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Michael Fellinger

Sustainable Asset Management for Turnouts

From measurement data analysis to behaviour and maintenance prediction

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This work is based on the dissertation *“Sustainable Asset Management for Turnouts: From measurement data analysis to behaviour and maintenance prediction”*, presented at Graz University of Technology, Faculty of Civil Engineering in 2020.

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Vorwort zur Schriftenreihe
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Das Institut für Eisenbahnwesen und Verkehrswirtschaft der Technischen Universität Graz beschäftigt sich als Institut der Fakultät für Bauingenieurwissenschaften mit der Eisenbahninfrastruktur, und zwar den bautechnischen Fragen des Errichtens des Fahrwegs, des Betrieb der Strecken und damit eng verknüpft seiner Wartung und Instandsetzung. Damit sind sämtliche für eine Betrachtung des gesamten Lebenszyklus der Infrastruktur erforderlichen Bausteine abgedeckt.

Das Einbeziehen wirtschaftlicher Bewertungen der Lebenszyklen erlaubt den Schwerpunkt „Nachhaltigkeit" umfassend in technischer, betrieblicher und wirtschaftlicher Sicht abzudecken. Die Forschungsfragen betreffen dabei das Gleislageverhalten, mit der Zielsetzung dieses prognostizierbar zu machen und damit die Voraussetzung für präventive Instandhaltung zu schaffen. Die Forschung des Instituts in betrieblicher Hinsicht umfasst Fahrplangestaltung und eine auf Nachfrageprognosen aufbauende Netzentwicklung sowie Auswirkungen unter-schiedlicher Verfügbarkeiten. Alle diese Themen werden im Forschungsbereich Life Cycle Management einer umfassenden wirtschaftlichen Bewertung zugeführt.

Mit diesem Ansatz versucht das Institut für Eisenbahnwesen und Verkehrswirtschaft seinem Anspruch, das System Eisenbahn in Forschung und Lehre zu vertreten, gerecht zu werden.

Sustainable Asset Management for Turnouts – From measurement data analysis to behaviour and maintenance prediction

In den bisherigen Veröffentlichungen dieser Schriftenreihe wurden die Voraussetzungen zur Umsetzung von Gleislageprognosen geschaffen, die zwischenzeitlich bei verschiedenen Bahnen implementiert sind. Dies betrifft das freie Streckengleis. Der nächste Schritt, der im vorliegenden Band behandelt wird, ist die Anwendung dieser Modelle und Bewertungsverfahren für Weichen. Die Fragen, wie sich der Zustand von Weichen über die Zeit unter Belastung ändert, erfordert exakte Statusdaten der einzelnen Weichentypen, da bei unterschiedlichen Weichen stark unterschiedliche Randbedingungen vorliegen. Im Unterschied zum freien Streckengleis, das mit dem Gleismesswagen befahren wird, ist kein spezifischer Weichenmesswagen im Einsatz. Zudem sind Inspektionsdaten, da es sich dabei um unbelastete Messungen handelt, für Prognosezwecke nicht geeignet.

Die Unstetigkeit der Steifigkeit der Weiche über die Weichenlänge stellt eine weitere Herausforderung zur Verhaltensprognose dar und erfordert eine exakte Positionierung und Synchronisierung der verschiedenen Messfahrten bzw. der verschiedenen Messsignale. Als erster Schritt musste jedoch die Ursache von Weichenneulagen identifiziert werden, die für Weichen auf Betonschwellen im Schotterverschleiß zu sehen ist. Daher konzentriert sich die vorliegende Arbeit auf eine exakte Positionierung der Messdaten, um die Voraussetzungen zur Zeitreihenbildung von Daten zu schaffen, die die Basis jeder technisch fundierten Prognose darstellen. Mittels Analysen der Veränderungen von Leistungsdichtespektren gelingt es ein Prognosemodell für den wesentlichen limitierenden Faktor der Nutzungsdauer von Weichen, den Schotterverschleiß, zu entwickeln. In Kombination mit dem Wissen aus Standardelementen kann eine Prognose des Weichenverhaltens und mit Hilfe dieser technischen Prognose die Methode des Annuitätenmonitorings zum Berechnen der wirtschaftlichen Nutzungsdauer auch für Weichen angewendet werden. Mit Hilfe der vorliegenden Forschungsarbeit konnte gezeigt werden, dass die Methodik zur Bestimmung der technisch wirtschaftlichen Nutzungsdauer auch für Weichen angewendet werden und damit die Frage, ob eine Weiche weiter instandgehalten werden soll oder eine Weichenneulage die über die gesamte Nutzungsdauer gesehen günstigere Alternative darstellt, beantwortet werden kann.

Peter Veit

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It is a pleasure for me to express my gratitude to the many people who have helped me or have been an important part of my life, for the last five years and, in some cases, beyond.

In the hope that I have not forgotten anyone, I would like to conclude by thanking all those special people who directly or indirectly supported and promoted me in the preparation of my dissertation and thus contributed to the present document.

Keine Schuld ist dringender, als die, Dank zu sagen.

Marcus Tullius Cicero (106 – 43 v. Chr.)

Abstract

Asset management generally involves three sub-areas, maintenance management, risk management and life cycle management. In life cycle management, the investment and follow-up costs for assets are considered holistically. Since the total life cycle costs result to a significant amount from follow-up costs (energy, maintenance, inspection, etc.), a singular view of the investment costs often is insufficient as a base for decision-making. In maintenance management, the aim is to optimise the asset availability by planning and controlling the processes of maintenance. This is always done with focus on sustainability. Risk management, in contrast, is primarily linked to possible risks within the overall process.

Turnouts play a distinct role related to the railway infrastructure. On the one hand, these infrastructure components show very high investment costs and, at the same time, short inspection and maintenance intervals. On the other hand, the demand for continuity in railway superstructure cannot be fulfilled by turnouts. Due to the continuously changing sleeper lengths, the varying number and type of fastenings, and the varying geometry of the sleepers, turnouts are considered to be extremely complex. This circumstance also manifests itself strongly in the operating and wear behaviour, since turnouts, in contrast to open track, have moveable parts. These are generally exposed to very high loads and, due to the geometric discontinuities, high dynamic forces have to be expected.

With an average service life of roughly 35 years, asset management creates considerable challenges for the responsible persons already at the beginning of the life cycle. Which maintenance is necessary at which point in time? How can the component condition and thus the necessary maintenance activities and their frequency be predicted? The condition of which component is responsible for the end of the service life and when does a turnout need to be reinvested? These and similar questions usually have to be answered at the beginning, in the context of asset management. In order to derive a reproducible and verifiable statement about the condition of a component and its development over time, models are required which consider all important boundary conditions and influences. Moreover, these models should be easy to handle and quite understandable.

Descriptive models are based on data which must fulfil certain characteristics. In addition to reproducibility and data availability, the underlying measured values must allow conclusions to be drawn about the current component condition. Therefore, the measurement data from the EM250 track measurement car were specified as basic data. These measured data are determined under the influence of the operating load and are therefore able to represent the real turnout behaviour.

However, the first step is to prepare the data available in time series dating back to the year 2001 for the assessment of turnouts. On the one hand, the position of the turnout within the various measurement signals must be identified, which means that synchronicity between the different measurement signals must be ensured and, in case of doubt, established. For an automated implementation related to a large number of turnouts, the developed systematic approach was summarised within an algorithm, called CoMPAcT. This also makes it possible to eliminate faulty measurements, to verify the plausibility of measurement data based on their characteristics and to make different directions of travel comparable with each other. In the following, these measurement data serve as base.

Although tamping is not one of the most cost-intensive maintenance activities, its value is determined by the short intervals. Similar to open track, the standard deviation of the longitudinal level in the wavelength range between 3 and 25 m over the entire length of a turnout is used to assess the geometrical condition as well as the necessity of tamping. In order to be able to extract the effect of a tamping process from measurement data, knowledge about past tamping operations is necessary in advance. As this information is not available everywhere in Austria, a methodology based on a linear prediction of the standard deviation, including the calculation of a prediction interval, was developed. This makes it possible to determine tamping operations which have been carried out, to extract their effect on the standard deviation of the longitudinal level and to use the information generated to predict future tamping tasks. Furthermore, the methodology mentioned above was able to identify areas of enhanced deterioration and to draw conclusions for an intensified maintenance of individual small-scale areas. The developed prediction model was prepared for later combination with life cycle management approaches.

The condition of the ballast also has a significant impact on the entire service life of turnouts. The ballast, as an elastic element necessary for the load distribution, wears due to the operating load and due to high dynamic forces caused by geometrical discontinuities. In the case of an inadequate condition, it is possible to clean the ballast. For this reason, a prediction model has been developed to forecast the necessity of this maintenance task. Again, based on the longitudinal level measurements, the changes in different wavelength ranges were analysed by calculating power density spectra. By approximating the power density spectra in a wavelength range between 3 m and 7.6 m by a linear function and by considering the slope of this approximation line, the roughness of the longitudinal level measurement can be evaluated. It is precisely this roughness of the measurement signal that is closely related to the ballast condition, and therefore a very high correlation between the gradient of the approximation line and the current ballast condition could be demonstrated.

For referencing the determined characteristic values, 15 turnouts were used, where a ballast cleaning was carried out. The calculated ballast condition index BCI was subdivided into four different categories, whereby each of them could be assigned to a specific ballast condition. It is therefore possible to draw conclusions about the component condition of the ballast, based on longitudinal level measurements. The generated knowledge was finally implemented in a prediction model which makes it possible to predict the necessity of ballast cleaning.

The systematic asset management approach mentioned at the beginning requires, among other things, predictions about necessary maintenance activities. In order to achieve this, based on the life cycle management methods described above for railways, the models created to predict tamping and ballast cleaning have been integrated into the existing methods, representing a major step towards life cycle management for turnouts. By calculating the life cycle costs or, subsequently, the annuities, i.e. the dynamic average annual costs, the technical necessity and the economic feasibility of maintenance tasks can thus be assessed and estimated, whereby all these conclusions can be derived from reliable and reproducible data.

Kurzfassung

Das Anlagenmanagement setzt sich im Allgemeinen aus drei Teilbereichen zusammen, dem Instandhaltungs-, dem Risikomanagement sowie dem Lebenszyklusmanagement. Im Lebenszyklusmanagement werden die Investitions- sowie die Folgekosten für Anlagen gesamtheitlich betrachtet. Da sich die gesamten Lebenszykluskosten zu einem großen Teil aus Folgekosten (Energie, Instandhaltung, Inspektion, u. a.) zusammensetzen, greift eine singuläre Betrachtung der Investitionskosten oft zu kurz. Im Instandhaltungsmanagement wird durch eine Planung und Steuerung von Instandhaltungsprozessen eine Optimierung der Anlagenverfügbarkeit angestrebt. Dies geschieht immer auch unter dem Gesichtspunkt der Nachhaltigkeit. Das Risikomanagement hingegen beschäftigt sich vorrangig mit möglichen Risiken innerhalb des Gesamtprozesses.

Weichen besitzen im Kontext zur Eisenbahninfrastruktur eine besondere Stellung. Einerseits weißen diese Infrastrukturkomponenten sehr hohe Investitionskosten bei gleichzeitig kurzen Inspektions- und Instandhaltungsintervallen auf. Andererseits kann der Forderung nach Kontinuität im Eisenbahnoberbau im Kontext zu Weichen nicht nachgekommen werden. Aufgrund der sich kontinuierlich ändernden Schwellenlängen sowie der unterschiedlichen Anzahl und Art der Befestigungen gelten Weichen als äußerst komplex. Dieser Umstand äußert sich auch stark im Betriebs- bzw. Verschleißverhalten, da Weichen, im Gegensatz zum freien Streckengleis, bewegliche Teile besitzen. Folgen davon sind hohe Betriebsbelastungen und aufgrund der geometrischen Unstetigkeiten hohe dynamische Beanspruchungen.

Bei einer mittleren Weichennutzungsdauer von rund 35 Jahren stellt das Anlagenmanagement die Verantwortlichen bereits am Beginn des Lebenszyklus vor erhebliche Herausforderungen. Welche Instandhaltungen sind über den Lebenszyklus hinweg notwendig? Wie kann der Komponentenzustand und somit die notwendigen Instandhaltungstätigkeiten und deren Häufigkeit vorhergesagt werden? Der Zustand welcher Komponenten ist für das Ende der Nutzungsdauer verantwortlich? Solche und ähnliche Fragestellungen müssen im Rahmen des Anlagenmanagements meist bereits zu Beginn beantwortet werden. Um eine belegbare Aussage über einen Komponentenzustand sowie dessen Entwicklung im Laufe der Zeit treffen zu können, sind Modelle notwendig, welche alle wichtigen Randbedingungen und Einflüsse mitbetrachten und dabei trotzdem möglichst einfach handzuhaben sind. Bereits dieser Wiederspruch zeigt das komplexe Umfeld, in welchem diese Arbeit angesiedelt ist.

Deskriptive Modelle basieren auf Daten, welche gewisse Eigenschaften erfüllen müssen. Neben der Reproduzierbarkeit sowie der Datenverfügbarkeit müssen die zugrundeliegenden Messwerte einen Rückschluss auf den jeweiligen Komponentenzustand erlauben. Als Datengrundlage wurden deshalb die Messdaten des Gleismesswagens EM250 festgelegt. Diese Messdaten werden unter der Einwirkung der Betriebsbelastung ermittelt und sind somit in der Lage, das reale Verhalten abzubilden. Es gilt allerdings in einem ersten Schritt die in Zeitreihen bis zurück ins Jahr 2001 vorhandenen Daten für die Beurteilung von Weichen vorzubereiten. Diesbezüglich muss einerseits die Lage der Weiche innerhalb der verschiedenen Messsignale identifiziert werden, weshalb auch die Synchronität zwischen den unterschiedlichen Messignalen sichergestellt sein und im Zweifelsfall hergestellt werden muss. Zur automatisierten Umsetzung wurde die entwickelte Systemantik in einem Algorithmus, CoMPAcT, zusammengefasst.

Andererseits besteht dadurch die Möglichkeit, Fehlmessungen zu eliminieren sowie Messdaten anhand deren Charakteristik auf deren Plausibilität hin zu überprüfen. Die somit aufbereiteten Messdaten dienen als Datengrundlage für sämtliche angeführten Untersuchungen.

Stopfeinsätze zählen zwar nicht zu den kostenintensivsten Instandhaltungstätigkeiten, deren Wertigkeit ergibt sich allerdings aufgrund der kurzen Intervalle. Wie auch beim freien Streckengleis wird zur Beurteilung der geometrischen Lage die Standardabweichung der Längshöhe im Wellenlängenbereich zwischen 3 und 25 m über die gesamte Länge einer Weiche herangezogen. Um den Effekt einer durchgeführten Weichenstopfung aus Messdaten extrahieren zu können, sind im Vorfeld Informationen über die Einsatzzeitpunkte notwendig. Da diese nicht flächendeckend vorliegen, wurde eine Methodik, basierend auf einer linearen Prognose der Standardabweichung inkl. der Berechnung eines Prognoseintervalls, entwickelt. Dadurch können durchgeführte Stopfeinsätze ermittelt sowie deren Wirkung auf die Standardabweichung der Längshöhe extrahiert werden. Ebenfalls konnten mittels der angesprochenen Methodik Bereiche erhöhter Verschlechterung identifiziert und Rückschlüsse auf eine intensivierte Instandhaltung kleinräumiger Bereiche getroffen werden. Das Prognosemodell wurde zur Kombination mit wirtschaftlichen Bewertungsansätzen vorbereitet.

Der Schotterzustand hat auch in Bezug auf Weichen einen gewichtigen Einfluss auf die Gesamtlebensdauer. Der Schotter als zur Lastabtragung notwendiges elastisches Element verschleißt durch die Betriebsbelastung sowie durch, als Folge von geometrische Unstetigkeiten, hohe dynamische Kräfte. Im Falle eines nicht adäquaten Zustandes kann eine Reinigung des Schotterbetts als Instandhaltungsmaßnahme ausgeführt werden, weshalb auch für diese Tätigkeit ein Prognosemodell entwickelt wurde.

Wiederum basierend auf den Längshöhenmessungen wurde die Veränderungen in unterschiedlichen Wellenlängenbereichen durch Kalkulation von Leistungsdichtespektren analysiert. Durch eine lineare Approximation dieser in einem Wellenlängenbereich zwischen 3 m und 7,6 m sowie durch Betrachtung der Steigung dieser Gerade kann die Rauigkeit der Längshöhenmessung beurteilt werden. Eben diese Rauigkeit des Messsignals steht in engem Zusammenhang mit dem Schotterzustand, weshalb eine sehr hohe Korrelation zwischen der Steigung der Approximationsgerade und dem aktuellen Schotterzustand in Bezug auf Weichen nachgewiesen werden konnte. Als Bezugswert sowie zur Referenzierung der ermittelten Kennwerte wurden 15 Weichen herangezogen, bei welchen eine Schotterbettreinigung durchgeführt wurde. Der berechnete Schotterzustandsindex BCI wurde folglich in vier Gruppen untergliedert, wobei jede einzelne einem spezifischen Zustand zugeordnet werden konnte. Es ist somit möglich, anhand von Längshöhenmessungen auf den Komponentenzustand des Schotters zu schließen. Das generierte Wissen wurde abschließend in ein Prognosemodell implementiert, wodurch sich die Möglichkeit ergibt, die Notwendigkeit einer Schotterbettreinigung vorherzusagen.

Die zu Beginn erwähnte Systematik des Anlagenmanagements setzt Prognosen über notwendige Instandhaltungstätigkeiten voraus. Um dies zu realisieren wurden, aufbauend auf den beschriebenen Methoden des Lebenszyklusmanagements im Eisenbahnwesen, die erstellten Modelle zur Stopf- und Schotterbettreinigungsprognose in die vorhandenen Methoden integriert, wodurch ein großer Schritt in Richtung Lebenszyklusmanagement für Weichen realisiert werden konnte. Durch die aufbauende Berechnung der Lebenszykluskosten oder in weiterer Folge der Annuitäten, also der dynamisch durchschnittlichen Jahreskosten, kann somit die technische Notwendigkeit und die wirtschaftliche Sinnhaftigkeit von Instandhaltungsmaßnahmen beurteilt und das Ende der Nutzungsdauer berechnet werden, wobei all diese Aussagen wiederum auf belastbare und reproduzierbare Daten zurückzuführen sind.

Contents

1 INTRODUCTION

Generally, railways are a track-bound transport system for the movement of passengers and goods (Schulz, 2014). The mechanism of automatic guidance ensures that rail vehicles follow the line of the track and, unlike road vehicles, there is no need to intervene in the direction of travel. However, this system also requires a special infrastructure, which can be characterised by long service lives, a high capital commitment as well as a high complexity of the different facilities. A total replacement value of around 45 billion euros (ÖBB-Infrastruktur AG, 2018) already shows the high financial expenditure of railway infrastructure facilities, taking the OeBB railway network as an example.

