Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 6.12
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.6.12

A Digital Twin Framework and Requirements for Lifecycle-Optimized Turnout Maintenance: A Crossing Case Study

K. Norberg[1], B. A. Pålsson[1], P. Torstensson[2], K. Odolinski[2] and A. Nissen[3]

[1] Department of Mechanical Engineering/CHARMEC, Chalmers University of Technology, Gothenburg, Sweden
[2] Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden
[3] The Swedish Transport Administration (Trafikverket), Borlänge, Sweden

Abstract

Turnouts are crucial assets within the railway system. However, their design makes them prone to deterioration and requires continuous inspection and maintenance. Failures typically result in train delays and associated socio-economic costs. Current maintenance practices remain largely reliant on manual, in-track inspections and follow a combined corrective/preventive strategy. This paper presents a digital twin framework for turnout maintenance, supporting a transition towards condition-based, predictive, and prescriptive strategies. The framework integrates inspection data to assess the current condition, deterioration models to forecast future condition, and a life-cycle cost model to evaluate maintenance scenarios. The crossing rail is used as a case study with inspection remarks and maintenance statistics from the Swedish railway network to identify the requirements of the digital twin. For example, rolling contact fatigue is a key damage mode to monitor and predict, as it drives most crossing rail replacements and urgent maintenance actions. The study highlights the potential benefits of adopting a digital twin for turnout maintenance while also identifying the critical research needs and development steps required for successful implementation.

Keywords: turnouts, switches & crossings, crossing, frog, maintenance, digital twin, condition monitoring, forecasting, deterioration, life-cycle costs

1 Introduction

Turnouts (switches and crossings, S&Cs) are necessary assets in the railway system. They enable trains to change track, which adds traffic capacity and resilience for the system. However, the inherent characteristics of S&Cs give rise to high maintenance needs and susceptibility to failures, resulting in delayed trains and socio-economic costs. Improving the maintenance and inspection regimes is essential to reduce costs and minimise traffic disruptions.

This paper presents a framework for a digital twin (DT, "*a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems*" [1]) to be used in connection to maintenance of S&Cs. The concept involves condition monitoring, condition prediction, and evaluation of maintenance action scenarios through life-cycle cost (LCC) analysis. The crossing rail (frog) is used as a case study to exemplify needs in connection with the framework. For this, statistics of inspection remarks and maintenance actions are used. In the end, the paper discusses and proposes requirements of the DT in the context of the crossing rail.

2 Turnouts, crossing rails and their maintenance

The Swedish railway system, managed by the infrastructure manager (IM) Trafikverket, consists of 14,400 km of track. In this, 10,400 S&Cs are installed, of which 6,200 are simple S&Cs (from one to two tracks, with one straight through route and one diverging route) installed on main tracks (excluding e.g. branch lines and rail yards). The simple S&C and its components are presented in Figure 1 and is henceforth the only S&C type considered. While varying significantly between individual assets due to factors such as traffic load, the average maintenance cost of an S&C has been estimated at 90 kSEK/yr (≈9 k€/yr), and the cost of renewal is 4.5 MSEK/S&C (≈0.45 M€/S&C) [2].

The most critical areas in terms of maintenance needs and traffic-disrupting failures are the switch system and the switch and crossing rails. As the switch system contains moving parts that are sensitive to environmental factors, and given the large number of failures associated with both the switch and its control system, it is the subsystem of the S&C that contributes most to train delays [3]. Predominantly, this is due to that the

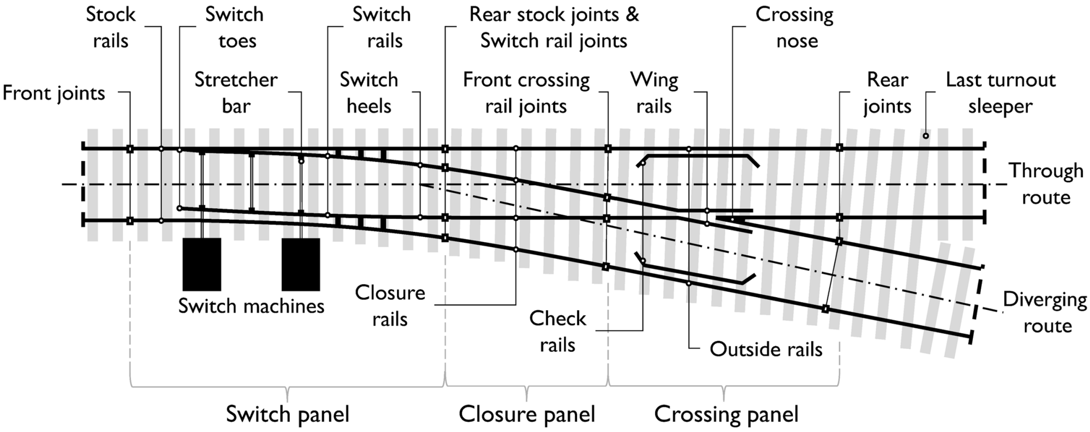


Figure 1: Illustration of a simple turnout and its components.

