikverket (2019) in its annual network statement has for instance reserved 6 hours in six days over several weeks as capacity windows for performing maintenance activities. We, therefore, consider a period of $n_{weeks} = 4$ or a month, at two different cases, namely weekdays with $n_{days} = 5, n_{hours} = 2$ and work performed during night-time (in total $2 \times 5 = 10$ h/week), and weekends with $n_{days} = 2, n_{hours} = 5$ during day-time (in total $5 \times 2 = 10$ h/week).

Certain windows allow for single-track traffic often in day-times whereas others correspond to total traffic shut-down typically during night-times. Therefore, we distinguish between two variants for MWs during the day, i.e., day-all and day-single, as in Table 7 which presents all three MWs variants with some main characteristics.

Table 7. Overview of the studied designs of MWs and their main characteristics.

Notation	Design of MWs	Potential traffic	Production loss	Work cost
day-all	MW-day & all track closure	Mostly passenger	High	Low
night-all	MW-night & all track closure	Freight	Low	Medium
day-single	MW-day & single-track (speed reduction)	Mostly passenger	Medium	High

We have previously mentioned that the asset degradation function is a characteristic of the model. Such functions are generally complex and can be obtained based on more knowledge about the assets. However, to study the effect of some simple variants, we consider two types that are illustrated in Figure 7. Type 1 corresponds to the exponential variant ($i = 3$) whereas type 2 is the linear degradation ($i = 1$).

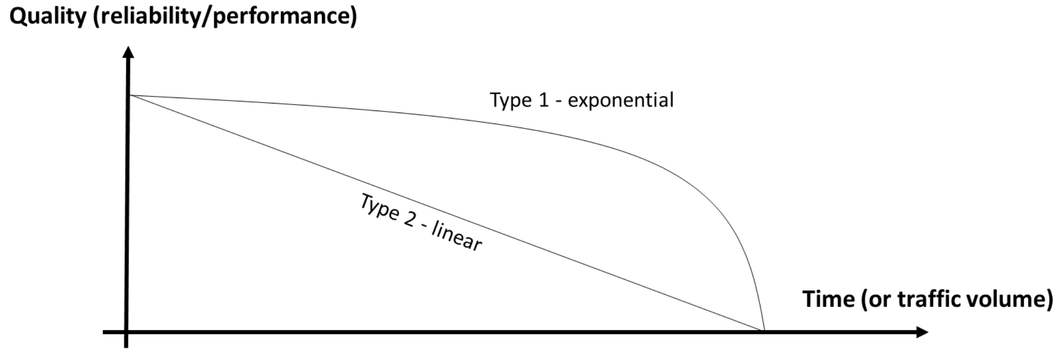

Figure 7. Examples of studied degradation functions.

Another important characteristic is the definition of the utilization rate. In this case study, we focus on two variants, namely utilization rate as the ratio of access time and as the ratio of the number of utilized slots. It is possible to include the utilization rate as the ratio of the number of performed activities. This is however difficult due to unavailable data about the detailed maintenance schedules. All the different test scenarios are presented in Table 8.

Several other possible characteristics could be studied using additional test scenarios. For instance, a different design of MW schedules (e.g., not periodic, over longer periods of time). This is possible by adopting a more flexible modelling of the MW schedule. Although useful for future applications of the model, this study focuses on estimating the social costs given fixed MW schedules. Other interesting characteristics include minimal quality and degradation functions. Most of these other variants are studied in the sensitivity analyses that are performed later in the case study and/or included in the Appendix.

Table 8. Overview of the scenarios that are tested and discussed in the result section, see Figure 7 for the corresponding degradation functions.

MW design	Degradation function	Utilization rate u as a share of utilized	Test scenario (notation)
day-all	Exponential ($i = 3$)	access time	day-all-exp-time
		slots	day-all-exp-slot
	Linear ($i = 1$)	access time	day-all-lin-time
		slots	day-all-lin-slot
night-all	Exponential ($i = 3$)	access time	night-all-exp-time
		slots	night-all-exp- slot
	Linear ($i = 1$)	access time	night-all-lin-time
		slots	nigh-all-lin- slot
day-single	Exponential ($i = 3$)	access time	day-single-exp-time
		slots	day-single-exp-slot
	Linear ($i = 1$)	access time	day-single-lin-time
		slots	day-single-lin-slot

4.3 Results and discussions

First, we look at the variation of the total gross social costs, i.e., without considering the benefits or gains in future production thanks to the increased reliability of the infrastructure assets.