Due to the long service life of sometimes more than 50 years and the associated high investment and maintenance costs, increased attention must be paid to the following aspects of asset management in the case of these wear-prone infrastructure facilities:

- Determination of type and optimum point in time for necessary maintenance tasks
- Boundary condition-specific selection of components to be used
- Determination about the optimum economic reinvestment date

All the mentioned aspects can be summarised by the term asset management, which clearly defines the first focus of this thesis. With regard to the service life realised in the railway industry, a systematic consideration under the aspects of this management approach is indispensable and absolutely necessary.

With reference to Austria, it can be observed that 5,897 turnouts are installed within class a track in the core railway network (ÖBB-Infrastruktur AG, 2018) which corresponds to 1.4 turnouts per track kilometre. A turnout is a railway infrastructure component which enables a rail vehicle to change the track without interrupting the ride. Due to the complexity of these facilities, maintenance activities with a higher frequency in relation to open track are necessary. On average, 335 turnouts are renewed every year (considered in the period between 2014 and 2018), 697 turnouts are ground, and 1,639 turnouts are tamped (ÖBB-Infrastruktur AG, 2018), which underlines the importance of these infrastructure components. In order to convert the high investment costs into a correspondingly long service life and thus ensure the economic efficiency, life cycle considerations are necessary. For this purpose, all maintenance activities during the entire service life must be known.

This is precisely the starting point of this thesis. The prediction of necessary maintenance activities is one of the core tasks in maintenance management (a sub-area of asset management). The forecast of maintenance activities is currently based largely on descriptive models. Thus, with regard to the maintenance prediction models, the question of the basic data source initially arises. There is a wide variety of data available for turnouts, but it is sometimes very difficult to answer questions about their significance and ease of interpretation. Once the appropriate data have been found, however, analyses must be developed in order to be able to derive the condition, on the one hand of the entire turnout and on the other hand in relation to individual components. Only the information about the current condition as well as its development over time can be used to derive future necessary maintenance activities. These described steps enable a reasonable implementation of an asset management system, because, as mentioned at the beginning, the follow-up costs of turnouts can partly exceed those of the investment many times - in some cases.

The development of an asset management methodology for turnouts is defined as the central topic of this thesis. At a later stage, an attempt is made to present all processes and developments as generally valid as possible. However, asset management is a discipline which cannot always be judged in general terms, rather the specific implementation in the respective country or company must always be considered. In the first part of this thesis, the theoretical principles of asset management are explained in more detail. These statements are generally independent and not country-specific. Since a large part of the developed methods and analyses were created in close cooperation with the Austrian Federal Railways as infrastructure manager (IM) and thus in relation to the rail infrastructure in Austria, all statements, problem definitions and conclusions refer to Austrian boundary conditions.

However, attention was also paid to the possibility of applying the developments in other countries, and these opportunities were also examined as far as possible. For this reason, an excursus is inserted at the relevant passages within the thesis, where either the application is also shown in other countries or an explanation is given as to why an application might not be possible for other infrastructure managers. At this point, however, it should be clearly stated that all data in this thesis were provided by the Austrian Federal Railways (OeBB Infrastruktur AG) for research purposes, and therefore these data relate exclusively to the railway infrastructure in Austria.

1.1 Objectives

The central objective of the present research work is to develop a methodology for implementing the basic ideas of asset management at the Austrian Federal Railways with regard to turnouts, as these management principles are already in use for open track (Landgraf & Enzi, 2016; Matthä, 2013). However, the isolated consideration of turnouts does not lead to the desired results. The infrastructure components in focus must be mapped, analysed and evaluated with all their interactions, both from a technical and an economic point of view.

The overall objective is a methodology which makes it possible to derive a decision for specific turnouts on whether to continue and, under certain circumstances, intensify maintenance tasks, or to renew the whole turnout. This decision has to take into account both technical requirements and economic considerations. The technical aspect determines the necessity, while the economic point of view evaluates the technical necessity and decides whether it is economically efficient. Thus, decisions concerning the life cycle are always seen as a combination of technical and economic considerations. Neither purely economic nor purely technical considerations would satisfy the idea of asset management.

In line with this approach, it is not sufficient to consider only the investment costs. Rather, all cost positions occurring during the entire life cycle have to be considered. A life cycle approach is indispensable for asset management and therefore these two terms have to be used interchangeably. Since a lot of preliminary work has already been done in this field of expertise, the basic approaches can be included and adapted slightly if necessary, so that the application for turnouts is also possible. After this short introduction, a description of the planned content is provided below for each chapter.

1.2 Structure and methodology

Starting with chapter 2, a general introduction to asset management on a normative level is provided. The most important terms as well as the basic approaches of asset management are presented. Since asset management, as the name implies, always refers to an asset, the following section will focus on turnouts. General facts, their structure and possible constructive characteristics as well as the analysis of the existing data in the OeBB rail network are considered. Following the idea of asset management, the methodology of life cycle cost considerations for railway infrastructure assets is introduced and the application of these approaches is shown. With regard to turnouts, circumstances are identified which currently hinder the implementation of asset management in the described manner. Based on this research, questions will be formulated which have to be answered completely within the scope of this thesis.

Chapter 3 deals at the beginning with the basic data question for the creation of descriptive models, which refer to a maintenance prediction. However, the measurement signals defined for all further considerations must be processed in a first step in order to extract the necessary information for turnouts. On the one hand, a methodology is presented for how turnouts can be automatically identified within measurement signals. On the other hand, the focus is placed on the evidence of synchronicity between different types of measurement signals and between different measurement runs. As a result, at the end, data are available which form the base for all analyses and which meet the special requirements for the analysis of turnout behaviour.

Chapter 4 uses the processed measurement data with the aim of detecting, describing and predicting necessary tamping operations for turnouts. For this purpose, it is necessary to know in advance which areas of a turnout are affected by the process and additionally when a tamping operation was carried out in the past. Therefore the development of an independent methodology was necessary. Based on the identified tamping operations and the processed measurement data, a model to describe the geometric deterioration was determined and validated. At the end, all the steps mentioned above were incorporated into the prediction model based on measurement data for the time of the next tamping action.

Chapter 5 deals with the investigation of a method for describing the condition of the ballast in turnouts. The basic procedure is similar to the one mentioned in chapter 4. Instead of geometrical changes, the change of measurement signals in different wavelength ranges is analysed and the ballast condition is assessed.

After the development of a model to quantify a good and a poor ballast condition, the deterioration process was analysed in detail. From these findings, a methodology for describing and predicting the ballast condition could be developed. In addition, it was thus possible to determine the necessity of ballast cleaning at an early stage, which in turn represents very valuable information for asset management.

The aim of chapter 6 is to implement the models for predicting maintenance activities developed so far into economic models, which have already been described in chapter 2, but with focus on turnouts. This implementation shows, on the one hand, the high potential of the investigated models but also, on the other hand, their limitations.

Using a selected example, the methodology of asset management, and in particular of life cycle management, is demonstrated, and the stability of the derived statements is validated by means of sensitivity analyses. Finally, critical considerations of the limitations are made in order to be able to derive further research needs and further research topics. Since this is a very practical research project due to the high dependencies in relation to measurement data and infrastructure-related information, all chapters attempt to derive the base for the developed models on a theoretical level. Afterwards, the actual implementation will be discussed. Nevertheless, the focus is on the practical implementation, since only this step allows for a latter validation of the models, and thus an acceptance can be achieved for the application of an asset management system, with reference to turnouts.

2 TURNOUTS, MANAGEMENT STRATEGIES AND LIFE CYCLE CONSIDERATIONS

Asset management generally describes the management of assets in a company. This approach or methodology enables an organisation to examine the demand and performance of assets on different levels (Deutsches Institut für Normen e. V., 2017). It also ensures the application of analytical approaches to manage assets throughout different phases of their life cycle. All stages are considered, from planning and re-construction to maintenance, any necessary extensions and modifications, and even decommissioning of a facility. This is why asset management in general can be described as a holistic approach (Deutsches Institut für Normen e. V., 2018).

2.1 Asset management

One of the most important tasks of asset management is to plan and consider investment and follow-up costs. The administration of the working capital as well as the spare part management is also the responsibility of the asset management in general (Deutsches Institut für Normen e. V., 2017). In summary and in a strongly abstracted form, asset management consists of three sub-areas, maintenance management, risk management and life cycle management (Figure 1).

Figure 1 The sub-areas of asset management.

Risk management is assigned only a subordinate role within this thesis, since all considerations, whether they relate to the optimisation of maintenance activities, for example, take place in an area which is not critical for safety reasons. Since the entire railway system must be safe at all times anyway, risk management offers only secondary importance in this context. Of course, this should not diminish the position of risk management in the overall system.

In this context, maintenance management is an important aspect. This discipline of asset management is responsible for a sustainable optimisation of the production processes and ensures a improvement of productivity (Deutsches Institut für Normen e. V., 2017).

Maintenance management also assumes the planning and control of maintenance work, develops strategies for this purpose and thus ultimately aims to optimise asset availability. Since the railway superstructure is a system subjected to wear and tear, a wide range of maintenance activities is necessary. Especially the definition of the necessary and appropriate activities as well as the optimal execution date are the most important factors in this context and therefore these topics are considered in detail afterwards.

Last but not least, life cycle management needs to be examined more closely, as it is a very central and important part of asset management. Life cycle management considers the investment costs and the follow-up costs for capital goods as a whole (Deutsches Institut für Normen e. V., 2017). Since the follow-up costs over the entire life cycle of an asset can exceed the pure investment costs many times, this part is becoming increasingly important. It is therefore essential to mention the methodology of life cycle costing (LCC), also in relation to turnouts (Lapasov et al., 2019).

Railway engineering is a discipline predestined for this approach, especially with extremely long service lives and, for the majority of cases, very high follow-up costs in relation to the total life cycle costs (van der Westhuizen & Gräbe, 2013). However, since life cycle management requires the results of maintenance management (the necessary maintenance activities determined from a sustainability point of view as well as their time of application) as input and since these information should, if possible, already be known prior to the installation of an asset, the entire asset management must be understood as an iterative approach.

The systematic optimisation of maintenance activities, the additional consideration of associated risks and the combination of these methodologies within approaches covering the entire life cycle can thus be achieved by implementing an asset management system.

2.1.1 Asset management in railways

One of the most central characteristics of asset management is the holistic view upon the life cycle, both in terms of costs and necessary maintenance tasks. Due to the already mentioned special features in the railway industry, this holistic approach is justified in any case. However, these methodologies are not only used in the railway industry, but rather in very widespread companies (both in the private and public sector) (Pal et al., 2003). However, the demand for the implementation of the principles of asset management as described above implies the exact knowledge of all influencing factors already at the beginning of the service life. Since both results and input data are now involved, the first step is to adjust the level of consideration. It does not make sense to model every special feature of every component in the railway superstructure (Veit, 2019). Rather, it seems to make more sense to implement strategic models based on network-wide observations, which represent typical situations and are thus based primarily on network-wide mean values (Marschnig, 2016).

2.1.2 Standard elements and standard working cycles

One of the basic methodologies for implementing asset management in the railway industry involves the use of standard elements.

Network-wide or strategic analyses cannot be made based on local specifics, but rather an abstraction and classification of the most diverse boundary conditions must be made in order to enable a holistic view. Furthermore, the asset management focuses, among other results, on the development of basic strategies which cannot be derived from specific and locally limited considerations (Marschnig, 2016).

With regard to the definition of standard elements, it must be noted that the behaviour of the specified infrastructure component does not change within the parameters combined in groups or changes only to such a small extent that a further subdivision would not make sense. Since far from all influencing parameters, their characteristics and effects are known in the railway industry, the following boundary conditions were defined as classification parameters (Veit, 2019):

- daily traffic load
- track or turnout construction (sleeper material, rail profile and rail steel grade)
- substructure condition
- number of tracks

Depending on the infrastructure component currently under consideration (open track, turnouts, bridges, interlocking systems or others), additional parameters such as a radius class in relation to the superstructure or the branching radius in relation to turnouts can result.

Standard elements are thus parameter combinations which represent a typical railway infrastructure situation. It is therefore obvious that there is not a standard element for all possible combinations, only the most frequently occurring parameter compositions are considered, which allow for a classification of large parts of the considered railway network. A parameter combination of a standard element for a turnout is shown in Figure 2.

type specification:	V_{max} = ...	# track:	substructure condition: ......
daily load	rail profile	rail steel grade	sleeper material
...... total gross tons per day	......	......	......

Figure 2 Standard element classification parameters.

After the considered track network has been classified by means of standard elements and thus also abstracted, the question about the necessary maintenance activities and maintenance quantities for the respective parameter combinations arises. These, in turn, can only be determined using network-wide mean values and statistical evaluations from the past. Expert knowledge was used to support this process and to verify the plausibility of the maintenance quantities determined (Marschnig, 2016). The input data for maintenance management at this level is thus a combination of experience, expert knowledge and statistical evaluations, which must be created separately for each parameter combination, i.e. each standard element. The validation, i.e. the comparison of the maintenance quantities derived from expert knowledge with those carried out in reality, shows very exact matches throughout the network, even though certain parameter combinations may differ (Fellinger, 2018).

The summary of all determined maintenance activities and their frequency over the entire life cycle is subsequently called standard working cycle and is shown in Figure 3 as an example, belonging to the standard element parameter definition in Figure 2.

type specification:	Vmax = ...	# track:	substructure condition:													
daily load	rail profile	rail steel grade	sleeper material													
...... total gross tons per day	......	......	......													
	service life	.. years	0	1	2	3	4	5	6	7	8		18	19	20	21
infrastructure renewal	# in service life	....	1	-	-	-	-	-	-	-	-		-	-	-	-
maintenance task #1	# in service life	....	-	-	-	-	1	-	-	-	1		-	-	-	-
maintenance task #2	# in service life	....	-	-	-	-	-	-	1	-	-		1	1	1	1
maintenance task #3	# in service life	....	-	-	-	-	-	-	-	-	-		-	-	-	-
maintenance task #4	# in service life	....	-	-	-	-	-	-	-	-	-		-	-	-	-
maintenance task #5	# in service life	....	-	-	-	-	-	-	-	-			-	-	-	-
maintenance task #6	# in service life	....	-	-	-	-	-	-	-	-		-	-	-	-	-
maintenance task #7	# in service life	....	-	-	1	-	1	-	1	-		-	1	1	1	1
maintenance task #8	# in service life	....	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		1.5	1.5	1.5	1.5	1.5
maintenance task #9	# in service life	....	-	-	-	-	-	-	-	-		-	-	-	-	-
maintenance task #10	# in service life	....	-	-	-	-	-	-	-	-		-	-	-	-	-
maintenance task #11	# in service life	....	-	-	-	-	-	-	-	-		-	-	-	-	-
maintenance task #12	# in service life	....	-	-	-	-	-	-	-	-		-	-	-	-	-

Figure 3 Exemplary structure of a standard working cycle.

Only through the combination of standard elements and standard working cycles the possibilities of asset management are now fully visible. By defining the boundary conditions under the usage of parameter combinations as well as by knowing the time and type of necessary maintenance during the entire life cycle, it is possible to calculate life cycle costs for the considered situation and subsequently to compare and benchmark different strategies / decision options.

2.1.3 From standard elements to life cycle costs

By replacing the maintenance quantities in the standard working cycle with their unit costs and forming the sum over the entire life cycle, the life cycle costs can be calculated for any configuration of parameters. Life cycle considerations must, however, be carried out under consideration of the topics reliability, availability, maintainability and safety (RAMS) (Veit, 2019). Among other things, reliability can be verified by the frequency and type of failures which occur. The system availability is taken into account as an evaluation criterion or benchmark parameter. Maintainability describes the possibilities of an asset for maintenance, and the area of safety can be taken into account via the consequences of possible failures. The description of the behaviour of a system and thus the evaluation of the asset by the methodology of life cycle costs requires analyses with respect to RAMS (Veit, 2019).

After the type and frequency of maintenance activities have been defined or determined in the standard working cycle, the transition from the activity itself to costs must be carried out in order to calculate life cycle costs. In addition to the material and labour costs, there is a further cost item which must be taken into account in any case: the costs of operational hindrances (Tzanakakis, 2013).

This cost component monetarily represents the unavailability of the railway infrastructure and is therefore an essential part of economic evaluations within the railway industry (Veit & Petri, 2008). Only by taking into account these costs, an optimisation of subsystems at the expense of the overall system can be prevented, thus favouring a system optimisation that considers all interactions. Therefore, it seems clear that the individual consideration and optimisation of special components related to the railway superstructure cannot be described as target-oriented. In such a complex system as the railway superstructure, attention must always be paid to the interactions; and, in most cases, these interactions are primarily decisive for the overall behaviour.

The sum of all the above-mentioned cost positions is calculated for all maintenance activities and, based on the required annual quantity according to the standard working cycle, integrated into the calculation. It is thus possible to create a rough overview of the cost distribution at a very early stage of asset management, for example, by splitting up the total life cycle costs of a turnout (straight turnout with a branching radius of 500 m, a 60E1 rail profile on concrete sleepers and a daily load between 45,000 and 70,000 total gross tonnes) as shown in Figure 4.

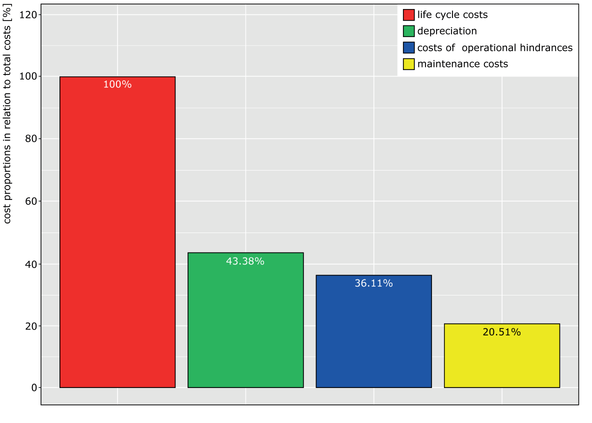

Figure 4 Turnout cost proportions in relation to the total life cycle costs.

About one fifth of the total life cycle costs are attributable to the maintenance area. Approximately half of the life cycle costs are caused by depreciation and thus by the investment. Based on network-wide mean values, it is therefore possible to derive statements about the expected life cycle costs. Following this idea, different scenarios / alternatives can then be compared with each other and basic strategies can be derived. The goal is thus an optimal asset management, the way to achieve this are optimised investment and maintenance strategies (Veit, 2019).

For example, using the methodology described, it is possible to create a specification for track components, differentiated according to the actual daily track load. This so-called component strategy was developed for the Austrian Federal Railways and was included in their regulations in 2001 (Veit, 2019). Furthermore, it is possible to evaluate innovative components economically, using this methodology without having to wait for decades of experience. The most famous example in this context is the use of under sleeper pads for concrete sleepers. The profitability of this additional investment could be proven for the Austrian Federal Railways (Marschnig & Veit, 2011) with the methodology described. Basic strategies could also be derived, and cost drivers identified with regard to turnouts. Investigations for the Austrian Federal Railways have shown that the main focus, regarded to the costs, is placed on the parameters of initial quality, substructure condition and water drainage, turnout density and radius class (Veit, 2006). Basic strategies could also be derived for turnouts, such as the use of a 60E1 rail profile for high traffic loads or the requirement that the switch panel must in principle be made out of a R350HT rail steel quality.