switch position not being under control, caused by, in descending order of occurrence, component failures, malfunction or wrong adjustment (35%) and presence of snow and ice (20%) [4].

The rail discontinuities in the switch and crossing panels introduce complex wheel–rail interactions, further described and discussed in e.g. [5], resulting in increased dynamic wheel–rail contact forces and higher deterioration rates than for rail in plain track. The forces are also distributed further down, affecting the deterioration of fastening, sleepers and ballast. From [3], it is found that failures in rail components and the crossing in particular are associated with long intervention times leading to delays of many trains. Despite the few failures, the total delay time for crossing failures is close to that of the control system of the switch. This makes the crossing rail a good candidate for a further case study to exemplify the needs and possibilities of the DT framework.

2.1 The crossing rail

The crossing rail is the central rail component within the crossing panel, and its function is to enable the train wheels to cross the rail paths of straight and diverging routes through the transition between the wing rails and the crossing nose. This study only considers fixed monoblock crossing rails cast in austenitic manganese steel (AMS), as these are the most common crossing rails on Swedish main lines, as well as common worldwide. AMS is a ductile material with substantial work hardening capability under load, with high toughness and wear resistance. However, when cast, the microstructure becomes heterogeneous and material defects like pores are common [6].

The transition between the wing rail and crossing nose introduces complex contact conditions, with typically a short instance of two point contact and, due to the conical wheel shape, relative sliding motion of the two contacts. Also, an impact is created by the change in vertical velocity. The deterioration modes affecting the crossing rail is essentially the same as for standard rail: wear, plastic deformation, rolling contact fatigue (RCF), and fatigue initiated outside of the running surface. However, the unique loading condition, combined with the material properties, gives rise to fault types that sometimes differ from standard rail. At the time of writing, the only official classification catalogue of rail defects associated with cast AMS crossing rails found by the authors has been established by Bane NOR, the Norwegian IM [7]. It makes distinctions between faults within the full cross-section (transverse crack), fault in the rail head (transverse, longitudinal, vertical and diagonal cracks and bent nose), fault in the running surface (micro-cracks, shelling, spalling, surface indents, squats), fault in welds and fault in the flange channel.

2.2 Today's maintenance regime

For S&Cs on Sweden's mainline railways, crossing rails are monitored almost exclusively through the manual on-site safety, maintenance and non-destructive testing (NDT) inspections. Visual inspection of faults is the main inspection point for all three inspection types as other NDT techniques are challenging due to the material composition for AMS. During maintenance inspections, wear measurements are also conducted. The periodicity of inspections varies depending on the traffic load per year and the speed limit, giving different inspection classes. The class with the highest periodicity should have six safety inspections, one maintenance inspection and one NDT inspection per year [8, 9].

Grinding, welding, and replacement are the maintenance actions available for the crossing rail. Preventive grinding is often performed to prevent accelerated geometrical deterioration of the contact geometry during the first cycles of the crossing rail life. Welding can be repair welding, where cracks are removed through local grinding and welding, and overlay welding, where the geometry is restored by adding material. Repair welding is the most common welding operation. Welding in AMS is a sensitive procedure that must be performed within a narrow band of parameters and relies on the expertise of the welder. Especially heating and cooling, increase risks of brittle carbide formation and internal cracking caused by residual stresses in the heat-affected zone [6]. This, together with the difficulty of establishing crack depths with only visual control, makes it hard to estimate the time needed for field repairs involving welding. Estimates of cost and periodisation of the different maintenance actions applicable to the crossing rail are seen in Table 1 [10].

Maintenance action	Threshold [MGT]	Cost [SEK/action]
Grinding	8	4,000
Welding	40	12,000
Replacement	100	300,000

Table 1: Estimated cost and threshold values for maintenance actions. 10 SEK $\approx$ 1 €.