Social costs

Figure 8 presents three subplots where each is showing the variation of total gross social costs as a function of the utilization rate of either the access time (X=time) or slots in the MWs. Each subplot corresponds to a particular design of the studied MW. Note that all the results in the figure are based on an exponential degradation function, the linear variant will be studied later in this section.

With no consideration of the benefits/gains, the total gross social costs increase with higher utilization rates of MWs, mainly due to increased work costs. The difference between the two definitions (time or slot) is lower, especially for higher utilization rates which are due to lower differences in terms of setup expenses, e.g., transport costs.

Note that the total costs when no slots are used (i.e., $u = 0$) correspond to the cost for train path cancellation which is pre-allocated for MWs instead of train traffic.

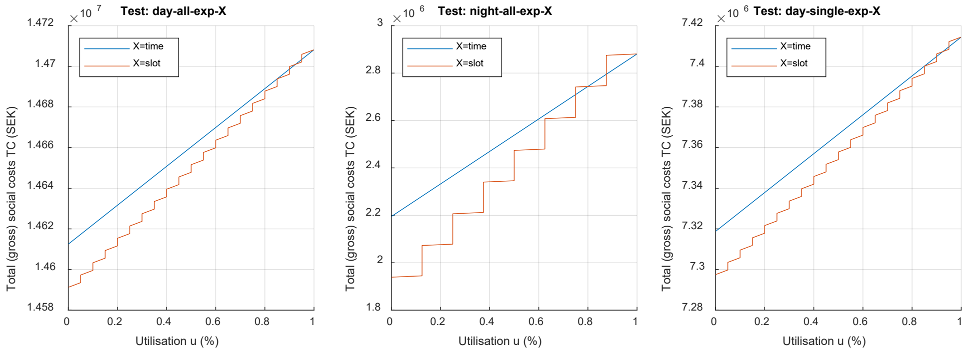

Figure 8. Total (gross) social costs as a function of the utilization rate for different test scenarios.

Second, we study the variation of the total net social costs including benefits and the corresponding minimal utilization rate of MWs. Figure 9 shows such variation for both definitions of utilization rates. For each definition, the figure compares the variations for different test scenarios, i.e., designs for MWs.

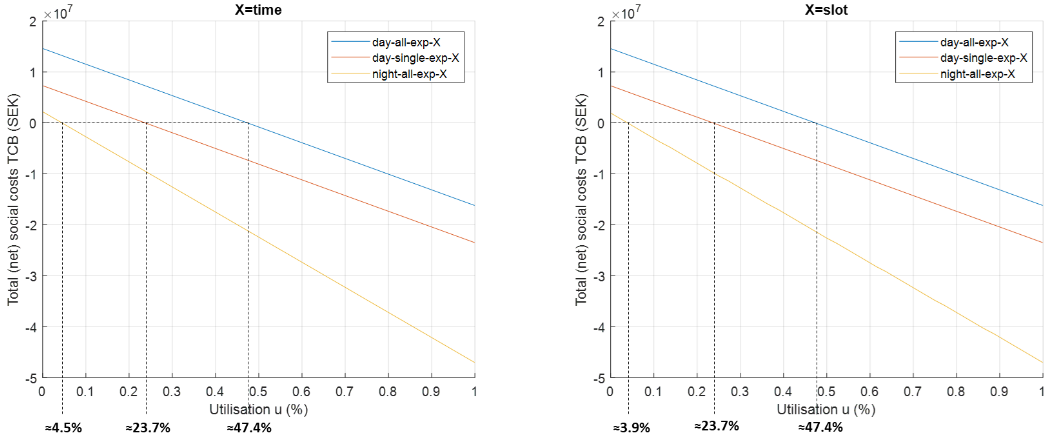

Figure 9. Variation of the total net social cost for different utilization rates.

Figure 9 also shows that there are only slight differences between the resulting social cost variation when using the two definitions. The MURs are around 4%, 23% and 47% depending on the test scenarios. As expected, night-time windows require lower minimal utilization whereas day-time windows have higher minimal utilization requirements, especially in case of full closure of the tracks. These are mainly driven by the higher loss in traffic production during peak times.

Note that in case of low utilization rates, many pre-allocated slots within MWs, although not utilized for maintenance, can potentially be beneficial for traffic production and increase its robustness in case of disruptions. These benefits, which could reduce the total net social cost, are however not included in the model. Moreover, the model does not account for several costs/benefits and externalities which could affect the resulting total net social cost. For instance, track access charges (revenues for the IM) including congestion charges, environmental effects (emissions and noise), and the costs of associations or missing connections are not considered.