Other studies applied similar methodologies to identify the cost drivers, especially for turnouts. It could be shown that in Sweden the inspection costs and the costs for periodic maintenance are the largest cost positions and that a reduction of the life cycle costs can be realised by means of optimising fixed inspection intervals (Nissen, 2009a, 2009b). All the mentioned results must be understood as results of considerations over the entire life cycle.

Since all the facts presented so far have been prepared in a largely component-neutral way, it is now time to specify the infrastructure component in focus more precisely. For this purpose, on the one hand, the definitions of turnouts as well as their technical characteristics and differences in comparison to open track are discussed. On the other hand, the rail infrastructure in Austria is used to show the different types, their distribution and, among other facts, their age structure. Thus, the following is intended to give an overview of turnouts and to provide all the facts that are specific for all further considerations.

2.2 Turnouts and their components

The term turnout is based on alternate places in river navigation and therefore the word is derived from evasion in German (Lay & Rensing, 2019). Turnouts allow the change of a rail vehicle from one track to another without having to interrupt the journey (Austrian Standard Institute, 2003). The number of installed turnouts influences the performance as well as the maximum speed possible on a line (Lichtberger, 2010).

The most important unique characteristic of turnouts is the presence of movable components. In order to ensure the correct position of all movable turnout parts before an individual train journey is permitted, turnouts must be equipped with a drive, a locking and a safety device (Lay & Rensing, 2019). Due to the most diverse requirements, route-related restrictions or operational necessities, most varied geometric designs have become established with regard to turnouts. A possible subdivision of the turnout types can be made based on their function into turnouts, diamond crossings and diamond crossings with slips (single / double) (Austrian Standard Institute, 2003). It should be noted that all further considerations refer exclusively to turnouts according to the widely used definition (Lay & Rensing, 2019).

2.2.1 Turnout components

Turnouts are very complex components of the railway infrastructure, which are assembled out of various parts. An overview of the most important components (based on (Hassankiadeh, 2001; Matthews, 2011) is shown in Figure 5.

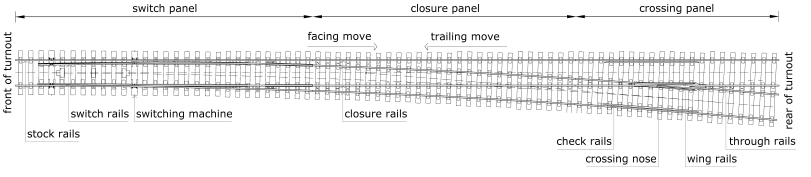

Figure 5 Designation of different turnout components.

The division into the switch panel, into the closure panel as well as into the crossing panel, indicated in Figure 5, was primarily intended to be based on normative regulations (Austrian Standard Institute, 2003). This subdivision is, in any case, necessary for later presented analyses. At this point the explanation of the exact reason for the chosen subdivision, apart the instructions within the regulation, is waived and will be done later. Instead, the most important components of a turnout will be discussed in more detail below.

2.2.1.1 Front of turnout

The front of the turnout is defined as the tangent intersection point between the branch and the main line (Matthews, 2011). From a design perspective, the beginning of the turnout is the area where the delivery units are divided, and thus the connection from open track to the turnout is realised. In the following, the front of the turnout is the reference point where the turnout begins for the presented analyses.

2.2.1.2 Switch panel

The switch panel consists of two half set of switches, each consisting of a straight stock rail for the main track and a curved switch rail for the branch track or vice versa (Austrian Standard Institute, 2003; Lay & Rensing, 2019). The transition of the vehicle from one track to the other takes place through the converging tip of the switch rail, which fits to the stock rail within the diverging direction of the turnout. Since the weakened switch rail profile cannot absorb the entire wheel load, it is lowered up to 14 mm below the upper edge of the stock rail (Matthews, 2011). In this area the switch rail takes over the guiding function while the stock rail is responsible for the load absorption (Schiemann, 2002).

2.2.1.3 Common crossing and crossing nose

The common crossing is located at the intersection area of the two rail lines (Austrian Standard Institute, 2003). Due to geometrical conditions, the running table is interrupted at this area and therefore a hit occurs as soon as a rail vehicle passes over this area. For this reason, the crossing nose is generally the most heavily loaded area within a turnout (Schiemann, 2002). Depending on the intended purpose and field of application, turnouts can in principle be designed with common crossings or switch diamonds.

2.2.1.4 Check rail

The check rails are installed on the stock rail side, opposite the common crossing. They are 20 mm higher than the rail (Matthews, 2011). The check rails are installed using check rail struts and supports. This arrangement is essential for the guidance of the rail vehicle, since in front of the common crossing, the way of the wheel can otherwise not be controlled. To prevent the wheel flange from entering the wrong track, check rails are installed to guide the opposite wheel and to ensure the correct direction of divergence (Lay & Rensing, 2019).

2.2.1.5 Wing rail (left-hand / right-hand)

The wing rail takes over the supporting function in the area of the common crossing gap. Starting at the bending point at the position of the crossing nose, the wing rails no longer run along the theoretical running table. These rails are guided outwards to clear the common crossing gap. The wing rail is then guided parallel to the running table of the common crossing and forms the flangeway (Lay & Rensing, 2019).

2.2.1.6 Rear of turnout

From a design perspective, the rear of a turnout is described as the point at which both rails (that of the main track and that of the branch line) are so far apart that both welding and lashing are possible. This point also allows the use of separate rail fastenings (Lay & Rensing, 2019). The rear of the turnout is also the point at which the delivery unit is divided, and this point is defined as the reference within this thesis where the turnout ends. In a narrower sense as well as with regard to all following analyses, the range of a turnout is associated with the section between the front and the rear of the turnout.

2.2.1.7 Insulated rail joints

Although the field of application of insulated rail joints (IRJ) is not exclusively limited to turnouts, these components are still being intensively analysed within this work. An insulated rail joint is a rail joint that mechanically connects two adjacent rails but at the same time electrically insulates them (Lay & Rensing, 2019). Due to safety requirements, it may be necessary to position an IRJ at the beginning and/or end of turnouts.

2.2.2 Construction types of turnouts

Depending on the track conditions, some turnout designs have become established which are installed as standard. The basic principle of a turnout remains untouched, only the geometry of the different turnouts is changed.

2.2.2.1 Straight turnouts

Single straight turnouts are composed of the straight main track and the curved branch track. When looking in the direction of the turnout's rear, a distinction can be made between a left and a right single turnout, depending on the direction of the branch line. If the radius of the branch line ends prior the common crossing, it is called a turnout with straight, otherwise with a curved common crossing (Lay & Rensing, 2019).

2.2.2.2 Curved turnouts (inside / outside)

Curved turnouts can be differentiated in terms of the direction of the branching line in outside and inside curved turnouts. In principle, curved turnouts are distinguished by a curved main track, in contrast to the straight main track of a straight turnout (Lay & Rensing, 2019). An inside curved turnout possess a layout, which has the branch line inside the curve of the main line. An outside curved turnout has the branch line outside the curve of the main line. If the direction of the main and the branching line is different, they are called different directional curved turnouts.

2.2.2.3 Diamond crossing and diamond crossing with slips

Diamond crossings emerge when two tracks are cut at the same height, whereby the crossing square is formed based on the four intersection points of the tracks (Lay & Rensing, 2019). Since this construction is intended to allow a rail vehicle to pass over it, no switch panel is necessary. In contrast to this, the installation of a curved connection with curved switch panels can enable a transition of the rail vehicles within the intersecting straight track lines. In this case this is called a diamond crossing with slips whereby two double as well as two single common crossings are necessary (Matthews, 2011).

After describing the individual components of turnouts and their different designs, the following section shows evaluations of the basic turnout type distribution in Austria.

2.3 Portfolio analysis of turnouts in the OeBB railway network

It seems initially useful to provide a classification. According to the specifications of the Austrian Federal Railways, tracks and turnouts are divided into different line classes (ÖBB-Infrastruktur AG, 2018). Line class a includes all tracks, turnouts and continuous main tracks in the station. Line class b describes all others, used for signal traffic and line class c includes all tracks and turnouts which are not secured by control and safety systems. An evaluation of the distribution of turnouts according to their line class can be seen in Figure 6, where roughly 42% are located on tracks, which are summarised in line class a. Based on this fact, all further considerations will be limited to turnouts in line class a.

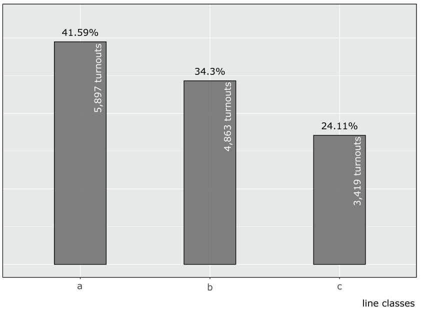

Figure 6 Number of turnouts in different line classes in Austria.

Evaluations of the superstructure components and geometries (Figure 7) are also extremely relevant. In relation to the turnout types, straight turnouts have the largest proportion of 64.5% in line class a. The following analyses focus therefore primarily on the consideration of this turnout design, whereby the methods to be developed are kept as general as possible. An application for different turnout types is therefore possible. With 33.5%, curved turnouts also have a significant percentage, which means that it will be necessary to analyse these turnouts in more detail at a later stage. The subdivision in terms of the branch radius shows that in line class a, with 46.3%, turnouts with a radius of 500 m are mostly installed. The three remaining relevant classes of radii (190 m, 300 m and 1,200 m) are almost equally distributed at around 17%. Again, all branch radii must therefore be included in following considerations, even if the focus is placed on turnouts with a branch radius of 500 m. According to the sleeper material, differences between open track and turnouts occur. In general, open track tends to be equipped with concrete sleepers (64%) whereby 11% are additionally executed with under sleeper pads (Landgraf, 2016). In contrast, more than half (55.3%) of all turnouts in line class a are equipped with wooden sleepers. 28.7% are equipped with concrete sleepers, whereby the trend towards turnouts with additional under sleeper pads (USP) is discernible with a proportion of 13.1%.

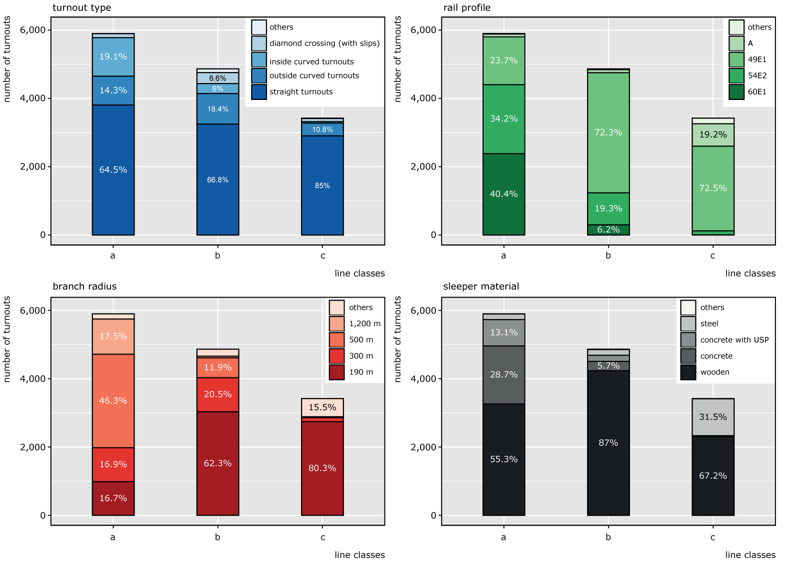

Figure 7 Superstructure and turnout geometries for different line classes in Austria.

The evaluations of the inventory data presented here are intended to provide an overview of the turnout structure in Austria. These results serve as a base for the definition of the turnouts to be considered in detail, by means of which the necessary models are developed and validated. Besides the purely component-specific evaluations, an analysis of the age structure also seems to be quite relevant in this context. For this purpose, all turnouts in the OeBB rail network were analysed again based on their current age (Figure 8).

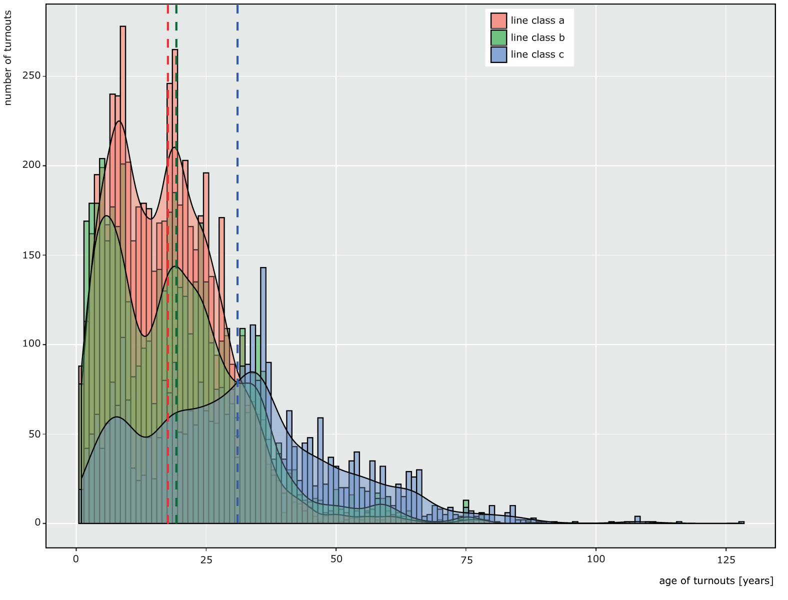

Figure 8 Age structure of turnouts in different line classes in Austria.

In relation to line class a, the average age of the turnouts installed (regardless of the turnout type) is around 17 years. This corresponds quite well with information concerning the network structure of the Austrian Federal Railways (ÖBB-Infrastruktur AG, 2018). If the average technical service life of 33 years is taken into account, it can be concluded that the real average value over the age of all turnouts in line class a corresponds almost exactly to the half average value of the technical service life. Thus, turnouts in line class a seem to be in a balanced age distribution, and the annual renewal rate of roughly 180 turnouts per year reflects the asset substance very well.

2.4 From strategic considerations to project decisions

The boundary conditions or parameter combinations defining a standard element have already been described in detail. Their combination with a standard working cycle has also been considered. After the focused infrastructure components have been defined, the standard working cycles can be filled with the necessary maintenance activities in a next step. The basic definition of which activities are necessary is based on statistical evaluations and is supported by expert knowledge. In the following, a list of all relevant maintenance activities together with a brief description about the individual tasks is presented.

2.4.1 Maintenance activities for turnouts

Maintenance is understood as all activities carried out within the whole life cycle in order to maintain the functionality or to restore it (Austrian Standard Institute, 2018). The activities which are necessary for turnouts and thus also shown within the standard working cycles are described in detail below.

2.4.1.1 Levelling - lining - tamping

In the following, instead of the three works mentioned in the title, only tamping is used synonymously. Tamping is necessary in order to compensate the changes in position caused by the loading and to bring the track or turnouts back into the correct geometrical position. In addition, tamping ensures a tight fit of the sleepers (Lichtberger, 2010). For this purpose, vibrating tamping picks which dip into the ballast around the sleeper are used to bring the ballast up to the required degree of compaction. The tamping of a turnout can be carried out either by means of tamping machines or with hand tools. For all further considerations within this work, tamping is understood to be a tamping operation with a tamping machine over the entire length of a turnout. Manual tamping of individual, locally limited areas of a turnout by means of manual tamping units are not standard activities and are therefore not considered within this work.

2.4.1.2 Grinding

The grinding of rails or turnout components is carried out to eliminate unevenness or small-scale rail defects. The rotating grinding discs or the oscillating grinding stones are pressed onto the rail under machine operation. This allows for a slight abrasion of the rail and thus a restoration of a perfect surface (Lichtberger, 2010).

2.4.1.3 Half set of switches exchange

The wear of the switch panel is mainly linked to the cumulative load. Depending on the proportion of trains running into the branch line, one side usually wears out more than the other. Hence, this maintenance refers to the exchange of a half set of switches (i.e. the switch and stock rail on one side of the turnout). The switch and stock rails of one side must always be replaced together, because these two components have to be adjusted to each other and smoothed in accordingly (Lay & Rensing, 2019).

2.4.1.4 Crossing nose exchange

The main criterion with regard to the crossing nose wear is again the cumulative load. Due to the geometric conditions in this area, a train generates high dynamic forces during the crossing, which lead to considerable wear and tear and may therefore make it necessary to replace the crossing nose.

2.4.1.5 Check rail exchange

Wear also occurs on the check rails due to the cumulative load. Because of the track guidance conditions in the area of the common crossing, the check rail must take over the guidance of the wheel in this area (Lay & Rensing, 2019) and thus wears out over time. In the context of this maintenance, the entire check rail including its fastenings is replaced.

2.4.1.6 Overlay / repair welding

As part of an overlay welding process, several weld lines are applied and thus any damage is welded on with a necessary increase. After the weld has cooled down, the necessary profile is produced by grinding (Schuler & Twrdek, 2019). By using this method, defects in turnout components such as spalling can be avoided.

2.4.1.7 Deburring

The term deburring means the removal of burrs by grinding, which can occur on turnout components due to wear (work hardening) (Lay & Rensing, 2019). The deburring of individual components is usually carried out by machine.

2.4.1.8 Rail pad exchange

In turnouts with concrete sleepers, rail pads are required to ensure the necessary elasticity and to reduce vibrations (Lichtberger, 2010). However, as they wear differently depending on the load, it may be necessary to replace them, otherwise the sleeper may be damaged.

2.4.1.9 Ballast cleaning/exchange

Under high operating loads, the ballast, especially in the case of concrete sleepers without under sleeper pads, is subjected to very high forces over its service life. As a result, ballast replacement or ballast cleaning is necessary with varying frequency. In the context of the present study, the observations concentrate exclusively on ballast cleaning, which is carried out with appropriate machines (automated ballast cleaning machines (Zuzic & Wörgötter, 2015)).

2.4.1.10 Sleeper screw hole renewal

A screw hole renewal is more likely to be counted as one of the actions that prolong the service life of the sleeper and serves to restore the adhesion of the sleeper screws on wooden sleepers. The old sleeper bore hole is drilled out and sealed with epoxy resin. Subsequently, the new sleeper screws with spring washers are screwed in. This ensures the required frictional connection.

2.4.1.11 Single sleeper exchange

On lines with a lower traffic load, it may be more cost-effective to simply change the sleepers instead of reinvesting the entire turnout, since the rail and ballast usually cause no problems here. In the case of some broken sleepers of a turnout (mostly in the common crossing area), it may be useful to replace or renew individual sleepers to extend the service life. During this maintenance activity, the broken sleepers are replaced by new ones, whereby the geometry and the position of the turnout remains unchanged.

2.4.1.12 Unplanned small-scale maintenance

Unplanned maintenance includes minor activities that are not statistically feasible or whose value would be too small to be recorded. Since the occurrence of defects correlates with the age of the superstructure, 50% of the average costs are applied in the first third of the service life, 100% in the second third and 150% in the final third. If service life is exceeded, analyses showed that the annual increase of these tasks is roughly 10%. This maintenance includes, for example, dowelling, changing the plates, regulating the guide width, carrying out position corrections or maintaining the insulated rail joints.