3 The digital twin framework

The high maintenance costs of S&Cs, together with frequent failures that disrupt train traffic, indicate significant potential for improvement in the current maintenance regime. Manual on-site inspections with periodicity up to eight times per year enable faults to be initiated and to propagate before detection and potential action. If the faults were discovered earlier, actions could be taken to minimise the risks of failures. Also, being able to quantify the likelihood of fault initiation based on the current asset condition would enable early planning of actions. Further, given the complex interactions between the subsystems and components within an S&C, the ability to compare different scenarios would also be desirable to optimise the maintenance. This calls for a changed maintenance regime where a DT can play a leading role.

Maintenance strategies are commonly divided into five categories: Reactive (unplanned actions performed after failure), Preventive (scheduled interventions to reduce failure risk), Condition-based (actions triggered by the observed condition), Predictive (actions guided by forecast of future condition), and Prescriptive (actions optimised by comparing future scenarios) [11]. Today's regime is mainly a combination of the first two. A DT can play an important role in making the transition to the latter three strategies. To explicitly link the proposed DT framework to different maintenance strategies, the following levels of DT implementation are defined:

- Level 1: Diagnostic digital twin
- Level 2: Predictive digital twin
- Level 3: Prescriptive digital twin

Figure 2 presents the overall general framework, including its connection to the physical asset, the monitoring and inspection techniques applied, and the resulting decision-making processes connected to the DT levels. The following sections describe each part of the DT in more detail, with the S&C as the guiding example.

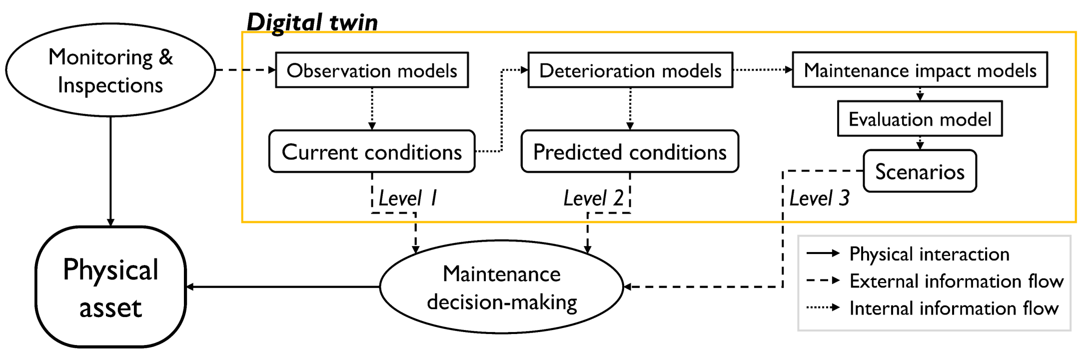


Figure 2: Overview of the digital twin framework.

3.1 Current and predicted conditions

The system can be viewed as a hierarchical structure consisting of multiple subsystems and components. Within an S&C, a subsystem may be represented by the crossing panel, while the crossing rail is an example of a component. Damage modes d represent how underlying deterioration mechanisms manifest as functional changes in a component or subsystem and are described by corresponding condition variables γ^d. Such variables may be directly measured (e.g. wear depth) or derived as condition indicators or indices (e.g. track geometry index). The condition of a component or a subsystem may be influenced by multiple damage modes simultaneously, and the collection of all damage-mode conditions describes the overall condition. The current condition of a damage mode is determined through observations (data from inspections or monitoring techniques). The condition is then determined through the associated observation model. One observation can be used for several damage modes using different observation models, and one damage mode can be monitored through several observations. The damage modes may have several condition thresholds which, when exceeded, trigger maintenance actions (Level 1).

From the current condition, the future condition can be predicted using deterioration models, generally defined as

$$\dot{\gamma}^d(\tau) = f(\gamma^d(\tau), \boldsymbol{\theta}^d) \tag{1}$$

where the deterioration rate $\dot{\gamma}^d$ at relative time τ (in traffic load, MGT) depends on the current condition and a set of parameters $\boldsymbol{\theta}^d$, for example, dependent on S&C design, loading conditions and the condition of other damage modes. Deterioration rate functions can essentially be derived in three ways: Mechanistic models (models derived from physics, material science, or mechanics), Semi-empirical (mechanistic structure with parameters calibrated using field data) and Fully empirical (data-driven, statistical regression of field outcomes). With known predicted conditions, maintenance can be planned based on when the condition thresholds are exceeded (Level 2).