Minimal utilization rate (MUR)

The calculated MURs of MWs may also depend on the variant of the model that we use. For instance, we have so far used an exponential type 1 degradation function. In Table 9, we present the resulting MURs using different variants of the model, i.e., shifts, track closure, definition of the utilization rate and degradation functions.

Table 9. Minimal utilization rates for other variants or test scenarios of the model.

Shifts	**Track closure**	**Test scenario**	**Minimal utilization rate (in %)**	
			X=exp ($i = 3$)	**X=lin** ($i = 1$)
Night	Full	night-all-X-time	4.5	8.0
		night-all-X- slot	3.9	6.9
Day	Partial (single-track)	day-single-X-time	23.7	41.9
		day-single-X-slot	23.7	41.8
	Full	day-all-X-time	47.4	83.5
		day-all-X-slot	47.4	83.5

Numerical results in Table 9 show that different minimal utilization rates are required in the various studied situations. Low rates (4-8%) are obtained during night shifts where train traffic volumes are lower. During day shifts with a high volume of traffic, the obtained rates are higher (23-42%) in case of partial closure of the tracks (single-track) whereas the utilization rates are the highest (47-83%) when all tracks are closed. Thus, having higher MURs is more appropriate for highly intrusive MWs while lower MURs could be used during low-volume traffic or when the windows are less intrusive. To use one goal for all MWs is therefore not justifiable from a social cost-benefit viewpoint.

Moreover, the results in the table indicate that there are no significant differences between slot and time-based definitions of the utilization rates. However, MURs are shown to depend on the degradation function of the assets (exp or lin), the time (day or night) and the space (single track or full closure). The MUR of MWs is the highest (up to 83%) when the asset quality degrades the quickest (lin) and when slots are scheduled during high-volume traffic (day).

However, such results assume, among others, that the maintenance contractors have perfect knowledge of the assets and can therefore perfectly plan the time and place to perform the maintenance activities. This is however not the case in reality as there is often a lack of reliable relevant information about the assets. Andersson and Hultén (2016) state that this uncertainty is further increased by the recent reforms in railways, e.g., deregulation (Ait-Ali and Eliasson, 2021). This means that maintenance activities may be performed earlier or later which leads to additional costs due to excessive maintenance (if earlier) or increased failure risks (if later). In what follows, we study the effect of such assumptions using sensitivity analysis on the asset degradation function, minimum functional quality as well as asset failure likelihood.

4.4 Sensitivity analysis

In the previous results, we assumed perfect knowledge of the asset and thus reliable estimates of parameters such as the shape of the degradation function (parametrized with the exponent i) and the minimum required asset quality (noted $Q_{\min}$). Uncertainty about these parameters can lead to more/less uncertainty in the resulting total social costs and hence the resulting MURs.

Therefore, we perform, in this section, different sensitivity analyses to study the effect of varying the values of these parameters ($i, Q_{\min}$) on the MURs. Since the model can run fast, a one at a time technique finds, in a few seconds, the MURs that are associated with a set of different values of the studied parameters. In the Appendix, we present additional analyses on other parameters, i.e., failure likelihood, traffic demand, and discounting rate.

Minimum asset quality

We assumed that the minimum asset quality is set to zero, i.e., $Q_{\min} = 0$. To study the effect of such assumption on the resulting MURs, we perform a sensitivity analysis on the value of $Q_{\min}$. The results of the analysis are presented in Figure 10 which shows the variation of the MUR for different values of the required minimum asset quality. The latter is presented in per cent compared to the quality value of a newly maintained asset, e.g., 15% corresponds to performing maintenance activities when the asset quality is lower than 15% of a newly maintained asset. The analysis is performed on the three studied scenarios with an exponential degradation function and a time-based definition of the utilization rates.

The analysis, as shown in the figure, indicates that the minimal asset quality has more effect when MURs are higher, and its effect is negligible in the case of lower MURs. Thus, more safety margin amplifies the required MUR especially for MWs during high-volume traffic.

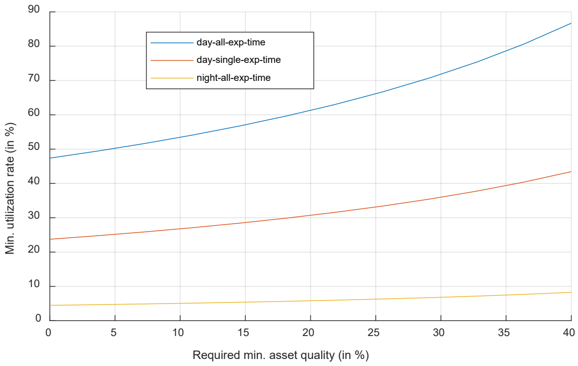

Figure 10. Variation of the MUR for different required minimum asset quality.