All mentioned maintenance activities are foreseen in the standard working cycles and must therefore subsequently be linked to their frequency. At this point, it seems advisable to remain on the strategic level and thus to explain the economic evaluation methods, before the implementation of the described methods for specific turnouts can be presented.

2.4.2 Economic evaluation methods for railways

The following section was worded in close reference to (Veit, 1999). In principle, all cost- and revenue-relevant effects must be considered through economic evaluations. An overview of the maintenance costs for each maintenance activity considered in detail is visualised in Figure 9 as an example for a standard turnout configuration (straight turnout with a branching radius of 500 m on concrete sleepers with a common crossing and a daily load of about 35,000 total gross tonnes). In grey the unit costs of the respective maintenance activities, and in red the total costs over the life cycle, i.e. the unit costs multiplied by the required quantity based on the standard working cycle, can be seen. Comparable cost ratios have also been found for turnouts and their necessary maintenance activities in Sweden (Nissen, 2009c). The presentation of the effects evaluated in monetary terms can subsequently be realised exclusively, both for investment and maintenance costs, through a cash flow analysis. A cash flow thus not only indicates the amount of a payment, but also its timing. Furthermore, a distinction must be made between static and dynamic economic analyses with regard to the basic methodology. Static models consider the input parameters to be constant over time and do not take the capital commitment into account.

For service lives of more than 30 years, however, the non-consideration of the time of payment is only an approximation, meaning that dynamic methods that increase or decrease the cash flows to a user-defined reference date are also necessary. In principle, a distinction can be made between the net present value method (NPV), the internal rate of return method (IRR) and the annuity method.

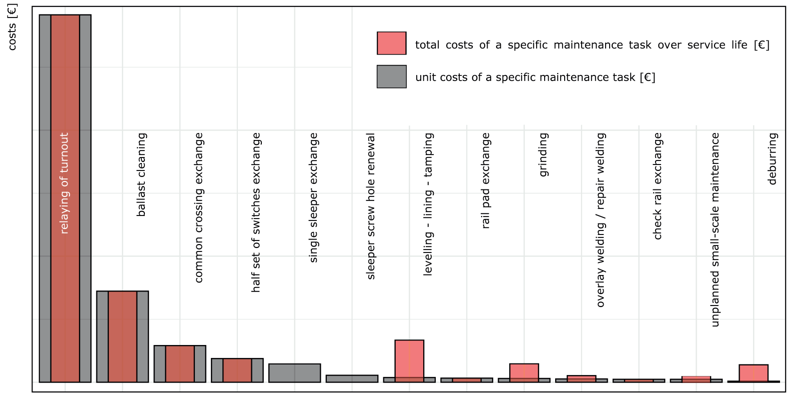

Figure 9 Comparison of unit and total costs for different maintenance activities.

The annuity method, the most universal of the three mentioned, is based on the calculation of the net present value $C_0(i)$ using Formula 1.

$$C_0(i) = \sum_{t=0}^{T} Z'_t \cdot (1+i)^{-t} \tag{1}$$

Z'_t is the cash flow currently under consideration, i stands for the imputed interest rate, and t describes the duration of the current observation. If the capital values determined in this way are multiplied by the capital recovery factor CRF, the annuity A can be calculated (Formula 2)

$$A = CRF \cdot C_0(i) \tag{2}$$

In general terms, the capital recovery factor CRF (Formula 3) distributes a monetary amount (in this case the capital value $C_0(i)$), taking into account the imputed interest rate i, into equal annuities A within a time period of length t.

$$CRF = (1+i)^t \cdot \frac{i}{(1+i)^t - 1} \tag{3}$$

Annuities can thus be understood as average dynamic annual receipts. The entire calculation method is again visualised in Figure 10. All calculations are made without taking inflation into account.

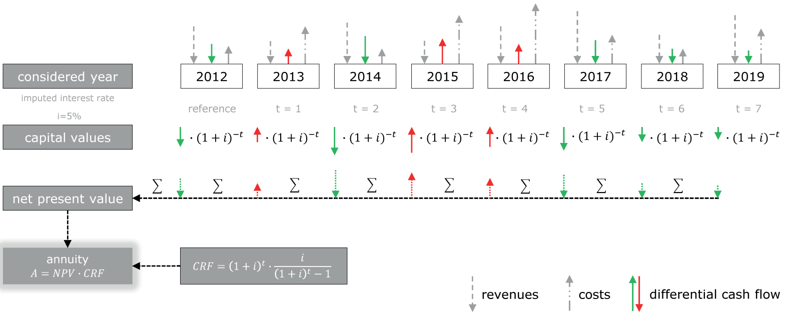

Figure 10 Annuity calculation methodology.

Another argument in favour of applying the annuity method is the fact that investments in a railway infrastructure in the context of asset management are internal rationalisation investments. These are therefore not directly linked to revenues. For this reason, the annuities A, can be interpreted as average, dynamically calculated annual costs.

When comparing different strategies based on standard elements and standard working cycles, priority should therefore be given to the strategy with the lower annuity, which would fully derive the economic decision criterion for different strategies.

2.4.3 Annuity monitoring

The following section was worded in close reference to (Veit, 1999). Based on the knowledge gained so far, the path from strategic considerations to project-specific decisions will now be shown. Therefore, the determination of the point in time for a reinvestment, based on economical and technical boundary conditions, will be discussed further.

The annuity monitoring method is used for the calculation of the desired reinvestment date (Marschnig & Veit, 2012). To determine the optimal time for a reinvestment, a maintenance strategy is calculated. An additional year of service life reduces the annuity, whereby this extension must be bought in return by maintenance (Veit, 2016). A minimum of the annuity curve (year 2015 in Figure 11) is therefore an indicator for the economic service life. In other words, from an economic point of view, the end of service life is reached when the reduction in depreciation related to a period t is smaller than the increase in maintenance and thus in average annual maintenance costs necessary to achieve this extension.

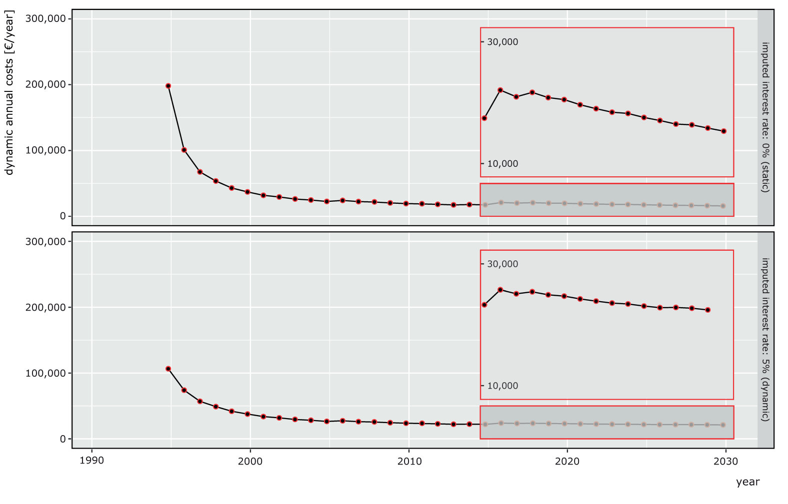

Figure 11 Exemplary annuity curve for a reinvestment decision.

In Figure 11, the annuity was calculated for one year at a time and plotted over the resulting service life. Both charts in Figure 11 refer to the same asset; only the imputed interest rate was varied. The areas marked with the red frame are only enlarged to allow for a detailed and graphical analysis of the annuity development even at the end of the life cycle, where it is most important to make a decision. By applying this methodology, it is possible to move away from standard situations and general strategies towards specific project decisions, which will be discussed in more detail in the next chapter.

2.4.4 Life cycle management for turnouts

Life cycle management is the location-specific implementation of strategies based on life cycle costs (Veit, 1999). For this purpose, specific data must be used and thus the local behaviour of turnouts must be taken into account in order to determine the optimum time for a maintenance activity or for a reinvestment. In order to be able to explain how turnouts behave or which maintenance activities are necessary at which point in time, it is necessary to define boundary conditions, analogous to the parameter definition of standard elements. However, these boundary conditions now refer to a specific turnout which has to be described, and no longer to a clustering and merging of turnouts of similar boundary conditions.

These considerations already reveal the first challenge with regard to life cycle management. The design of turnouts (sleeper material, rail profile, branch radius and others) is available in the form of simple lists. These registers neither currently offer a connection to geographical information systems (GIS), nor are they linked to further data sources. A standard element of a turnout has as a parameter for example the percentage of trains that use the turnout in the diverging direction. In Austria, this percentage was defined with 20% (equivalent to 80% of the trains passing straight) for standard element considerations. However, as specific situations are now being considered, this value must be verified. Although there is little opportunity to do so, as in Austria only very rudimentary information is available about the passage direction of turnouts. Another example could be the consideration of the turnout dimensions. There is currently no link between the lists containing the superstructure parameters of turnouts and the corresponding turnout drawings. Therefore, it is only possible to obtain information about the dimensions of certain parts of turnouts to a very limited extent or via detours.

In summary, initial difficulties in the implementation of life cycle considerations for turnouts can be identified. These are the data acquisition related to inventory data on the one hand and the holistic data management system for turnouts on the other hand.

For these specific advisements, standard working cycles cannot be used for further consideration. Rather, other ways must be sought to determine the necessary maintenance activities for the turnout currently under consideration. All the maintenance activities that come into consideration have already been explained. It is now all about the question of which activity has to be carried out at which point in time. Therefore, the idea of developing prediction models for various maintenance activities is generated. Based on such models, the necessary tasks in their type and frequency could be predicted, and thus the complete implementation of a life cycle management could be realised. It is precisely this requirement that could end the work at this point, as such prediction models for turnouts have so far been a vision of the future.

In light of this, a further reason for the difficulty of the implementation of an asset management system can be identified. Descriptive models for predicting the condition and for further derivation of necessary maintenance activities are currently not available. With regard to the development of maintenance task prediction models, the first step is to clarify the basic data. On the one hand, the underlying data must be able to depict the real behaviour of turnouts during the passage of a train. The demand about a realistic model for predicting maintenance activities can be covered only in this way. On the other hand, these data must be available in very long time series and must be reproducible. Last but not least, the data forming the base for maintenance predictions must be available for a large number of turnouts.

In summary, further complications can be identified within the implementation of a management strategy based on life cycle considerations. In order to be able to predict the behaviour of turnouts and thus the occurring wear and tear, and subsequently the necessary maintenance for implementation in a working cycle, a large amount of data is required. This data must meet very specific requirements. The possibility of linking it in relation to the data management for turnouts mentioned above is also one of the central requirements for further developments.

Once the question of the data base has been clarified, the focus must be placed on the integration of this data into descriptive models. It is therefore necessary to develop models that are capable of describing the condition of a turnout, both holistically and broken down to individual components. Only by knowing the current condition as well as the development of this condition over time it is possible to predict further developments and thus to plan any necessary maintenance activities at an early stage.

Since neither the data collection and the data base nor the models to be derived from this data are currently clarified or available, the implementation of an asset management system for turnouts cannot be considered for the time being. Only the development of the prediction models mentioned above and thus the overcoming of all difficulties would allow the implementation of a detailed life cycle management for turnouts and facilitate a sustainable asset management for these railway infrastructure components.

2.5 Research questions

In the context, the complexity of the currently formulated obstacles becomes apparent. On the one hand, models are necessary which depict the occurring wear, both in relation to the overall system and in relation to individual components, and which can thus predict maintenance activities. These models should be based on reproducible data which represent the real behaviour and should be available over long time series. Last but not least, these data should be integrated into a data management system that can establish connections to other data sources through a variety of possible links.

The following research question can thus be derived from the circumstances described:

Research question 1

How can individual turnout data sources be linked? Which information is indispensable and therefore to be treated with priority?

Research question 2

Is it possible to adapt or process the existing measurement data of the track recording car in order to extract information for turnouts? What would a possibly necessary reworking process look like?

Research question 3

Do these measurements provide sufficient information on the geometric conditions under loading to deduce turnouts' behaviour? Is it possible to derive maintenance activities from these data?

Research question 4

Do smart analysis methods also allow for component-specific condition monitoring? Is reality described with sufficient accuracy?

Research question 5

Is it possible to combine technical models and economic aspects to predict the optimum time for a maintenance activity or a turnout replacement?

Research question 6

Is there a need for a separate additional turnout measurement car? Which data are missing nowadays?

3

CoMPAcT – DATA SOURCES AND THEIR PREPARATION FOR TURNOUTS

The following chapter contains methods, results and text passages, some of which have already been published (Fellinger et al., 2019; Fellinger, Neuhold, & Marschnig, 2020; Fellinger, Wilfling, & Marschnig, 2020a, 2020b). Text passages of the same wording are appropriately marked.

This chapter shall be introduced with a definition regarding the turnouts to be considered. The necessary data management and the planned data structure are also described, since these topics are closely related to the actual measurement data and their preparation, and it is necessary to define the objects of investigation at this point and in relation to the further progress of the thesis.

3.1 Definition and delimitation of the objects to be examined

The selection of the turnouts to be investigated in the further course of this research work is of high importance. On the one hand, all relevant parameters, which were shown and declared as significant in section 2.3, must be considered. On the other hand, it must also be ensured that corresponding information is available on the turnouts under consideration, which allows meaningful analyses.

3.1.1 Definition of considered turnouts

For an in-depth analysis, a total of 45 turnouts are defined (Table 1), whereby a further division into three groups is applied. The first 16 turnouts (EBW01 up to and including EBW16) in Table 1 are turnouts for which no abnormalities have been documented within the last ten years, neither with regard to their overall condition nor with regard to their behaviour. These turnouts are primarily used to implement the methodology of post-positioning, to learn from experience and of course also for the purpose of developing all necessary analysing procedures or methods. Furthermore, attention was paid to the greatest possible parameter diversity in accordance with section 2.3. The following 14 turnouts (EBW17 up to and including EBW30) were defined with regard to ballast problems. Through various discussions with regional managers responsible for turnouts, it was possible to identify turnouts where ballast problems are known to prevail. Because a necessary ballast cleaning could be identified as a very large maintenance cost block (Figure 9), these turnouts were selected to validate methods for evaluating the ballast condition which has already been described using various approaches. For these 14 turnouts, information about the ballast condition for a specific point in time are available. The last 15 turnouts (EBW31 up to and including EBW45) were also selected in close relation to the ballast condition. For these turnouts a ballast cleaning was carried out in the period between 2010 and 2020. These turnouts will be used to derive a model for the classification of the ballast condition and to carry out a clustering, whereby the ballast condition before and after the ballast cleaning is used as a reference. The geographical location of the selected turnouts is shown in Figure 12. All 45 turnouts have in common that all maintenance activities are well documented, the turnout dimensions are available in terms of installation drawings, and the necessary measurement data are available in the form of a database.

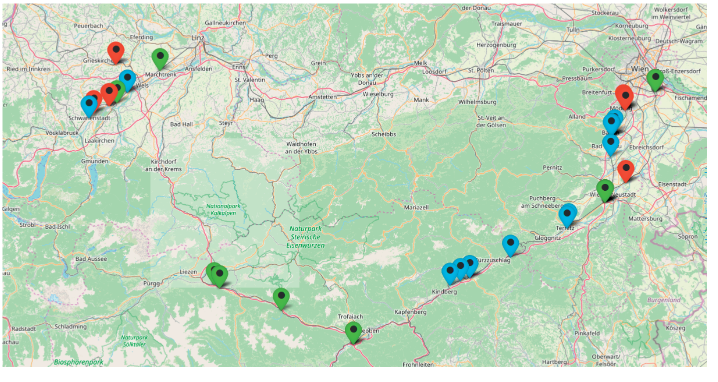

Figure 12 Geographical location of all turnouts considered in detail.

name	type	rail profile	branch radius	sleeper material	installed
EBW01	straight turnout	54E2	500 m	wood	1986
EBW02		60E1	500 m	concrete (USP)	2007
EBW03		60E1	500 m	concrete (USP)	2007
EBW04		54E2	500 m	wood	1984
EBW05		54E2	500 m	wood	2009
EBW06		54E2	500 m	wood	2013
EBW07		60E1	500 m	concrete	1999
EBW08		60E1	500 m	concrete	1994
EBW09		60E1	1,200 m	concrete	2005
EBW10		60E1	1,200 m	concrete (USP)	2002
EBW11		60E1	1,200 m	concrete (USP)	2002
EBW12		60E1	1,200 m	concrete	2002
EBW13		60E1	1,200 m	concrete	2002
EBW14		60E1	500 m	concrete (USP)	2017
EBW15		60E1	500 m	concrete (USP)	2017
EBW16		60E1	1,200 m	concrete	2005
EBW17		60E1	500 m	concrete	1996
EBW18		60E1	500 m	concrete	1996
EBW19		60E1	500 m	concrete	1996
EBW20		60E1	500 m	concrete	1996
EBW21		60E1	190 m	concrete	1996
EBW22		60E1	190 m	concrete	1996
EBW23		49E1	500 m	wood	1980
EBW24		49E1	500 m	wood	1980
EBW25		60E1	1,200 m	concrete	1994
EBW26		60E1	1,200 m	concrete	1994
EBW27		60E1	1,200 m	concrete	1994
EBW28		60E1	1,200 m	concrete	1993
EBW29		60E1	500 m	concrete	1995
EBW30		60E1	500 m	concrete	1995
EBW31		60E1	500 m	concrete	1997
EBW32		60E1	1,200 m	concrete	1991
EBW33		60E1	1,200 m	concrete	1993
EBW34		60E1	1,200 m	concrete	1993
EBW35		60E1	500 m	wood	1988
EBW36		60E1	1,200 m	concrete	1993
EBW37		60E1	1,200 m	concrete	1993
EBW38		60E1	1,200 m	concrete	1993
EBW41		60E1	1,200 m	concrete	1997
EBW42		60E1	1,200 m	concrete	1997
EBW43		60E1	1,200 m	concrete	2014
EBW44		60E1	500 m	concrete	1991
EBW45		60E1	1,200 m	concrete	1993

Table 1 Listing of reference turnout parameters.

3.2 Data sources

The basic data selection is of great importance for mapping the behaviour of turnouts. In principle and in context to the data, two different approaches can be distinguished (Minbashi, Bagheri, Golroo, Arasteh Khouy, & Ahmadi, 2016):

- The first possibility is the introduction and development of new inspection technologies in order to determine the component condition in a specific way and thus to be able to derive necessary maintenance activities based on it.
- The second approach can be specified by analysing historical measurement data and deriving a deterioration model, whereby the necessary maintenance activities can then be deduced from such models.

Both approaches have in common that the basic data must be reproducible and objective and ideally available over long periods of time. It must also be ensured that these data are able to represent the real behaviour of turnouts (Fellinger et al., 2019). In the following, the two approaches (Minbashi, Bagheri, Golroo, Arasteh Khouy, & Ahmadi, 2016) will be examined with regard to their implementation possibilities for describing the turnout behaviour and the existing data sources will be compared. However, the basic prerequisite for the final selection of the fundamental data is the fact that the measurements are already available and that new measurement systems do not have to be implemented first.