3.2 Scenarios

With known current conditions and models for predicting future behaviour, it becomes possible to evaluate different maintenance strategies. To enable this, the effects of maintenance activities must be accounted for in the deterioration models. Different maintenance actions influence both the condition and the subsequent rate of deterioration in different ways. Component replacement restores the condition to an as-new state, whereas repairs or adjustments may only partially restore the condition and can alter the post-maintenance deterioration rate. This is the case, for example, for welding and grinding of crossing rails, as shown in [12]. Moreover, maintenance activities may affect multiple damage modes simultaneously and can be applied at different system levels, such as the component level (e.g. welding) or the subsystem level (e.g. tamping). These effects can be represented through maintenance impact models.

Furthermore, to compare different maintenance scenarios, an appropriate evaluation model is required. This study proposes an LCC assessment to minimise the cost of selecting maintenance actions.

3.2.1 Life-cycle cost assessment

LCC assessments consider all costs incurred over a system's lifetime in an equivalent currency, and aim to support decisions that minimise total cost. Given the strong physical and social interdependencies within an S&C and its maintenance and inspection regime, the economic model proposed continuously considers the full asset. First, costs are divided into investment and operating costs, namely the renewal cost C_r, which includes all costs associated with the design, procurement, and installation of a new asset, and the operating cost C_o, which covers all costs incurred during the operational phase. The total present value (TPV) for a full life-cycle scenario s, which spans from the installation ($\tau = 0$) to the time of the next full renewal ($\tau = T_{\text{r},s}$), can, based on e.g. [13], be computed as

$$\text{TPV}_s = C_\text{r} + C_\text{o}, \quad C_\text{o} = \sum_{\tau=0}^{T_{\text{r},s}} \frac{C_\text{o}(\tau)}{(1+r)^{\tau/\tau_\text{yr}}} \tag{2}$$

where τ_yr is the yearly traffic load (τ/τ_yr is thereby the number of equivalent years), and r is the discount rate per year. Since the timing for renewal might differ in the different scenarios, TPV cannot be used for a valid comparison, as it favours short life. Instead, the annuity (ANN) is used, which spreads the TPV evenly over the equivalent number of years. The annuity is computed by multiplying the TPV by the capital recovery factor (CRF) [13] as

$$\text{ANN}_s(\tau) = \text{CRF}(\tau) \cdot \text{TPV}_s, \quad \text{CRF}(\tau) = \frac{(1+r)^{\tau/\tau_\text{yr}} \cdot r}{(1+r)^{\tau/\tau_\text{yr}} - 1}. \tag{3}$$

As the purpose is to minimise the overall costs, the optimal renewal timing for the scenario $T_{\text{r},s}$ emerges as the point at which the annuity reaches its minimum.

The costs during operation can for an S&C be further detailed into maintenance costs $C_\text{o,m}$, inspection costs $C_\text{o,i}$, traffic capacity costs $C_\text{o,c}$ and traffic disruption costs $C_\text{o,d}$ (as in [3, 10] but separating maintenance and inspection costs), as

$$C_\text{o}(\tau) = C_\text{o,m}(\tau) + C_\text{o,i}(\tau) + C_\text{o,c}(\tau) + C_\text{o,d}(\tau). \tag{4}$$

Maintenance and inspection costs include all costs directly associated with the activity, like materials and labour. Traffic capacity costs are the cost of lost potential train operation due to the allocated time for these activities. Traffic disruption costs are the costs associated with delayed traffic due to failure and/or corrective maintenance.

The proposed DT framework integrates inspection data, deterioration modelling, and economic evaluation to support lifecycle-oriented maintenance decision-making for assets like S&Cs. While it can initially be applied using existing inspection data within today's maintenance regime as a basic Diagnostic DT, it offers clear potential for progressive development through enhanced monitoring, implemented and improved deterioration models, and refined cost assessments, enabling a transition towards a Prescriptive DT. A case study of the crossing rail is used to illustrate this potential and identify directions for future work.

4 Case study of the crossing rail

As one of the critical components, the crossing rail is selected as a case study to understand the needs and possibilities in the context of condition monitoring of mechanical deterioration and associated maintenance actions to inform the design of the DT. This is done through a statistical study stemming from [14].