Degradation function

In the previous test scenarios, we have distinguished between two shapes for the degradation function, i.e., linear ($i = 1$) and exponential ($i = 3$). In this sensitivity analysis, we will study the variation of the MURs for more variants of the degradation function, i.e., different values of i. The results of the analysis are shown in Figure 11 for values of i between 1 and 5.

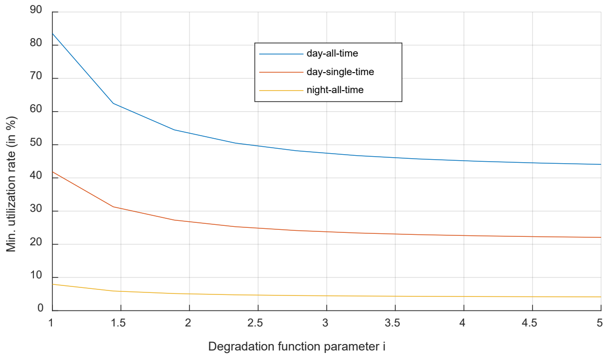

Figure 11. Variation of the MUR for different shapes of the degradation function.

A higher value of i means that the asset is degrading slower. The results indicate that MURs decrease when increasing the value of i, especially when slightly higher than 1. Thus, more resilient assets can considerably reduce the MURs, especially in the case of MWs during high-traffic volumes.

5. Concluding remarks

In this section, we discuss some conclusions and provide ideas for possible future works.

5.1 Conclusions

Based on a case study from the Swedish Southern main line, we estimated the MURs for justifying the capacity allocation of the MWs. Our results indicate that Trafikverket can improve MWs-related policies by specifying segment-based minimal utilization rates. The case study provides some numerical examples regarding which MURs should be required for different segments, e.g., designs of MWs and traffic situations. These results indicate that MWs during low-volume traffic may only require a 4-8% utilization rate, while partial closures and full closures during high-volume traffic increase the minimal utilization rates to 23-42% and 47-83%, respectively. Moreover, we show that the adopted definition of the utilization rate does not play an important role, especially in the case of MWs requiring higher utilization rates, e.g., "hot" MWs and important "islands" as mentioned before.

Sensitivity analyses of values relating to the asset knowledge highlight the importance of the degradation function and the adopted minimal asset quality, and to a lesser extent the failure likelihood and traffic volume. These can substantially affect the required MUR in different scenarios, especially in the case of MWs during high-volume traffic. It is therefore important to collect data about the infrastructure assets to gain more knowledge about, e.g., how the asset quality degrades over time/traffic, and minimal quality/safety standards. In this context, further analysis can be performed to study how the risk of late maintenance affects MURs.

In addition to the previously described improvement actions, a minimal rate of utilization could be used in setting incentive levels for performance-based maintenance contracts. Clearer agreements between the stakeholders, e.g., maintenance contractors and IM, including the required minimal utilization rates could give incentives to increase the capacity utilization and therefore reduce the overall maintenance and traffic costs. Moreover, IMs can use the method to compare

MWs and their MURs in sections with different characteristics, e.g., traffic type, service frequency, and failure risks.

The approach that we present in this study can also be applied to solve other planning problems within and outside the railway sector. For instance, major road/railway maintenance or renewal projects with flexible pre-planned slots can be more efficiently scheduled by knowing the total social costs/benefits that are associated with a given utilization of the slots compared to an alternative one. Moreover, such projects can be further assessed ex-post and thus allow for feedback to the contractors for improvements in their future operations.

5.2 Future works

Several improvements and applications of the model can be suggested for future studies. For instance, the model can be extended to consider more flexible designs of MW schedules and allow for differentiation of the costs and benefits between different weekends/weekdays. In this way, the model can be further used to find more efficient schedules for MWs.

Moreover, the social cost function can be extended to include several external costs that are omitted in this study, e.g., track access charges and environmental effects. Thus, the optimization model of the maintenance schedules can be steered by a more realistic social cost function. This is, however, only useful when the required data is available to quantify these externalities in the studied application or the case study.

The model can also be extended by considering additional assets and can be used for economically smarter planning of maintenance activities. For instance, AI methods guided by the CBA model can be trained using relevant data to learn economically efficient maintenance plans, e.g., when and where it would be optimal to schedule (preventive) maintenance activities.