The declared aim of this thesis is to use existing data sources for all analyses. The potential as well as the possibility to generate new information regarding turnouts from existing data without having to introduce new measuring systems shall be explored. For this reason, the current data situation for turnouts has to be analysed in detail.

3.2.1 Visual turnout inspection

The visual inspection should ensure that the turnouts are in a proper condition. To guarantee meaningful inspection results, it is essential to additionally consider the surrounding track during the inspection and to compare the results between the different professional divisions, especially between the track division and the control and safety technology division (Lay & Rensing, 2019). The current inspection method for turnouts at the Austrian Federal Railways provides fixed time intervals for execution. Depending on the daily load and the maximum speed, turnouts are divided into categories. Based on this classification, inspection intervals ranging from three to twelve months are assigned in a further step (Wilfling et al., 2020).

During a visual inspection, safety-critical limit values are checked, defined geometric characteristic values are measured, and the general system condition is subjectively assessed (Wilfling, 2017). On the one hand, this is a very cost-intensive and potentially dangerous process, since several employees have to carry out a condition assessment and various measurements directly at the turnout (Wilfling, 2018b). On the other hand, the mapping of the real behaviour of a turnout based on these parameters and the reproducibility of these data is considered critical (Wilfling, 2018a). Even the derivation of trends and the observation of the development over time does not allow for any clear conclusions about the behaviour or about maintenance activities that might be necessary (Wilfling et al., 2020).

3.2.2 Automated and machinery-based turnout inspection

In order to eliminate the negative aspect related to the reproducibility and objectivity of visual inspections, an automation would be possible. The technologies currently available have been examined with regard to their potential and their possibility for an automated turnout inspection (Wilfling, 2017). Innovative camera technologies (Bongenaar, 2012) and laser measurements are used to describe the rail profile and to evaluate rail wear (Zarembski et al., 2011). In principle, an automated inspection of turnouts, based on the inspection activities regulated by guidelines, would be possible with minor restrictions (Wilfling, 2017). The issue of reproducibility and the subjective description of the condition would thus disappear, but three circumstances still have to be considered from a technical point of view:

- On the one hand, full automation can currently only be achieved by combining different measurement systems (Wilfling et al., 2020). This requires both measurement vehicles and fixed installed measurement equipment. Only the combination of these two systems would enable an almost complete automation.
- On the other hand, the possibility of mapping the real behaviour by certain systems must be examined (Wilfling, 2017). To ensure this aspect, turnouts would have to be passed during inspection with the normal operating load as well as at normal operating speed. However, this is not fully guaranteed with the systems currently available, so although the automated turnout inspection has great potential, further development in this area is still necessary.
- The inspection vehicles would also have to be integrated into the railway safety concept, as otherwise employees would again be needed on site and thus in the danger zone of the track.

3.2.3 Track measurement car data for the description of turnouts

In order to overcome the disadvantages of the described methods for the inspection of turnouts and to find a data source which is able to reproduce the real behaviour in detail, the measurement data of the track measurement car are considered. These data are measured under load as well as during a passage at operating speed. However, the equipment of the measurement car has been developed to determine data for open track and not specifically for turnouts. Due to the various measuring systems, this is a very objective data source, which can be classified as reproducible in any case. However, in order to verify the actual suitability of this data with regard to the description of turnouts, the individual measurement systems as well as their measurement methods are described in detail in a first step. The main focus is placed again on the situation in Austria. However, the fact should not be neglected that the majority of all measurement runs take place in the straight line of a turnout, and therefore measurement data are only available for this section. A description of the branching line based on this data source is therefore impossible.

3.2.3.1 Train passage distribution for turnouts in Austria

In order to validate this fact, the distribution of train movements within turnouts is shown below. The focus is mainly on determining the percentage of trains running in the through direction and the percentage of trains running in the diverging direction. As mentioned above, almost exclusively measured data of the through direction are available. Whether this circumstance already represents a reason to reject the data of the measurement car as a base for further analyses shall be checked. For this purpose, an evaluation based on the loading data of about 7,550 turnouts in the OeBB rail network, without consideration of line classes or the installation situation, will be carried out. However, it can be assumed that these are mostly turnouts situated in line class a. The load data are from June 2019 and are divided into three subsets:

- total load at the front of the turnout (1)
- proportional load at the rear of the turnout - main line (2)
- proportional load at the rear of the turnout - branch line (3)

After data cleaning, filtering of implausible load values and elimination of empty data sets, the loading data of 4,042 turnouts could finally be analysed. Figure 13 shows the percentage load of the main line (2) in relation to the total load of the turnout (1). The main emphasis here is on high percentages, which means that a large proportion of turnouts in Austria are operated almost exclusively in the through direction.

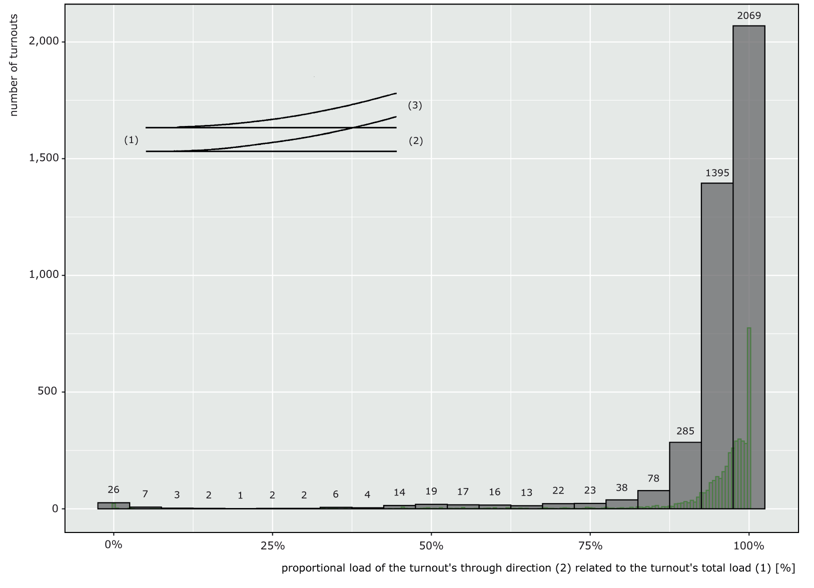

Figure 13 Proportional load of the turnout's through direction.

This fact therefore correlates very strongly with the load assumptions on which the standard elements are based (section 2.4.4). It can be summarised that exactly 3,827 of the 4,042 turnouts evaluated are used mainly (which means with more than 80% of the total load) in the through direction.

As a conclusion to this evaluation, it can be noted that, due to the high frequency of passages in the straight line, a significant wear must there be expected (always in comparison to the branching line). Therefore, the mentioned circumstance can be classified as uncritical with regard to the existing measurement data. The lack of measurement data from the branching line is not a deficiency for the overall assessment of the turnouts, although certain considerations, for example the condition description about the half set of switches, is not possible based on this data.

3.2.4 The standard track recording car EM250

This section was worded in close reference to (Hanreich et al., 2002; Hanreich, 2004). An efficient and objective evaluation of the track can only be carried out by a track measurement car. The EM250 is based on a standard RIC passenger train with four axles (Figure 14 - (Presle, 2000)).

Figure 14 Standard track recording car EM250 of the Austrian Federal Railways.

Magnetic brakes were eliminated in order to accommodate a measuring frame. The following measuring systems, among others, are attached to this measuring frame (labelled with number 1 in Figure 15 (Becker, 2013)):

- laser-based gauge measuring system OGMS
- laser- and camera-based systems for the rail profile measurement ORIAN
- gyroscope and acceleration measurement systems (inertial measuring unit IMU)

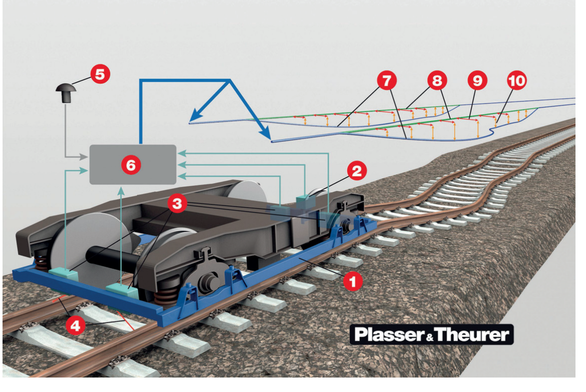

Figure 15 Working principle of the track geometry measuring system.

The measuring frame guarantees a constant parallel alignment of the sensors and the IMU (labelled with number 2 in Figure 15) according to the rail surface, so that the IMU can be used as a reference level for the track measurement.

3.2.4.1 Laser-based gauge measuring system OGMS

In this context OGMS is an abbreviation for optical gauge measurement system. The system used is based on the methodology of laser triangulation (Presle, 1994).

Consisting of a gauge measuring beam, two lasers, two scanning mirrors and two line scan cameras (Figure 16 (Presle, 2000)), the system is able to measure the gauge (Zaayman, 2013) via two gauge measuring points on each side of the track, 14 mm below the top of the rail.

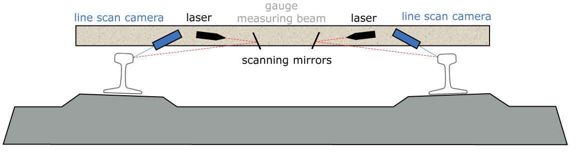

Figure 16 Working principle of the OGMS track gauge measuring system.

Measured values of the gauge are available every 25 cm. In the following, this sampling rate is specified in data breaks (DB), whereby a fixed distance of 25 cm always prevails between two data breaks. All measured values recorded by this measuring system are summarised within measurement channel group 1.

3.2.4.2 Laser- and camera-based systems for the rail profile measurement ORIAN

This system is based on four lasers (marked with number 3 in Figure 15), operating in the invisible wavelength range, which causes an array to be projected onto the rail. Using two cameras, an image is taken from each side of the rail, from the rail head to the rail foot, and analysed using real-time image processing. This arrangement makes it possible to measure all parameters of the rail profile, such as height, wear or rail inclination (Zaayman, 2013; Jovanovic & Zwanenburg, 2002). All measured values of this measuring system have a sampling rate of 2.5 m and are handled in measurement channel group 2.

3.2.4.3 Inertial measuring unit POS/TG

This measurement system is based on navigation systems from aviation and shipping (Mostafa et al., 2001). For this purpose, the existing track measuring system OGMS was combined with an inertial measuring unit (IMU), which works with gyroscopes. This measuring unit is also mounted on the measuring frame (marked with number 1 in Figure 15). The position of the track is calculated by a double integration of the translational and rotational accelerations, whereby a combination with the gauge measurement is necessary for this purpose (Oberlechner & Zywiel, 2001). In order to determine the track position geographically exactly, a combination with a differential Global Positioning System (dGPS) is realised. The alignment and longitudinal level measurements of this system are available every 25 cm, just like the track gauge measurements of the OGMS.

All measured values recorded by this measuring system are subsequently stored within measurement channel group 3. In contrast to the other measurement signals, the alignment and longitudinal level measurements are subdivided according to their available wavelength ranges. The signals with the suffix medium represent a wavelength range between 3 m and 25 m, also known as D_1 (Austrian Standards Institute, 2008). Before 2015, the signals with the suffix long represent a wavelength range between 1 and 70 m. After an adaptation in 2015, these signals include a wavelength range between 25 and 70 m. This wavelength range is also known as D_2 (Austrian Standards Institute, 2008).

3.2.4.4 Analogue measurement channels

In addition to the measuring systems mentioned, the vertical axle box accelerations are also measured. The corresponding sensors are attached directly to the axle boxes (Plasser & Theurer, 2010), the accelerations are measured analogously and stored digitally as weighted average values (RMS). Due to the fact that only an average value over a certain length is stored, as opposed to the raw signal of the measurement, these acceleration measurements have no significance for further analyses, even if a fundamentally high potential for acceleration analyses is assumed with regard to the condition description of turnouts.

3.2.4.5 Measuring accuracy

Above all, appropriate attention must be paid to repeatability or reproducibility. The reproducibility was verified within successive measurement runs and the standard deviation of individual measurement parameters was evaluated over the entire number of tests. Maximum values for the standard deviation of 0.5 mm prove that the determined measurement data of the track recording car are reproducible, even if the definition of a reference measurement run is necessary for data post-processing. The intended GPS-supported synchronisation of the location is a valuable tool for reliably assigning the track geometry and track measurement data to their locations (Oberlechner et al., 2001). Due to the used methodology, measurement data with a location assignment are available. These data also have the necessary accuracy to be used for the analysis of open track.

Due to the different measuring systems and the different measurement runs carried out under load and the guaranteed reproducibility of the measurements, the measured data of the EM250 track measurement car are used as base for all following considerations. With regard to the gauge measurements, these data are available back to the year 2001; all measured values from the IMU are available starting in 2005.

An almost gigantic amount of data is thus available for investigating the turnout behaviour. A summarised list of the measurement signals used for further application, including their sampling rate, availability and measuring channel group affiliation, is shown in Table 2.

measurement signal	measurement channel group	sampling rate	available
half gauge unfiltered*	1 – optical gauge measure	25 cm (1 DB)	since 2001
half gauge filtered*	1 – optical gauge measure	25 cm (1 DB)	since 2001
gauge unfiltered	1 – optical gauge measure	25 cm (1 DB)	since 2001
gauge	2 – optical profile measure	> 25 cm	till 2015
base gauge	2 – optical profile measure	> 25 cm	till 2015
cant*	2 – optical profile measure	> 25 cm	till 2015
gauge	2 – optical profile measure	100 cm (4 DB)	since 2015
base gauge	2 – optical profile measure	100 cm (4 DB)	since 2015
cant*	2 – optical profile measure	100 cm (4 DB)	since 2015
alignment medium (3-25 m)*	3 – inertial measure	25 cm (1 DB)	since 2015
alignment long (1-70 m)*	3 – inertial measure	25 cm (1 DB)	till 2015
alignment long (25-70 m)*	3 – inertial measure	25 cm (1 DB)	since 2015
profile medium (3-25 m)*	3 – inertial measure	25 cm (1 DB)	since 2015
profile long (1-70 m)*	3 – inertial measure	25 cm (1 DB)	till 2015
profile long (25-70 m)*	3 – inertial measure	25 cm (1 DB)	since 2015

Table 2 Measurement signals for further application.

The measurement signals marked with * in Table 2 are available for the right and left rail. However, turnouts require special properties with regard to the measurement data in terms of their short length and their variable stiffness in longitudinal direction. Subsequently, a description of the measurement signal suitability for turnout applications is given.

3.2.5 Necessary measurement signal characteristic for turnout analysis

As deduced in the previous section, the measurement signals of the EM250 are in principle suitable to provide the basic data for further turnout analyses. Due to the circumstances mentioned above, however, three further characteristics are necessary to enable the application of these measurement data for turnouts:

- First and foremost, the possibility to identify turnouts automatically in a measurement signal should be mentioned. In principle, the geographical position of a turnout is given within the track measurement data. If these two sources of information would match perfectly, an automatic identification of turnouts in measurement signals would not pose a problem. The reality, however, unfortunately looks a little different, and therefore other methods have to be found in order to identify turnouts in the measurement signal and to intersect this position with the real location of a turnout.

- If the position of a specific turnout is found in the measurement signal, this range must be transferred to all possible measurement signals of one measurement run. This procedure, however, requires synchronicity of all measurement signals within one measurement run. Again, theory differs from practice, as this requirement is not completely fulfilled in reality.
- Last but not least, the area of a turnout must not only be known within one measurement run, but rather for all existing measurement runs. In addition, time series analyses should provide information about the behaviour, which means that all measurement signals must be synchronous not only within one measurement run, but also within time-depending considerations. If this is not the case, time series analyses compare different points with each other and there is the risk of misinterpretations. Here again, it can be seen that the methods for positioning the measurement data mentioned in the previous chapter work well, but that these methods are not sufficient for the observation of turnouts.

3.3 Data processing methodology enabling turnout analyses

In order to be able to guarantee the three specifications mentioned, a structured methodology was developed which, on the one hand, checks the requirements and, on the other hand, makes appropriate corrections if these requirements are violated, in order to ensure the necessary measurement signal properties. Synchronicity between different measurement signals is not ensured by any displacement, but rather by systematic correlations.

3.3.1 Measurement signal-based turnout identification

In order to enable an automated identification of turnouts in measurement signals, it is necessary to search for specific characteristics which only occur in the area of turnouts. From this point of view, optical measurements are the best choice. The gauge itself is not a measured, but rather a calculated signal. As shown in Figure 16, the two half gauges are measured from the centre of the measuring frame to the right and to the left. However, with regard to the turnout identification, the unfiltered half gauges are relevant. Due to the optical conditions that prevail in the area of a common crossing, a clear characteristic (green deflection between position 1060 and 1080 in Figure 17) can be observed in the measurement signal of the rail on which the common crossing is located. On the opposite side, a characteristic curve of the half gauge measurement can also be seen (blue deflection between positions 1060 and 1080 in Figure 17). The reason for this measurement discontinuity is the check rail, which covers the actual rail, which is why an error value is issued.

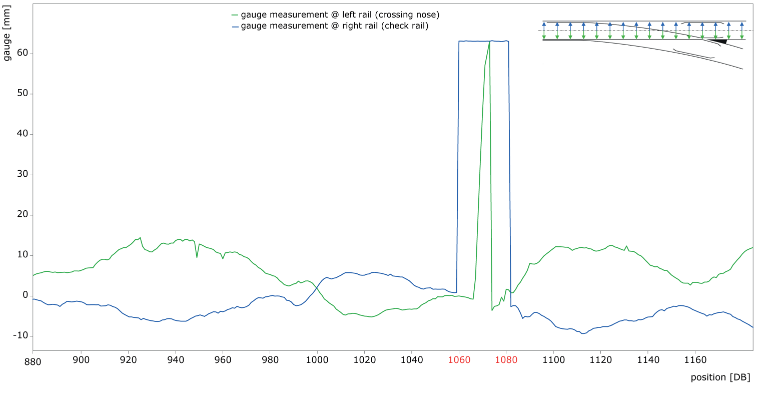

Figure 17 Half gauge measurement signals to identify a turnout.

By means of the location-conform identification of these two characteristics, a turnout can be identified perfectly within the unfiltered half gauge measurement. The direction of travel during the measurement can also be derived from the characteristic of the deflection on the side of the common crossing. If the turnout is passed through from the front of the turnout towards the rear of the turnout (facing move), the half gauge signal on the side of the common crossing initially shows a moderate increase up to a maximum value, followed by a very abrupt drop. If the turnout is travelled in the opposite direction, i.e. from the rear towards the front of the turnout (trailing move), an exactly mirrored characteristic can be seen, as shown in Figure 18.