4.1 Descriptive statistics from inspection remarks

In [14], all inspection reports for S&Cs in Sweden during the years 2015-2024 (548 732 remarks) were analysed. First, an overall fault categorisation resulting in 12 categories by related area (e.g. rail, switch machine, track gauge/fastening) was established. All remarks classified within the rail category were analysed to identify the fault type, the action taken, and the general location within the S&C (e.g. component or subsystem). For the fault type classification, a free-text analysis using a pre-trained BERT model [15] was complementing the pre-defined classes in the inspection reports. Fault categories based on the major damage mechanisms were defined: Geometry (wear, plastic deformation), RCF (e.g. shelling, cracks at running surface, squats), Other Surface Faults (OSF; more vague faults on the surface, however, found as being mostly RCF-related) and Other Rail Faults (ORF; other fatigue cracks, faults in welds). Including these classifications, the inspection reports were then combined with the asset database (BIS) and the traffic database (Lupp). Unless otherwise stated, the presented descriptive statistics consider inspection remarks for simple turnouts, with fixed crossing rails and nominal rail of 60 kg/m (1st generation: UIC60 from year $\sim$1990. 2nd generation: 60E from year $\sim$2015), that are situated at track sections allowing for speeds over 80 km/h, and where the remarks have resulted in an action being taken. In total, this corresponds to approximately 2,500 S&Cs. Assuming consistent inspection regulations, unchanged inspection classes for individual S&Cs, and full compliance with inspection requirements over time, this represents data from approximately 195,000 inspections.

Figure 3 shows the number of remarks that result in different maintenance actions and their division into fault categories on the left and their inverse on the right. The action called Other contains remarks with an unknown action. Welding is the action that is performed the most (42%), followed by grinding (36%) and replacement (18%). Looking at fault categories instead, Geometry is the most frequent fault type (67%),

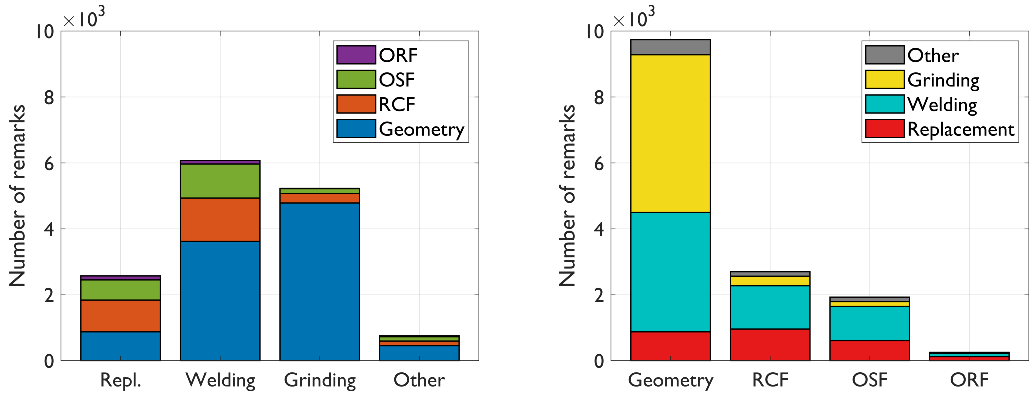


Figure 3: Left: Amount of remarks per action made, with division of fault categories. Right: Number of remarks per fault category, with division of actions. RCF = Rolling contact fatigue, OSF = Other surface faults, ORF = Other rail faults

followed by RCF (18%) and other surface faults (13%), whereas other rail faults have very few remarks (2%). Most of the grinding events, and also the majority of welding events, are connected to geometry faults. Considering RCF and OSF as the same type of faults, this is the majority of causes for the replacement of the rail. Very few of the RCF and other surface faults result in grinding. In addition, a total of 14,626 remarks were reported, implying that faults in the crossing rail were identified in approximately 7.5% of inspections, under the conservative assumption that at most one fault was reported per inspection.

In [14], it was also found that the majority of remarks required action within three months (74.1%), whereas remarks requiring intervention within two weeks accounted for 9.1%, and urgent remarks represented only 0.7% of the total. The two latter categories are considered reactive, as they typically necessitate changes to planned maintenance activities. The distribution of performed action distributions is similar across priorities (time of needed intervention), except for urgent faults, where replacement dominates (71% versus ∼15–25% for other priorities). A similar pattern is observed across fault categories, with RCF and other surface faults accounting for 66% of urgent faults, compared to ∼20–45% for other priorities.