Acknowledgements

This project has received funding from the Shift2Rail Joint Undertaking (JU) under grant agreement No 881778. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Shift2Rail JU members other than the Union. Note that this paper reflects only the view of the authors, and that the JU is not responsible for any use that may be made of the information it contains. The authors are grateful to Matts Andersson for reviewing the paper and for improvement recommendations. We are also grateful to Kristofer Odolinski for earlier references and to Jan-Eric Nilsson for earlier comments and suggestions, and Magnus Wahlborg for project administration.

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Appendix

In addition to the previously presented sensitivity analyses, similar analyses have been performed on other parameters. Although these analyses show that the results are insensitive to these parameters, we present some of them in this appendix.

In the gain in future production, we have assumed a fixed failure likelihood, i.e., $p = 0.1$ in the baseline case. In this analysis, we study the effect of varying such likelihood on the resulting MURs. Figure 12 shows the variation of the MURs (compared to the baseline case) when failure likelihood is increased from 10% up to 30%.

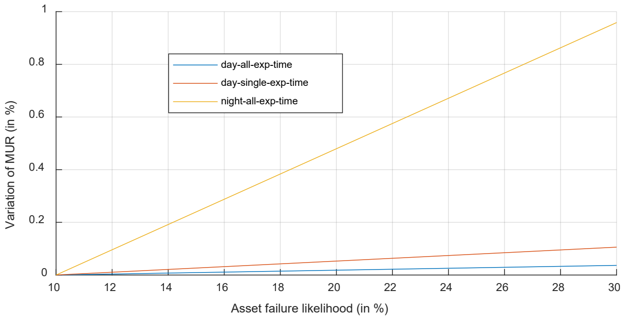

Figure 12. Effect of varying asset failure likelihood on the MUR.

The results indicate that the increase in MUR is the highest for MWs that are planned during low traffic such as night shifts. This increase is however still marginal, for instance, a 30% increase in failure likelihood increases MUR by less than 1%. The increase in other MWs is even more marginal.

Furthermore, we look at the effect of varying traffic volumes on MURs for three different scenarios. Figure 13 shows how the MURs are affected by increasing/decreasing traffic volumes up to 200%.

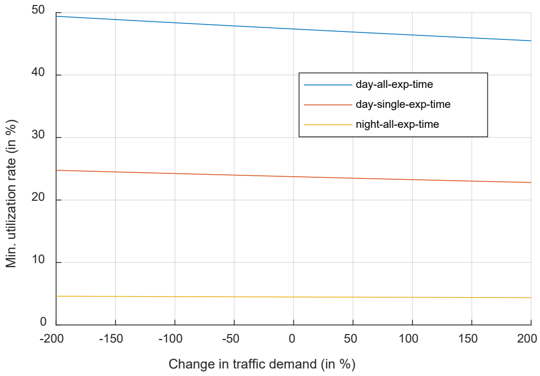

Figure 13. Variation of MUR for different changes in traffic volumes.

Traffic volumes seem to have minor effects on MUR, especially during MWs which are scheduled in low-traffic scenarios. The highest variation (+/-5%) is obtained for MWs scheduled during day-time with full closure of the track. MURs are unexpectedly decreasing when traffic demand increases. This means that, with increasing traffic demand, future gains in reliability increase faster than losses in traffic production. This is mainly due to using the same degradation function for different traffic demands. The shape of the adopted degradation function should depend on the traffic volume (and train weights), i.e., higher traffic demand and heavier trains should lead to faster asset degradation.

Finally, we investigate the effect of the discount rate on the MUR for different MWs. For this, we vary the rates of discounting between 2% (low) and 7% (high). Figure 14 shows how MURs vary when the discount rate changes.

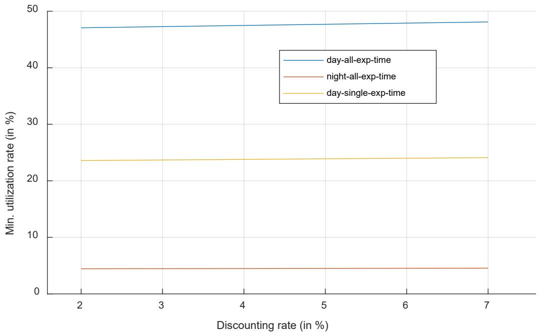

Figure 14. Variation of the MUR for different discounting rates.

The effect of discount rates on MURs seems to be marginal. This can be because we are studying shorter time periods (compared to larger investments), e.g., the studied frequent maintenance activities often take place on average once per year.