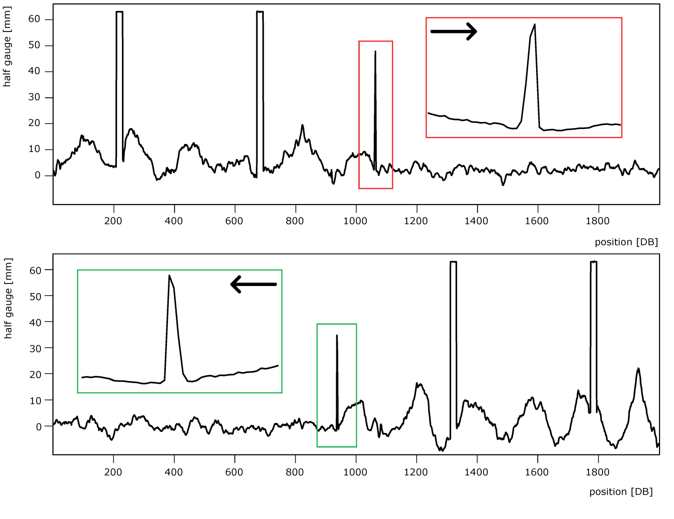

Figure 18 Half gauge signal at the common crossing for different travel directions.

This fact must also be taken into account for further considerations. In Austria, for example, the line between Gloggnitz and Vienna was changed from left-hand to right-hand traffic in 2012, meaning that the main traffic direction of each turnout located there changed at this time. With the knowledge of the signal characteristics, however, a time series can still be formed by mirroring the measurement signals of the gauge measurement, thus ensuring comparability. These findings were of course also implemented within the whole positioning algorithm which is presented later.

By additionally looking at the manufacturing design drawings of the turnouts, an exact link between the measurement signal and reality can be established. The distance between the beginning of the check rail and the first valid measuring point after the common crossing gap can be determined by the measurement signal-based observation of both unfiltered half gauge signals. If this distance is now transferred to the detailed geometrical drawing of the turnout, starting at the beginning of the check rail, the difference to the theoretical common crossing gap can be determined there. If this distance is transferred back into the measurement signals, the most exact possible point of the theoretical crossing nose is obtained. Starting from this point, all distances from the turnout drawing can be transferred into the measurement signals, which means that in the measurement signal of the half gauge, each point of the turnout can be clearly defined and thus identified.

3.3.2 Methodology for validating measurement signal synchronicity

The next step is to transfer the identified turnout area from the unfiltered half gauge measurements into all other existing measurement signals. This procedure, however, presupposes the synchronicity of all measurement signals, so initially it must be determined what synchronicity means and how this property can be verified.

3.3.2.1 Definition of synchronicity

Synchronicity with regard to measurement signals means that identical points must have an identical location. Since the railway is a system subject to wear, and this wear is also reflected in the measurement signals, validation of synchronicity is difficult. For this reason, the following different methods are compared.

3.3.2.2 Dynamic Time Warping DTW

Dynamic Time Warping refers to an algorithm mapping value sequences of different lengths to each other, whereby this methodology was originally developed for speech recognition. This method has also been applied to the observation of measurement data in the railway industry (P. Xu et al., 2015).

The problem with the DTW approach, however, is that the considered measurement data sets are also subjected to stretching / compression in order to ensure the best possible synchronicity. However, this is in contradiction to the measurement car, since a maximum length deviation of 1‰ (equivalent to a deviation of one meter at a measurement distance of one kilometre) is guaranteed for all measurements. This method is therefore out of consideration under the Austrian conditions for assessing synchronicity, since it is not the measure of synchronicity which is assessed, but the measurement signals are modified in such a way that the highest possible correlation prevails.

3.3.2.3 Cross correlation function CCF

Another approach deals with the implementation of the cross-correlation function to assess synchronicity. This methodology has also been applied in the context of track geometry measurements, even with a special focus on turnouts (Hovad et al., 2019). It is a comprehensible and reasonable approach to assess synchronicity by means of correlation calculation, and the suitability of this methodology has been proven beyond doubt (Hovad et al., 2019). However, the following difficulties are apparent when applying this method in the Austrian context:

- Due to the present software implementation of the cross correlation, both data sets must have an identical length.
- Furthermore, both data records must have a length that corresponds to a power of two, otherwise the data records will be filled with zero entries.
- The direction of the necessary displacement can only be determined in a second calculation step, requiring considerably more computing time.

Since the software-technical boundary conditions are specified by the cooperation with the Austrian Federal Railways, a further possibility to assess the synchronicity of two measurement signals has to be found.

3.3.2.4 Euclidean distance function EDF

An obvious methodology is the more detailed consideration of the Euclidean distance to evaluate synchronicity. If the existence of a minimum distance between two measurement signals is defined as a necessary criterion for synchronicity, this can be assessed by means of an Euclidean distance function EDF (Figure 19 (b)). The Euclidean distance $d_{P_1|P_2}$ between two points P_1 and P_2 (Figure 19 (a)), with the coordinates x_1 and x_2 respectively y_1 and y_2, is generally defined as the distance measurable in two-dimensional space, which can be calculated using Formula 4.

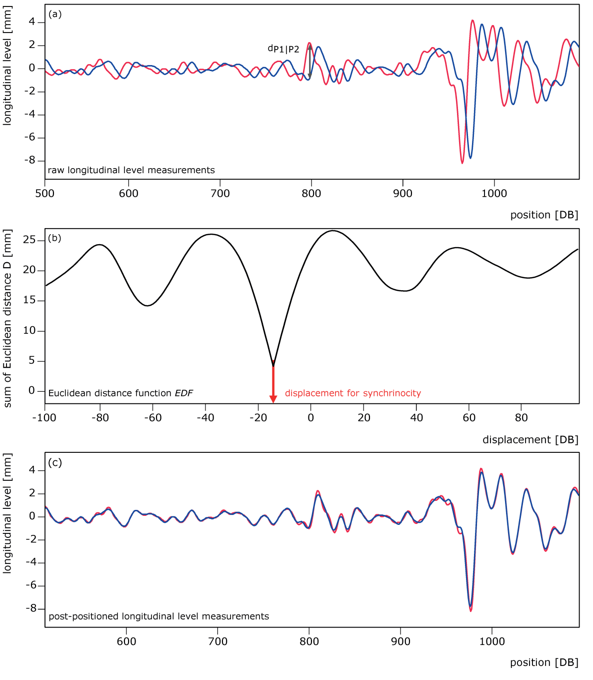

Figure 19 Principle of synchronicity validation using the EDF.

$$d_{P_1|P_2} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{4}$$

The difference of the squared x-coordinates is not relevant with respect to the synchronicity validation for the calculation of the distance, since this term has to be provided as a result by calculation of the Euclidean distance function. The calculation of the Euclidean distance $D_{M_1|M_2}$ between two measurement signals M_1 and M_2 of length L can therefore be reduced to Formula 5.

$$D_{M_1|M_2} = \sqrt{\sum_{i=1}^{L} \left(y_{i|M_1} - y_{i|M_2}\right)^2} \tag{5}$$

If one measurement signal is now defined as locally fixed, and the position of the second measurement signal is varied, the Euclidean distance can be calculated for each new positioning. If the values calculated in this way are plotted over the respective displacement of the second measuring signal, the Euclidean distance function is obtained (Figure 19 (b)). By considering the x-coordinate of the minimum within this function the synchronicity can be assessed as follows:

- If the minimum of the distance function EDF is located at x = 0, a shift of 0 data breaks is necessary to obtain synchronous measuring signals. The two signals under consideration are therefore already synchronous.
- If this is not the case, the x-coordinate of the minimum is exactly the value by which the second measurement signal must be shifted to be synchronous with the first measurement signal. Due to the signed calculation, the direction of the necessary shift is also clearly defined, making this method ideally suited for implementation within algorithms.

The result, i.e. the post-stationed measurement signals, which are synchronous according to the specified definition, can be seen in Figure 19 (c). The above-mentioned method can be used regardless of the type of measurement signal, and the described methodology is thus applied to all synchronicity considerations within this thesis.

3.3.3 Validating the synchronicity within one measurement run

Below, the application of the mentioned methodology for all relevant measurement signals (Table 2) within one measurement run is shown. However, the methodology itself is no longer in focus, but rather the underlying measurement relationships of individual signals.

3.3.3.1 Validation of synchronicity within measurement channel group 1

As already shown in Table 2, all signals delivered by the OGMS are summarised within measurement channel group 1, whereby the initial signal, the unfiltered half gauge measurement, is defined as the starting point or reference measurement signal due to its characteristic and in context to the possibility of identifying turnouts. The turnout area identified in this signal shall now be transferred to all measurements of this measurement channel group, and therefore synchronicity between the individual signals must exist.

The synchronicity between the unfiltered and filtered half gauge signals, on the side of the common crossing as well as on the side of the check rail, can be verified quite effectively. Since the difference between these two signals is only the filtering of incorrect measured values (in the area of the common crossing and in the area of the check rail), the synchronicity can be assessed by calculating the EDF. The situation is shown graphically in Figure 20. For all considered turnouts and measurement runs, a constant offset of 1 DB between the unfiltered and filtered half gauge measurements could be determined and automatically applied to all these measurement signals, so that synchronicity is ensured.

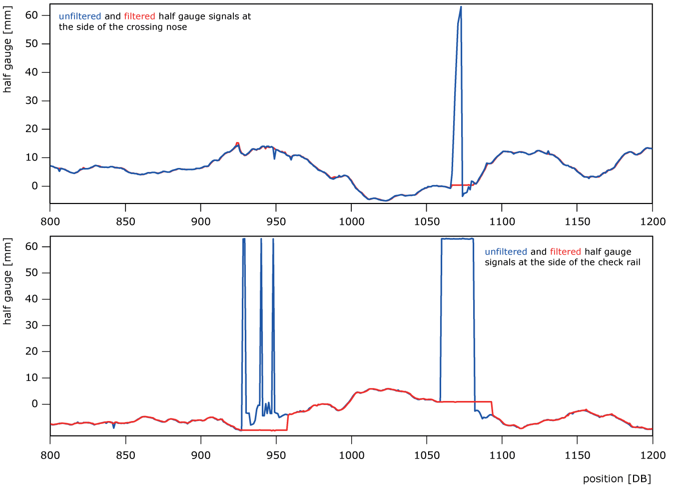

Figure 20 Synchronicity between unfiltered and filtered half gauge signals.

The next step is to check the synchronicity between the two filtered half gauge measurements and the (full) gauge signal. Since the synchronicity cannot be assessed without further investigation, the gauge is calculated by combining the two half gauge measurements. In turn, this calculated signal can be compared with the actual measured gauge and the Euclidean distance between the two signals can be calculated. It can be seen for all turnouts that the filtered half gauge signals are synchronous with the measurement of the gauge, allowing the identified turnout range to be applied to each measurement signal of this measurement channel group. Thus the processing of all measurement signals in the first measurement channel group is completed.

The signals of measurement channel group 2 are also optical ones. Due to the measuring principle (section 3.2.4), a gauge measurement is also present within this group, making it very easy to validate the synchronicity between measurement channel group 1 and 2.

Synchronicity between the first two measuring channel groups could be determined for almost no turnouts and almost no measurement runs. The identified displacements are visualised in Figure 21, the range of the occurring displacements extends between +11 DB and -19 DB. However, these displacements between the two gauge measurements of measurement channel group 1 and 2 are, at the same time, necessary displacements for establishing synchronicity. Therefore it is possible to apply the region of the turnout also to the gauge measurement of measurement channel group 2.

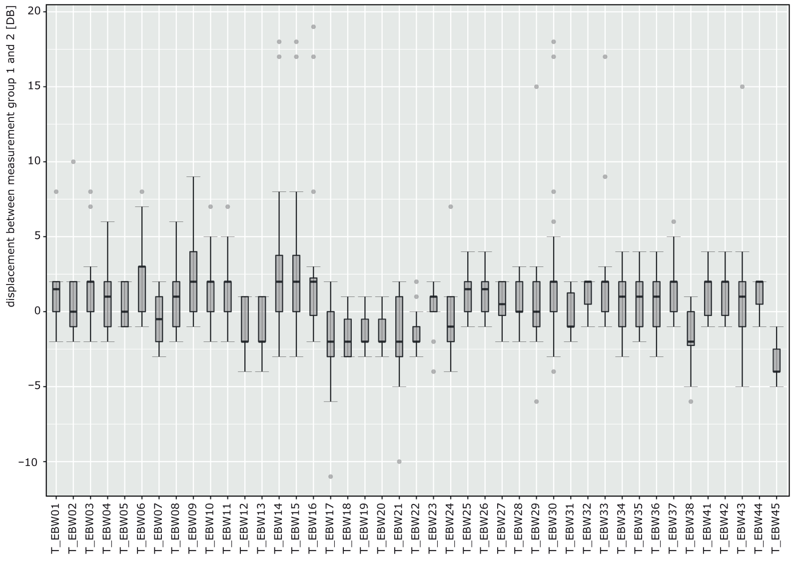

Figure 21 Identified displacements between measurement channel group 1 and 2.

3.3.3.2 Validation of synchronicity within measurement channel group 2

Subsequently, the synchronicity within the measurement channel group 2 has to be validated as well. After the turnout area has already been transferred to the gauge measurement within this group, the synchronicity between these gauge signals and the measurement of the base gauge is now considered. In theory, the gauge and the base gauge only differ in their amplitudes, but the characteristic must be approximately identical (Figure 22). In this case, the calculation and application of the EDF is also very well suited to identifying displacements. No displacement between these two measurement signals could be determined for any turnout, which is why the synchronicity can be confirmed. Further, it is possible to transfer the turnout range also to the base gauge measurements.

After the base gauge measurement, only the rail cant measurements of the right and left rails are left within the measuring channel group 2. Further steps are necessary to validate their synchronicity. Based on the rail cant, converted from a measured angle towards a distance, the rail base gauge measurements as well as the top width, a gauge signal can be calculated (Figure 22). Using this signal it is possible to compare it with the measured one and to rate the synchronicity. This procedure does not show any necessary shifts between the calculated and the measured gauge signals. Therefore the synchronicity of the rail cant signals to all other signals of the measurement channel group 2 could be confirmed.

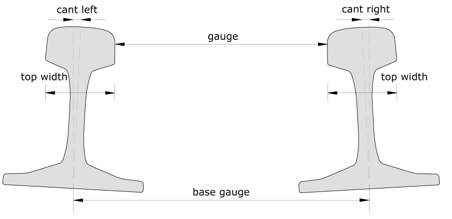

Figure 22 Different gauge measurement values.

In summary, it can be observed that no shifts between the individual signals could be identified even within the measurement channel group 2, and thus all signals in this group are synchronous. The determined turnout range can be transferred to all measuring signals of measurement channel group 2 (gauge, base gauge and cant), thus completing the processing of the signals of this group.

3.3.3.3 Validation of synchronicity within measurement channel group 3

To prevent systematic deviations, measurement channel group 1 is used as reference and the synchronicity with measurement channel group 3 is assessed. Due to the description of the IMU measuring method (section 3.2.4), it is known that there is a dependency between the filtered half gauge measurement (measurement channel group 1: red signal in Figure 23 (a)) and the alignment measurement medium (measurement channel group 3: blue signal in Figure 23 (a)). However, this is not directly visible within a comparison (Figure 23 (a)). After applying a bandpass filter (Butterworth fourth order with cut-off wavelengths of 5 m and 20 m) a similar characteristic can be observed (Figure 23 (b)).

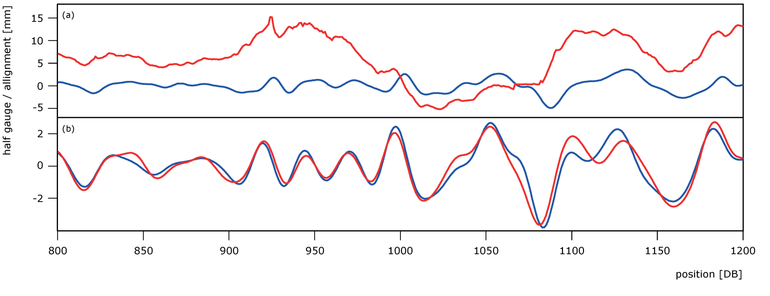

Figure 23 Relationship between half gauge and alignment measurements.

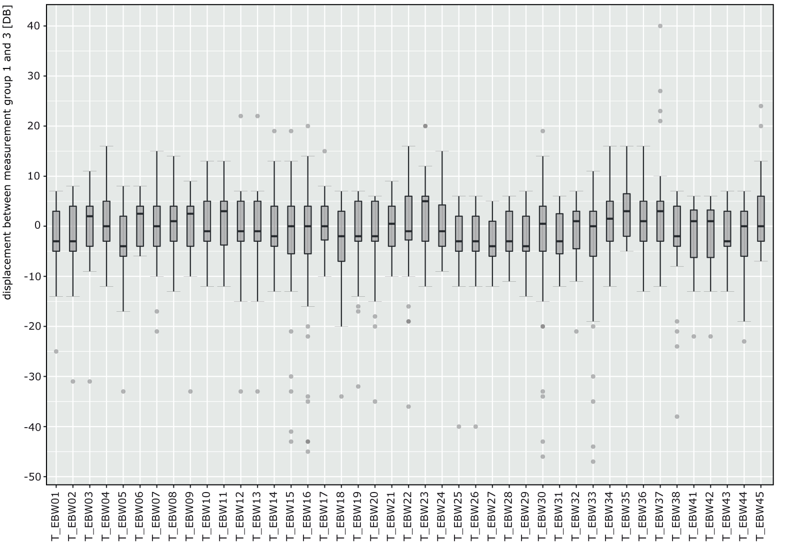

Figure 24 Identified displacements between measurement channel group 1 and 3.

Consequently, nothing prevents the calculation and application of the EDF. Between the two currently considered measurement channel groups there are necessary shifts for all processed turnouts. In other words, the measuring signals of the OGMS (measurement channel group 1) are not synchronous with the measurement signals of the IMU (measurement channel group 3). However, it was possible to calculate the necessary displacement (Figure 24), ensure synchronicity with the alignment medium measurements (wavelength range: 3-25 m) and thus transfer the turnout area to these measurement signals as well.

The synchronicity between the alignment measurements medium and long must also be examined more closely and, due to the change in the wavelength ranges, must be carried out in a time-differentiated manner. Prior to 2015, the synchronicity between the two alignment signals can again be assessed using a wavelength filter in which both signals are reduced to identical wavelength ranges. This procedure showed synchronicity between the alignment measurements medium and long. After 2015, it is not possible to assess the synchronicity due to the change in the wavelength ranges, since there are no longer any overlapping ranges between the medium and long signals. For this reason, synchronicity must be assumed for the time and verified later. However, this preliminary assumption is quite justified, based on the results of the observations made before 2015, since synchronicity was shown during this observation period. Therefore, nothing prevents a transfer of the turnout area to the alignment long measurements.

The next step is the combined consideration of alignment and longitudinal level measurements (wavelength range D_1). Since the alignment refers to the y-direction, and the longitudinal level measurements to the z-direction of the track coordinate system (Austrian Standards Institute, 2008), it is impossible to find a dependency between the two signals. In the absence of alternatives, the first approach is to assume synchronicity between the alignment and the longitudinal level measurements. The verification of this assumption can, only be confirmed or refuted by time series observations.

All determined displacements up to now are based on a systematic scheme, according to the different measurement systems. At the end of the post-processing, all measurement signals must be synchronous even within time series observations, which also makes it possible to verify the assumption made about the synchronicity between the alignment and the longitudinal level measurement. In this context it becomes apparent that the initial assumptions of synchronicity between the two measurement signals were not correct.