Figure 4 shows a timeline of the average number of maintenance actions done on crossing rails per S&C and year since the S&C was installed, including logarithmic regression curves. Only UIC60 is included due to risk of data contamination if the different 60E design is included, and the S&Cs included in the dataset have an estimated average traffic tonnage of 9.59 MGT/year. Grinding is the action most often used in the first years. However, after just four years in track, welding is becoming more commonly used than grinding, which is then the case for the remaining years. Replacement is performed in an increasing amount up to around 10-12 years. Interestingly, already in year 2, there are replacements of crossing rails, and the number of grinding and welding events is high. All maintenance actions show a clear saturation,

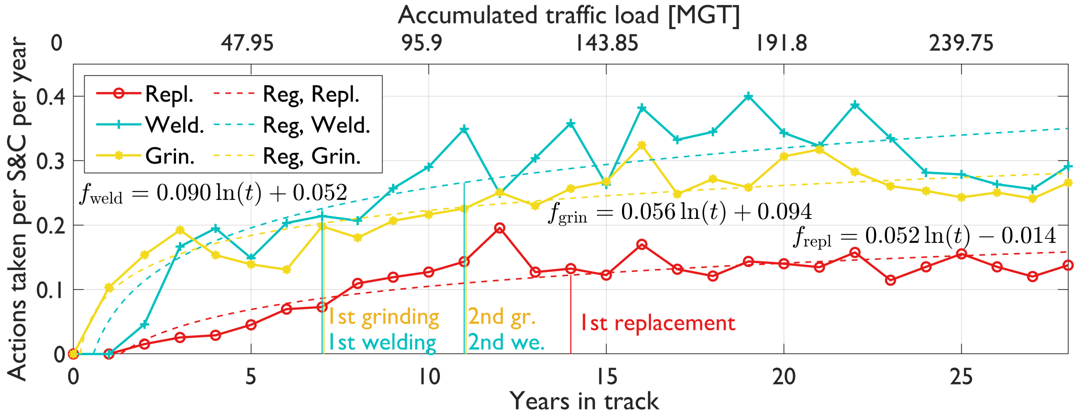


Figure 4: Intensity of actions performed on crossing rails per S&C and year, including logarithmic regression curves f_{action}. Times of expected maintenance actions (up to the first replacement) are indicated, based on the cumulative regression curves. Based on UIC60. Average tonnage of 9.59 MGT/yr/S&C.

which can be explained by the great amount of individual S&Cs situated in different parts of Sweden, stressed by varying traffic and environmental conditions leading to different life-cycles. After flattening out, the periodicity of welding and replacement corresponds well to the ones in Table 1. However, grinding is made way less than expected, which can be partly explained by the requirement of proactive grinding, adding one grinding event per replacement, which is not included in these statistics. Also, more non-recorded proactive grinding can be carried out than the regulated. The decrease in welding and grinding actions after 23 years could possibly be explained by the renewal strategy from the IM, where more critical S&Cs have been renewed to the new generation (60E), whereas the less critical S&Cs with corresponding lower maintenance needs have not been renewed. Increased accuracy would be found through individually trustworthy data on the traffic load per S&C and looking at the time since crossing rail replacement rather than renewal of the S&C.

4.2 Life-cycle cost impact

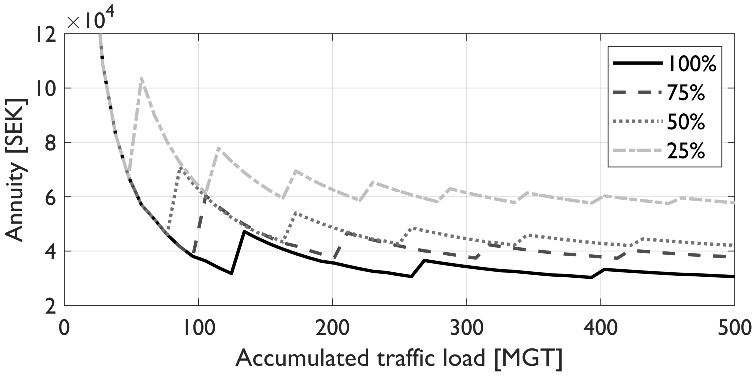
Using the regression curves in Figure 4 together with the costs in Table 1, a simple LCC analysis of the crossing rail can be performed, only taking maintenance costs into account. In Figure 5, the ANN is calculated for four percentiles of the cumulative integral of the replacement-intensity regression curves. For the 100% case, the crossing rail is assumed to be replaced in the year when the integral first reaches 1, after which the regression pattern restarts. For the 75% case, replacement occurs when the integral reaches 0.75, and similarly for the other percentiles. Grinding and welding intensities also restart at each replacement, and one additional grinding operation is added at every replacement according to the regulated preventive maintenance. The high increase of ANN for the lower percentiles shows that crossing rails affected by a loading regime resulting in frequent replacements costs much more than less frequently replaced crossing rails. As the data is based on the average annual traffic load, the smaller percentiles can also be seen as the effect of higher traffic loads, or other parameters that might result in an intensity increase of crossing rail replacement. This example shows the influence of the maintenance intensity on the annual maintenance costs. Assuming that today's maintenance isn't optimised, it demonstrates the potential for cost savings through a changed maintenance regime. Also, it does not account for additional costs of used capacity, train delays and inspections.