Depending on the position of the measurement car during the measurement run currently under consideration, an offset of +6 DB or -8 DB between alignment and longitudinal level measurements in the wavelength range D_1 could be determined. This can be explained by the fact that the reference point of the IMU does not coincide with the reference point of the measuring car, but the position of the measured data always refers to the reference point of the measuring car. After this systematic positioning error had been corrected, synchronicity could be determined within time series observations between the alignment and the longitudinal level measurements in the wavelength range between 3 m and 25 m. For this reason, it is also possible to transfer the identified area of the turnout to the longitudinal level measurements medium, even if some detours were necessary.

In the next step, the longitudinal level measurements medium D_1 and long D_2 (Austrian Standards Institute, 2008) are again considered together. As with the alignment measurements, the issue of no longer overlapping wavelength ranges is also present in relation to the longitudinal level signals. The procedure can therefore be understood analogously, and the results are also identical. Between the longitudinal level measurements medium and long, at least for the period before 2015 as well as for all considered turnouts, the synchronicity of the measurement signals could be determined, which is why this circumstance can be assumed also after 2015. Using the detours described above and retaining the original system and methodology, it is therefore possible to determine the turnout areas even within the medium and long longitudinal level measurements. This is one of the most important steps or results, since it is thus possible to identify a turnout in the longitudinal level signal unambiguously and reproducibly, which was previously only possible via estimations.

At this point the process of data preparation is terminated. Although there would be further measurement signals available to check for synchronicity, these signals are exclusively derivatives of the longitudinal level (superelevation, twist, cross level (Zaayman, 2013)). If the above-mentioned signals are required in further succession, they can be calculated from the post-processed and post-positioned measurement signals of the longitudinal level. Thus, all relevant measuring signals of one measurement run could be checked for their synchronicity, and necessary displacements for ensuring synchronicity could be determined. It is thus possible to transfer the area of a turnout, identified within the unfiltered half gauge measurement, to all possible measurement signals.

3.3.4 Validating the synchronicity of different measurement runs

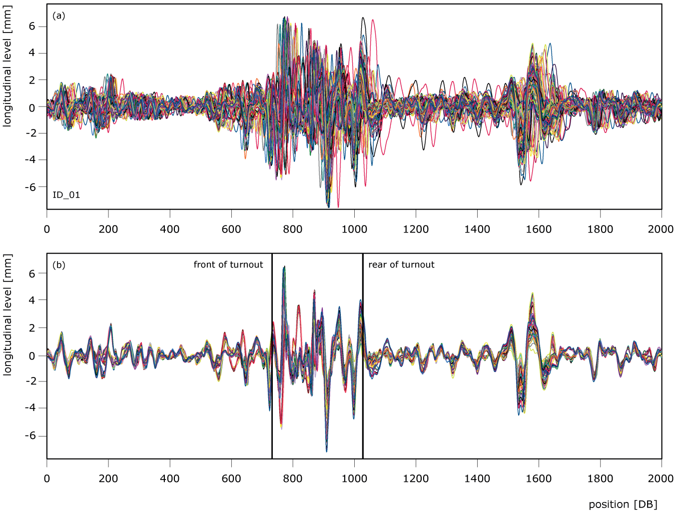

Figure 25 Longitudinal level signals before (a) and after (b) post-positioning.

The methodology described can be carried out for each measurement run. In order to complete the process or to ensure that the requirements for the measurement signals formulated in section 3.2.5 are fulfilled, additional analysis must be carried out between the individual measurement runs. For this purpose, the calculation of the EDF is used again. In this case, however, the input parameters are not the raw data of the different measurement signals, but the signals already post-positioned in time sequences. This step is thus a kind of validation, since the process is only completed when the synchronicity within time series observations can be proven for all measuring signals. A relevant visualisation of such data set is shown in Figure 25. The upper plot represents longitudinal level measurements over a length of 500 m (200 DB) of a turnout as raw signals.

The lower graph represents the identical data, but in edited and therefore synchronous form. In addition to the synchronicity, the different turnout areas (front of turnout, rear of turnout) can also be identified in the lower plot, which consequently provides the necessary measurement signal properties for describing turnouts, as mentioned in section 3.2.5.

3.3.5 Automated implementation of the post-positioning methodology

As could be shown in the previous section, the methodology for the validation of synchronism is always based on the calculation of the EDF. Due to the large number of measurement signals and measurement runs per turnout, the actual implementation is rather complex. For this reason, the entire methodology was automatically combined in the form of an algorithm, called CoMPAcT, which is an acronym for **Co**ndition **M**onitoring and **P**rediction **A**nalyti**c**s for **T**urnouts. This program code is available in different software packages, always in compliance with the requirements of the Austrian Federal Railways and contains some more sequences besides the mentioned methodology:

- A possibly necessary mirroring of the measuring signals in relation to the main traffic direction is carried out so that all turnouts can be represented identically, regardless of the passage direction or the geometrical installation situation.
- An identification of the travelled line within the turnout during the measurement is carried out; and, in case the branch line is passed, this measurement run is excluded from all further analyses due to comparability issues.
- Measurement runs or measurement signals with a necessary displacement of more than 100 m are also removed before further processing, meaning that invalid or implausible measurement data / measurement runs can be excluded.
- Likewise, there is no further consideration of measurement signals that show an error value in the area of the turnout, whereby these measurement signals / measurement runs are also automatically removed.
- As the last control sequence, all already positioned measuring signals are checked again for their synchronicity; and, as a result, a comparison of the determined deviations before and after the application is made (Figure 26).

In total, the algorithm consists of 59 independent sequences, which are linked together by a start sequence. The data import was also implemented in a separate sequence in order to keep the flexibility high. This sequence is currently designed to the requirements and specifications of the Austrian Federal Railways. This means that the naming of the individual measurement signals as well as the basic data structure is predefined.

For each measurement signal of each measurement run as well as for each turnout, a section of 500 m (2000 DB) is defined as input signal. The middle of the signal should approximately coincide with the beginning of the turnout under consideration. Due to the flexible structure of the algorithm, however, an adaptation to other data structures can be implemented easily.

The final validation as to whether the entire post-positioning process was completely successful, is necessary because the input data are always real measurement signals. Even if the fundamentals for the positioning algorithm have been determined very carefully and based on theoretical principles, the real measurement signal behaviour must always be taken into account. In some cases, circumstances occur which cannot be considered within automatically operating program code, so a final check is essential. For this purpose, the necessary shifts before and after the application of the positioning algorithm are summarised and presented on the one hand by boxplots and on the other hand in tabular form (Figure 26). With regard to the positioned signals, a maximum deviation between two measurement signals of (absolute) one DB must not be exceeded, otherwise an error message is generated.

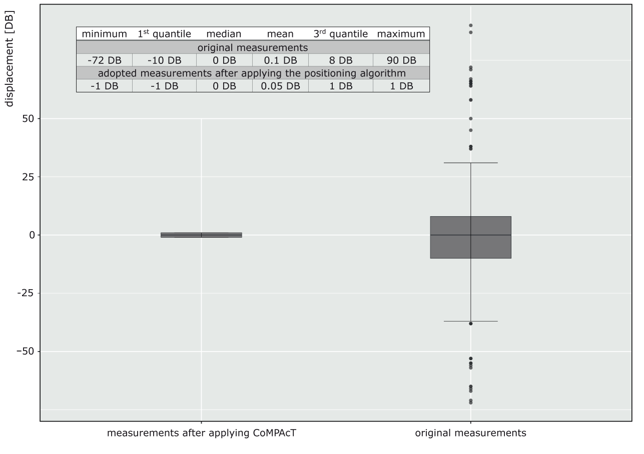

Figure 26 Example of a final control plot for post-positioned measurement signals.

3.3.6 Displacement matrices

In order to have to execute the complex and quite time-consuming process of data preparation only once per turnout (or, as can be shown later, ones per track section) and to create a platform-independent possibility for data processing, the determined displacements are summarised and stored in displacement matrices.

Within such a matrix the column designations refer to the measurement signals S_j. Each individual row represents a measurement run M_i, and the entries within the matrix correspond to the signed displacements $\Delta M_{i[S_{j-1};S_j]}$ necessary for synchronicity (Formula 6).

$$\begin{bmatrix} \Delta M_{1[S_1;S_2]} & \Delta M_{1[S_2;S_3]} & \Delta M_{1[S_3;S_4]} & \cdots & \cdots & \Delta M_{1[S_{j-1};S_j]} \\ \Delta M_{2[S_1;S_2]} & \Delta M_{2[S_2;S_3]} & \cdots & \cdots & \cdots & \vdots \\ \Delta M_{3[S_1;S_2]} & \cdots & \Delta M_{3[S_3;S_4]} & \cdots & \cdots & \vdots \\ \Delta M_{i[S_1;S_2]} & \cdots & \cdots & \cdots & \cdots & \Delta M_{i[S_{j-1};S_j]} \end{bmatrix} \tag{6}$$

Thus it is achieved that a repositioning of the measurement signals can only be performed by loading the displacement matrices, even without knowledge of the exact methodology. As a result, a uniform starting point for further turnout analyses is created, regardless of whether identical software solutions are used or not. This concludes the entire topic of data processing in relation to turnouts; and, therefore, a short excursus takes place on applications of the methodology which go beyond the sole consideration of turnouts.

3.4 Further application of the developed methodology

The algorithm CoMPAcT and the basic methodology described above addresses a general problem of many infrastructure managers. With regard to the measurement data of the track measurement car, there is the need to provide a database with synchronous measurement data as a starting point for all analyses. The existing data base, i.e. the quality of the input data for the developed positioning algorithm, is completely sufficient for analyses of open track, which are partly based on influence lengths of 100 m and more. However, it must be assumed, but cannot be proven at this point, that the possibility of a detailed examination of measurement signals could also lead to more detailed statements about the behaviour or necessary maintenance tasks, also for open track. For this reason, two applications are presented below which, although they have nothing in common with the analysis of turnouts in the narrower sense, do offer a possibility of examining the developed algorithm and showing the different areas of application in this context.

3.4.1 TwinPEAKs - synchronisation of two digital twins

The evaluations presented below were prepared within a project called TwinPEAKs, a research project commissioned by OeBB Infrastruktur AG and voestalpine Railway Systems GmbH. The starting point for the project was the assumption, based on physical simulations, that individual defects in the track's longitudinal level change their x-position in the course of deterioration.

This innovative finding contrasts with many measurement data positioning methods which have been considered correct up to now (namely exactly those that position measurement data in the form of a peak-to-peak shift). This fact has to be validated using real track geometry data. Of course, the original positioning quality of the track measurement car data is not sufficient for this purpose, hence the data of ten single failures were initially processed by the developed positioning algorithm, and only these data were used for further simulations. Figure 27 shows an example of the descriptive analyses based on the CoMPAcT algorithm. The upper graph (a) visualises the input data, in the middle (b) the underlying post-positioned data are shown, and the lower measurement signal curve (c) describes a small subrange of the measurement data, which is investigated in more detail.

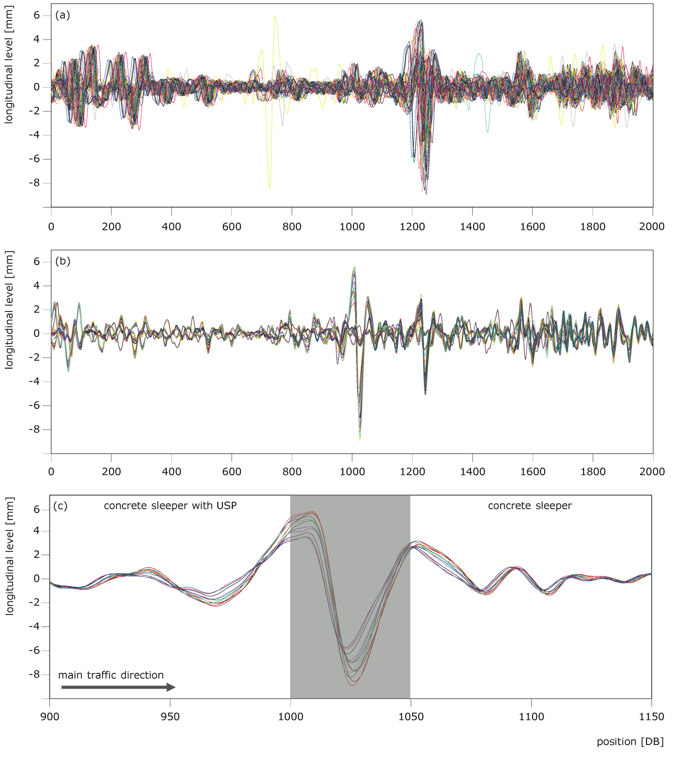

Figure 27 Example analyses to show the migration of a single failure - TwinPEAKs.

The single failure moves between position 1000 and 1050 in the main traffic direction and in the direction of a higher superstructure stiffness. In this context, no further details will be given on the individual analyses and the findings derived from them, as these are not directly related to the present work.

Rather, it should be emphasised that the applicability of the positioning methodology is not only limited to turnouts, but that it can also be useful for analyses about open track.

3.4.2 Measurement data positioning for longer track sections

Finally, a presentation of an investigation on the possible application of the positioning algorithm with regard to longer track sections is given. Up to now, 500 m sections of measurement data have always been treated as input data. In order to demonstrate the full potential of the post-positioning methodology, measurement signals with a length of about 8 km were used instead of the usual input data and the entire process was carried out without further adjustments. As a criterion for verifying whether an application is also possible on significantly longer track sections, the synchronicity was calculated within the post-stationed longitudinal level measurements D_1, and thus the necessary displacements were determined. The window required for this purpose was shifted by its position sliding over the length of the input data, thus describing the synchronicity depending on the length and the position of the input data. The result is thus a kind of characteristic curve, which shows the necessary displacement at each point of the input data set depending on the current position (Figure 28). If this displacement is constant over the entire length and ideally equal to zero, there is no reason why the methodology could not be applied to longer sections. Otherwise, additional precautions must be taken.

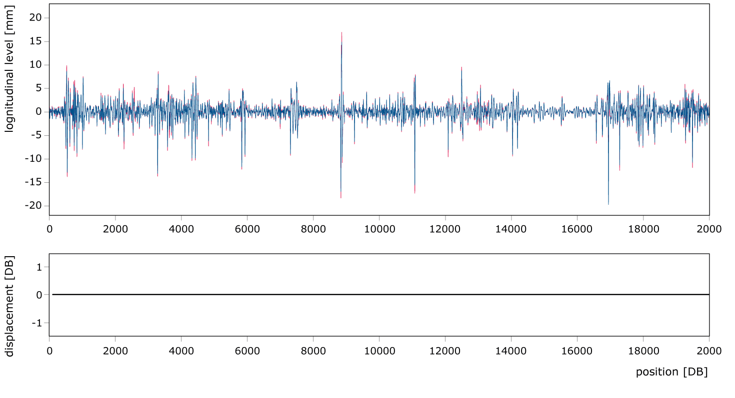

Figure 28 Validation of the post-positioning method for long track sections.

It could be shown in this context that a constant necessary displacement of 0 DB results for a large part of the considered measurement runs over the distance of the input data of about 8 km, which makes it possible to confirm the possibility of application to longer track sections. From time to time, however, measurement signals appeared which, in relation to the position, showed different necessary displacements in a range between 0 and 2 DB.

This fact is not very worrying, because a length fidelity of 1‰ is guaranteed by the measurement car in relation to the real length of the track, and this value is therefore observed. However, the basic suitability of the positioning methodology for measurement data of longer track sections can be confirmed.

In summary, the two use cases were able to demonstrate the application of the positioning methodology in relation to different issues and validate its possibilities. It has been shown that the algorithm is in principle capable of being applied to other problems. With regard to the turnout analysis, this can again be seen as confirmation for the optimal and correct implementation of the researched correlations. Actually, there is no reason why CoMPAcT should not be applied for all measurement data records in order to increase precision.

3.5 Conclusion

At the beginning, the restrictions necessary for the further purposes of this work with regard to the number of turnouts under consideration were formulated.

In order to identify the most suitable data source to analyse the turnout's behaviour, a comparison of some currently available data sources was carried out. The data of the visual inspection were not considered further due to their none reproducibility and subjectivity. The data of an automated turnout inspection were found to have great potential, but these data are currently not fully available. Finally, the data of the track recording car were determined as the base which is best suited allowing for a description of turnouts. However, the actual suitability had to be validated more intensively.

In order to understand how individual measurement data are determined or how the measurement car is constructed in principle and which dependencies exist, the individual measurement systems were described, and the principle resilience of the measurement data was explained. Based on the findings – or rather on the fact – that a turnout cannot be clearly identified based on the position of the measurement signals, a methodology had to be developed which enables the identification, within all measurement signals.

In a first step, the position of the turnout in the measurement signal of the half gauge was identified, and the theoretical crossing nose in the measurement signal was determined. Subsequently, the turnout area was transferred to all other measurement signals. In order to realise this, synchronicity between the various measurement signals must be available, so this requirement was checked in advance. For this purpose, a comparison of suitable methods was carried out, whereby the choice was finally made for the refraction of the Euclidean distance. This method was implemented to verify the synchronicity.

According to the definition of the methodology, all measurement signals within a measurement channel group were first examined, and afterwards the analysis of different measurement runs took place. For this purpose, the synchronicity was always assessed first. If the measurement signals are synchronous, there is no need for action, otherwise the measurement signals are shifted accordingly. The findings can be summarised:

- Applying a constant shift of one DB to all half gauge and to all gauge signals, the synchronicity within the first measurement channel group can be confirmed.
- The synchronicity between the measurement channel group 1 and 2 could not be confirmed in any case. The shifts are in a range between +11 DB and -19 DB.
- In measurement channel group 2, synchronicity could be confirmed for all signals.
- Again, synchronicity could almost not be detected between the measurement signals within measurement channel group 1 and 3. Depending on the considered turnout as well as the accrual measurement run, these displacements are situated in a range between +40 DB and -47 DB.
- Within the third measurement channel group, a systematic error between the alignment and the longitudinal level measurements was identified, and a method was subsequently developed to eliminate it. After this step, all signals within measurement channel group 3 were synchronous.

The fact that the areas of application are not limited to turnouts was shown by an excursus focusing on two implemented projects. The focus was on the description of the growth of single failures, on the one hand, and the possible application for post-positioning of measurement data over a longer distance, on the other.

The final point is a reflection on the formulated research questions (section 2.5). The first question dealt with the topic of the necessary data and was stated in detail:

Research question 1

How can individual turnout data sources be linked? Which information is indispensable and therefore to be treated with priority?

Answer to research question 1 – part 1

Very briefly and in a very simplified way, the whole research question could be answered with the demand for a "digital turnout file". In order to generate a more precise statement, the question must be divided into two areas. With regard to the second part, a wide variety of information and also sources of information were used in the context of this chapter.