4.3 Requirements for the digital twin framework

The DT framework presented in this work represents a capability that infrastructure managers currently lack. Given the extensive existing and planned maintenance commitments in railway infrastructure, developing such a capability is essential to ensure effective and economically justified maintenance decision-making, as without a tool of this kind it is difficult to demonstrate that maintenance strategies are implemented optimally. This section discusses the potential capabilities and challenges of the DT framework in connection to the crossing rail. The discussion is separated based on the three DT levels discussed in Section 3 and showcased in Figure 2.

4.3.1 Monitoring the current conditions

Assessing the current condition of components and systems requires monitoring relevant damage modes using clearly defined condition indicators. Reliable monitoring techniques, in combination with suitable observation models, is then necessary to measure these indicators. Table 2 presents examples of damage modes associated with the crossing rail. The table should not be considered as definite, but it illustrates possible directions for future work. The case study highlights the significant impact of RCF on maintenance demand, both in terms of the number and severity of reported faults, making early detection of these particularly important. In addition to observed



Percentile	min(ANN)
100%	30,173
75%	37,358
50%	41,884
25%	57,423

Figure 5: Annuity based on percentiles of the cumulative integrals of the regression curves in Figure 4. Table shows lowest ANN for each case. (10 SEK $\approx$ 1€)

Damage mode	Description	Associated risks
RCF initiation	Initiation of rolling contact fatigue due to rolling and sliding contact, at the surface or subsurface	Failure
Geometry: RCF risk	Geometric features increasing the risk of RCF initiation, e.g. sharp edges or lipping	RCF
Geometry: Impact	Geometric feature connected to impact load at contact transition, e.g. dip angle	RCF, Rail body cracks, (Sleepers, Ballast)
Geometry: Wear	Rail cross-section loss due to wear and grinding	Rail body cracks
Rail body cracks	Cracks outside the running surface	Failure

Table 2: Examples of damage modes associated with the crossing rail.

faults, it is beneficial to monitor condition indicators associated with the risk of initiation. For example, sharp edges and lipping are well known to increase the risk of crack initiation in these areas. Furthermore, structural load absorption, influencing the risk of crossing-rail foot cracks as well as ballast fouling and sleeper bending cracks, is directly affected by impact loads during wheel–rail contact transitions [16]. These impact loads are closely linked to the downward–upward wheel motion occurring during the wheel–rail contact transition, commonly expressed through the dip angle, which therefore constitutes a key damage mode to monitor and is also associated with increased RCF risk. Material loss due to wear is another important damage mode, as it directly affects the load-bearing capacity of the component. This aspect becomes increasingly critical if the use of preventive grinding is expanded. Finally, rail body cracks, such as foot cracks, are infrequent but need to be monitored due to the potentially severe consequences of rail breakage. While current manual inspections would be able to assess all damage modes in Table 2, shorter inspection intervals or continuous monitoring offer additional potential. Such monitoring could be enabled through, for example, on-train and on-track technologies, including sensors, cameras and scanners, as well as complementary solutions such as drone-based inspections.

4.3.2 Predicting the future condition

Reliable deterioration models are essential for predicting future condition. As discussed earlier, such models may be physics-based, data-driven, or a combination of both. Mechanistic models can provide valuable insight into long-term deterioration but are typically computationally intensive and sensitive to uncertain inputs, often leading to miscalculation. Conversely, acquiring sufficient field data is costly and time-consuming. The increasing deployment of on-track and on-train monitoring technologies offers opportunities for improved data availability, but also introduces challenges related to data volume and interpretation. A combined approach, in which physically motivated deterioration models are calibrated using field data, therefore represents a practical starting point. Regardless of the modelling approach, deterioration rates depend on the current condition and a set of influencing parameters whose identification and quantification are critical. These parameters can be investigated using statistical analysis of historical data or through numerical studies. Finally, interactions between components within the S&C must be considered, as deterioration of one component can influence others. For example, a deteriorated crossing rail induces high dynamic wheel–rail contact forces, which accelerate ballast deterioration.

4.3.3 Evaluating the life-cycle costs of maintenance scenarios

In order to use the DT with LCC minimisation to choose a maintenance action, confidence in the LCC model is needed. Its effectiveness depends on the quality of its inputs, requiring accurate cost data tailored to the specific S&C. In addition to up-to-date maintenance and inspection costs, traffic capacity costs and traffic disruption costs must be context-specific, as their economic impact varies significantly with traffic type and location. The DT must also account for maintenance effects. For example, the heat management and execution quality during welding introduce risks that can influence the resulting condition and subsequent deterioration. Quantifying such risks is therefore essential for realistic scenario evaluation.

5 Conclusions

This study presented a digital twin framework to support a transition in inspection and maintenance practices for S&Cs from predominantly manual and reactive towards condition-based, predictive, and prescriptive strategies. By integrating inspection and monitoring data with deterioration modelling and LCC assessment, the framework provides a structured basis for comparing maintenance scenarios and supporting cost-optimal decision-making. The case study on crossing rails demonstrated that although geometric defects occur most frequently, RCF is the primary driver of component replacement and a substantial reason for repair welding, making it crucial to monitor and predict. Further studies are needed at all levels of the framework. Overall, the results indicate that the implementation of a digital twin has considerable potential to reduce maintenance-related costs and socio-economic impacts by enabling earlier fault detection and informed, data-driven maintenance planning over the full life-cycle of the asset.

Acknowledgements

The current work is part of the activities within the Centre of Excellence CHARMEC (CHAlmers Railway MEChanics, www.chalmers.se/charmec). It was produced as part of the Mistra InfraMaint research programme with funding from Mistra, the Swedish Foundation for Strategic Environmental Research, the Swedish Transport Administration through its science and innovation-portfolio Vidmakthålla (Maintain) and infrastructure contractor NRC Group.

References

[1] E. VanDerHorn and S. Mahadevan. Digital twin: Generalization, characterization and implementation. *Decision Support Systems*, 145:113524, 2021.

[2] Trafikverket. Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0, 2020.

[3] A. Ait Ali, K. Odolinski, B. A. Pålsson, and P. Torstensson. Evaluating the mix of maintenance activities on railway crossings with respect to life-cycle costs. *European Journal of Transport and Infrastructure Research*, 24(1):1–29, Jun. 2024.

[4] S. K. K. Bysani, B. A. Pålsson, and E. Kabo. Multibody simulation of derailment risk in railway switches due to gauge narrowing caused by foreign objects. *Vehicle System Dynamics*, 0(0):1–24, 2025.

[5] B. A. Pålsson. *Optimisation of Railway Switches and Crossings*. PhD thesis, Chalmers University of Technology, 2014.

[6] C. Andersson. Formation and characteristics of white etching layers on austenitic steels. Master's thesis, Chalmers University of Technology, 2023.

[7] Bane NOR. Teknisk regelverk: Overbygning, vedlikehold, sporveksler, 2026. `https://trv.banenor.no/wiki/Overbygning/Vedlikehold/Sporveksler` (Accessed: 2026-03-10).

[8] Trafikverket. TDOK 2021-0311 Säkerhetsbesiktning - Banöverbyggnad, 2025.

[9] Trafikverket. TDOK 2021-0312 Underhållsbesiktning - Banöverbyggnad, 2023.

[10] K. Odolinski, A. Nissen, and A. Ait-Ali. Finding a better renewal time and improved contract design for switches and crossings. Technical report, 2023.

[11] I. Errandonea, S. Beltrán, and S. Arrizabalaga. Digital twin for maintenance: A literature review. *Computers in Industry*, 123:103316, 2020.

[12] L. Xin, V. Markine, and I. Shevtsov. Analysis of the effect of repair welding/grinding on the performance of railway crossings using field measurements and finite element modeling. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 232(3):798–815, 2018.

[13] P. Veit and S. Marschnig. Asset management fahrweg. In *Handbuch Eisenbahninfrastruktur*, pages 903–947. Springer, 2024.

[14] K. Norberg, P. Torstensson, A. Ait-Ali, K. Odolinski, B. A. Pålsson, and A. Nissen. Rälfel i spårväxlars korsingsräler: Vad besiktningsanmärkningar lär oss om feltyper, grundorsaker och underhåll för att förebygga trafikstörningar, 2026. Conference presentation, Transportforum 2026, Linköping, Sweden.

[15] Martin Malmsten, Love Börjeson, and Chris Haffenden. Playing with words at the national library of sweden – making a swedish bert, 2020.

[16] Henrik Vilhelmson, Björn A Pålsson, and Jens CO Nielsen. Assessment of structural requirements for crossing panel design using dynamic load case scenarios. In *Proceedings of the Sixth International Conference on Railway Technology: Research, Development and Maintenance*, 2024.