Answer to research question 1 – part 2

The most relevant data are, on the one hand, the measurements from the track recording car, the superstructure data of the turnouts, the information about the load situation as well as the geographical information. Although these are only the most fundamental ones, this list does not claim to be exhaustive. New analysis methods make new data necessary, so the possibility of integrating new data sources must in any case be provided. On the other hand, all information on maintenance activities already performed is necessary, i.e. a kind of "medical record". Only if there is complete information about the wear and tear which has occurred over time, about the maintenance activities that have become necessary, and about the current component condition, statements can then be made with regard to the life cycle. A substantiation of this statement is presented in chapter 6. Thus, the first part of the research question presented can also be answered. It is not so much about the technology as about the methodology of the link. As the present chapter has illustrated, turnouts are almost point-shaped infrastructure objects if viewed in a wider context. The data linking should always be based on geographical information. Since a methodology has been developed which allows for the identification of individual components of a turnout in various measurement signals, it is also possible to link these with the position data of the turnout. By means of a unique identifier it is also possible to bind the "medical record" permanently to this object, whereby a comfortable possibility must be created to enable access for authorised persons. The "digital turnout file" can only work if it is quickly retrievable, clearly structured and above all up-to-date and complete.

Research question 2

Is it possible to adapt or process the existing measurement data of the track recording car in order to extract information for turnouts? What would a possibly necessary reworking process look like?

Answer to research question 2

Whether additional information for turnouts can be extracted from the processed measurement data or by combining various data sources will only be revealed in chapter 4 and chapter 5. The nature of a possible post-positioning process was clarified in detail in this chapter. Using measurement data intended for open track, the position of a turnout was identified, the measurement signal synchronicity was ensured, and the data was processed / stored in an appropriate form. It can be summarised that, in order to be able to derive accurate statements about the turnout condition in the following chapters, the existing data was prepared in the best possible way.

4 INVESTIGATION ABOUT GEOMETRICAL PROPERTIES OF TURNOUTS

The following chapter contains methods, results and text passages, some of which have already been published (Fellinger et al., 2019; Fellinger, Neuhold, & Marschnig, 2020; Fellinger, Wilfling, & Marschnig, 2020a, 2020b). Text passages of the same wording are appropriately marked.

When a train passes over a turnout, enormous forces are exerted. Especially in the area of the switch panel when driving along the branching line or when passing the common crossing. Depending on the speed of the train, partly very high dynamic forces occur (Ossberger et al., 2019). The fact that the stiffness of a turnout changes in longitudinal direction, due to constructive conditions such as differently long sleepers or differently designed fastening points, has a reinforcing effect (Loy, 2006). Especially the discontinuous stiffness in the common crossing area and the abruptly changing stiffness at the transition from long to short sleepers or vice versa have a particularly negative effect on the forces introduced into the superstructure. A higher or faster change of the geometrical parameters can be a result. The entire superstructure, essentially consisting of rails, sleepers and the ballast, is an elastic system which can deform and, due to its elastic properties, strives to return to its original state (Lieberenz & Wegener, 2009). A large part of the elasticity comes from the ballast itself. Additional elastic elements such as rail pads, under sleeper pads or under ballast mats reinforce the elastic behaviour or give the superstructure the necessary elasticity. Additionally, a significant reduction of vibrations can also be achieved by using under sleeper pads (Loy et al., 2019).

Ultimately, a high load introduced by trains leads to a deterioration of the track geometry. This can conduct to anomalies, causing the track to deviate more continuously from its ideal geometry, which can no longer be guaranteed. To avoid such a situation or to reverse the process, the superstructure must be maintained at regular intervals. Tamping is the most common maintenance task in the track and for turnouts (Zauner et al., 2019). By lifting and straightening, the original geometrical position is restored as far as possible, thus increasing the ride comfort to a condition close to the original level and thus also ensuring the proper functioning of the railway superstructure. The fact that tamping is a technologically very complex operation is examined in more detail below.

4.1 The process of tamping

The principle process of individual sleeper tamping is visualised in Figure 29 (Katore et al., 2018). In a first step (Figure 29 (a)), the tamping machine or tamping unit must be positioned centrally above the sleeper to be tamped, with the tamping tines surrounding this sleeper on both sides. The lifting and straightening unit works in connection with a measuring system and picks up the rail, lifts the entire track into the predetermined position and corrects the vertical and horizontal position. This step (Figure 29 (b)) is summarised under the term levelling. Once the nominal position of the track is fixed, the tamping units are lowered. The vibrating picks dip into the ballast and stop at a predetermined depth (Figure 29 (c)). The tamping tines vibrate to ensure that the ballast stones are rearranged. The controlled vibration greatly reduces the force required to insert the picks into the ballast. In the last step (Figure 29 (d)) the tamping tines compact the ballast below the sleeper, in the space created by the lifting process. The tamping machine then moves forward, and the process is repeated. Behind the tamping machine, the track is in the required geometrical condition (Katore et al., 2018).

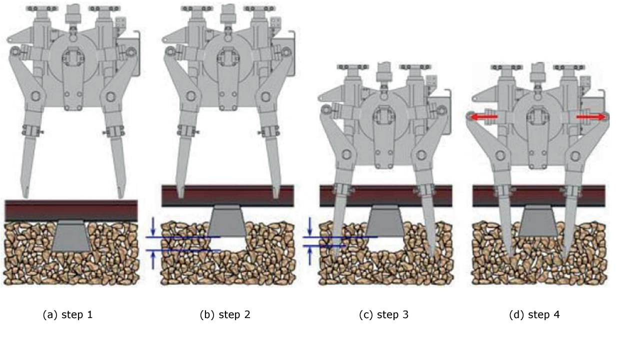

Figure 29 Basic tamping process.

The tamping of turnouts poses technologically very high requirements both on the machine and on the operating staff. For this reason, assistance systems have been developed which, especially with regard to turnouts, facilitate the tamping process and meet the high quality requirements (Auer et al., 2018). Due to economic demands, the tamping units used have been further developed. While in the early days it was standard practice to tamp only the ballast below one sleeper in a single operation, nowadays it is possible to tamp up to four sleepers simultaneously (Auer & Wenty, 2017).

After explaining why a turnout, in relation to its geometric position, deteriorates over time and showing possibilities of how and by which maintenance activity this deterioration can be compensated, the next section deals in more detail with the possibilities of describing the current geometric conditions within turnouts.

4.2 Geometrical description of turnouts

In order to be able to assess the geometric conditions within turnouts, characteristic values or quality values are necessary, whereby the reference to the already processed measurement signals should not be lost. In order to calculate such a quality signal and thus to be able to evaluate the necessity of a tamping task, the calculation of the standard deviation of the longitudinal level has been established with regard to open track (Arasteh et al., 2012; Vikesland, 2019). This statistical parameter describes the variation of the values around their mean and thus serves as an indicator for irregularities of the longitudinal level signal or as a representative value for the classification of ride comfort (Luber, 2011). This quality value is also used to validate the necessity of a tamping action (Arasteh, 2013). With regard to open track, the basic calculation methodology still needs to be considered.

According to the valid guideline (Austrian Standards Institute, 2008), the standard deviation of the longitudinal level is calculated in the wavelength range D_1 with an influence length of 200 m. For maintenance decisions, the local information of track position deviations which need to be corrected is of importance. Due to the proposed window width of 200 m, however, a large local fuzziness in the results can be detected. If the window width is reduced, the level of detail with regard to the location of irregularities increases. Thus, comparability of standard deviations require the same evaluation length (Luber, 2011). The circumstance of the comparability of the standard deviation with different lengths of influence is also of importance with regard to turnouts, which is why this topic is dealt with in detail in section 4.4.1.

Various attempts to describe the geometrical situation using individual characteristic values were made for turnouts. Initial approaches were based on calculating the maximum settlement and the difference in longitudinal level signals between two measurement runs (Khouy et al., 2014). For this purpose the common crossing gap was determined within the longitudinal level measurements in order to identify the position of the turnout. By observing the difference area between two measurement runs, the settlements in the area of the crossing nose can be concluded as a function of the cumulative load. However, this is always a relative consideration, and for this reason another method based on nine geometric parameters in the area of the common crossing was introduced. Based on this method, various statements about the settlements in this section could be made, however, this method was not developed for the analysis of the geometrical behaviour of the entire turnout (Khouy et al., 2014). By filtering longitudinal level measurement signals, the identification of the turnout area could be realised in a further investigation. Based on the standard deviation of this measurement signal, it was possible to compare different turnouts and to derive conclusions from this (Nissen et al., 2010). Thus, the standard deviation of the longitudinal level was again confirmed to be able to generate statements about the geometric conditions in turnouts.

On the one hand, these findings meant that the standard deviation of the longitudinal level could be used to assess the geometric conditions and that this method appears to be very well suited (Fellinger, Wilfling, & Marschnig, 2020a). However, the underlying data must relate exclusively to the area of the turnout, so a calculation with the aid of a sliding window for turnouts is not considered to be appropriate. The fundamental data of the longitudinal level measurements are thus eliminated in front of the turnout as well as behind the turnout, before the actual calculation of the standard deviation is applied.

4.3 Characterisation of geometric changes over time

As described in detail, in the following the standard deviation of the longitudinal level in the wavelength range D_1 is used to consider the change with respect to the geometrical conditions of turnouts. The question whether the measurement signal of the right or left rail is used (Nissen et al., 2010) does not arise in this context. In order not to overly depict specific characteristics caused by special areas within turnouts (such as the common crossing), an averaging between the measurement signals of the right and left rail takes place. Based on this signal, the standard deviation is calculated for further analysis.

The described aim of these investigations is to create a possibility for the prediction of tamping activities. Within this consideration it is assumed that the entire turnout is worked through. Therefore, the calculation of the standard deviation is also based on the longitudinal level measurement over the entire turnout area (from the front to the rear of the turnout - Figure 5). To decide whether the geometrical conditions require tamping, the entire turnout can be considered homogeneous. By this assumption it is naturally also believed that the turnout behaves constantly over the entire length, since otherwise a common consideration would not be arguable. Also, the different behaviour of the right and left rails is not considered in this context. The circumstances described will be examined in more detail in section 4.4.2 and are thus neglected for the time being.

4.3.1 Validation of different deterioration models

The geometric deterioration behaviour of tracks has been investigated in various studies. Most refer to longitudinal level measurements (Soleimanmeigouni & Ahmadi, 2016) or to a combination of different track measurement parameters. If focus is put on these models which are based on longitudinal level measurements, different methods for abstracting the deterioration process can be identified. The most common methods rely on linear or exponential modelling (Zwanenburg, 2007).

A linear model for the estimation of the standard deviation from longitudinal level measurements over time offers a very convenient possibility to obtain information about the geometric condition. Due to its simplicity, these models are also suitable for predictions (Wen et al., 2016). The standard deviation of the longitudinal level was used as base for the deterioration rate comparison of various railway infrastructure constructions such as bridges, turnouts or stations (A. Ramos Andrade & Teixeira, 2011). A linear modelling was applied; and, due to the simple derivation of a deterioration rate from the calculation of the linear regression, it was possible to compare the different types of structures. To investigate the effects of tamping on the deterioration of the track geometry, linear modelling about the relationship between the standard deviation of the longitudinal level and the time of measurement was also used (Audley & Andrews, 2013). The linear relationship allowed investigations about the quality achieved after tamping and conclusions for the British rail network to be drawn.

An exponential model (Elkhoury et al., 2018; Holzfeind et al., 2009) for describing the standard deviation of the longitudinal level over time, however, may be probably more physically correct, although more difficult to interpret. TwinPEAKs (section 3.4.1) probably shows that the deterioration of one point, based on the longitudinal level signal, may be exponential.

The deterioration modelling of track geometry is of great importance, especially with regard to the optimisation of tamping operations. By approximating the relationship between the deterioration rate and the time since the last tamping operation by means of an exponential model (Quiroga & Schnieder, 2010), an optimisation of the process for providing necessary tamping actions for a high-speed line in France could be realised. Even if the deterioration of quality values between two maintenance operations can be described linearly, the overall course of quality can be explained and abstracted very precisely by an exponential model (A. R. Andrade & Teixeira, 2015).

A direct comparison of an exponential and a linear deterioration model was made using the track geometry data from Austria (Neuhold et al., 2020). The study was again based on the longitudinal level measurements and calculated standard deviations. The linear modelling was given priority, not too much because of a higher quality of adaptation, but rather because of the easier handling and the clear derivability of a deterioration rate. The possibility of linear modelling was also confirmed for the entire OeBB rail network (Vidovic, 2016).

With regard to turnouts, only a limited number of investigations are known, which are based on different models for representing the temporal deterioration of track measurement car data. The standard deviation of the longitudinal level in the area of turnouts tends to be linear over time (Minbashi et al., 2017). However, more detailed investigations were not mentioned, as the study pursued a different purpose, and the calculated standard deviation of the longitudinal level or its progression was only necessary as a reference. A representation of the axle box accelerations during travel over a turnout shows a largely linear development over time (Kaewunruen, 2014), whereby these are not directly track measurement data and again the investigation of the process was not the actual aim of the study.

Since the presented literature for turnouts could not identify a clear model to describe the geometric change over time, more in-depth investigations are necessary. Therefore a comparison of the two most common models, a linear as well as an exponential one, is carried out. Nevertheless, the standard deviation of the longitudinal level is and remains the characteristic criterion for the description of the current geometric condition in turnouts.

4.3.2 Deterioration model comparison

Although the research carried out could not provide a clear deterioration model, it was possible to limit the possibilities to two methods. For this reason, a comparison of a linear and an exponential approach for abstracting the deterioration of the longitudinal level standard deviation over time is presented below. Longitudinal level measurements in the wavelength range D_1 between the front and the rear of the turnout are used as input. The formulation of the linear (Formula 7) and the exponential (Formula 8) model is given below.

$$SD_t = a + b \cdot t \tag{7}$$

$$SD_t = a \cdot e^{b \cdot t} \tag{8}$$

Figure 30 shows that there is almost no difference between the two models with regard to the accuracy of adjustment. To substantiate this statement, Figure 31 shows a comparison of the adjustments of the models to the real data, represented by the coefficient of determination R^2, for a large number of turnouts. This evaluation shows that there is almost no difference between the two models. Due to the easier handling as well as the possibility to directly derive a deterioration rate, the linear model will be used in the following to describe the deterioration of the standard deviation over time.

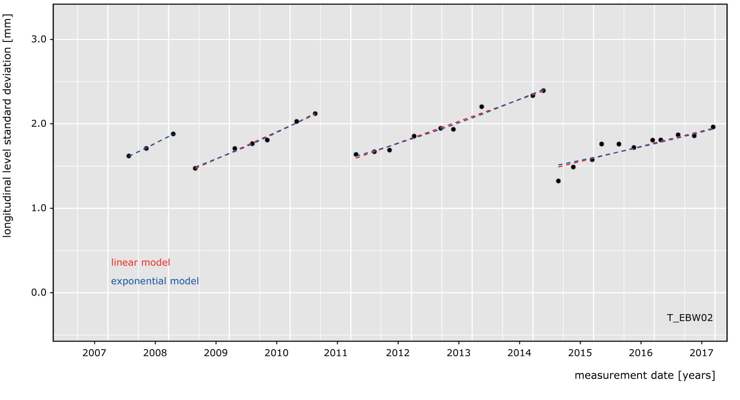

Figure 30 Linear and exponential standard deviation deterioration trend.

However, when looking at Figure 30, it is noticeable that the entire deterioration process can be reproduced by a piecewise sequence of linear deterioration chains. This means that the cause of the sudden improvements which is visible between the linear sections of deterioration must be found, or the effect which can be achieved must be investigated.

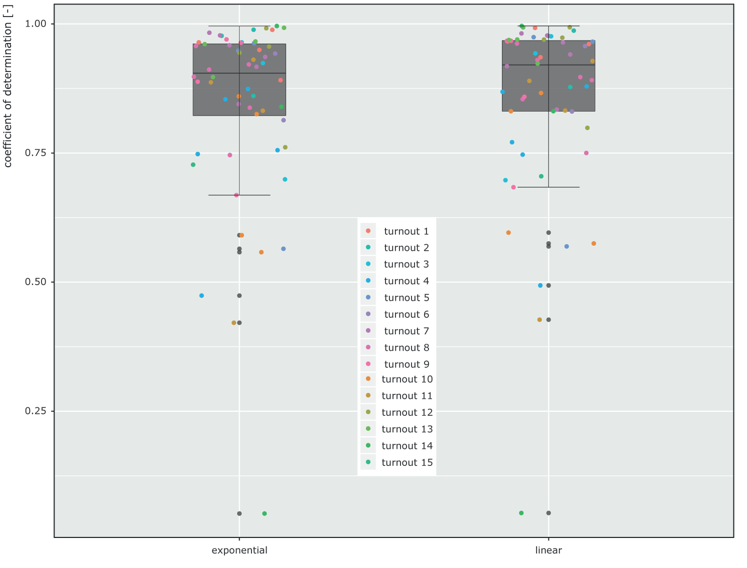

Figure 31 Comparison between linear and exponential deterioration model.

4.3.3 Considerations concerning the effect of tamping actions

An increase in the standard deviation of the longitudinal level occurs, as explained at the beginning of the chapter, due to wear. Conversely, an improvement of this statistical characteristic value can only be achieved by maintenance. With regard to the standard deviation of the longitudinal level, the decisive maintenance activity is undisputedly tamping. If historical data about dates of tamping operations for all turnouts were available, it would be easy to extract the effect of tamping from the standard deviation of the longitudinal level and to incorporate this knowledge into a prediction model. Unfortunately, the reality looks different. With regard to the Austrian boundary conditions it is not possible to generate information about all tamping operations of a turnout automatically. A necessary central data management system for this purpose is currently not available. With a great deal of effort, a large part of the tamping operations for twelve turnouts could be reconstructed through intensive research and discussions with regional managers. Therefore, developing a methodology which makes it possible to identify the dates of past tamping activities is inevitable. Only after this information is available, the actual research about the effect of turnout tamping can be continued.

4.3.4 Method to identify past tamping actions for turnouts

Since the large influence of turnout tamping on the standard deviation of the longitudinal level could already be shown, these data again constitute the base for all subsequent considerations. The developed methodology is based on the assumption that a turnout will show a similar behaviour in the future, which was already observable in the past. Hence, the linear continuation of time series from the standard deviation of the longitudinal level is used as primary criterion. A similar approach has already been used to predict tamping operations for open track and to develop methods for the optimisation of maintenance planning (Caetano & Teixeira, 2016).

For this purpose, the method developed here provides, starting with the first two measurement runs, a prediction of the standard deviation of the longitudinal level, which is determined and calculated during the following measurement run. If less than two measured values are available, no forecast can be calculated, and no prediction interval can be determined. However, this will be discussed in more detail later. This prediction is based on a linear trend extrapolation and is subsequently compared with the actual value. This predicted value thus corresponds to the expectation of the value of the standard deviation at the time of the next measurement run, based on the progress and magnitude of the past measurement run standard deviation. By means of a comparison between the predicted and the actually measured values, three cases can be distinguished (Figure 32):

- case A: The predicted and the actual value are almost identical
- case B: The predicted value is significantly lower than the actual value
- case C: The predicted value is significantly higher than the actual value

Case A is an ideal linear progression, which has no influence on the detection of past tamping actions. If this circumstance occurs, it can be concluded that no maintenance has been carried out, since the turnout behaves exactly as expected.

If case B occurs, this means that the standard deviation suddenly behaves significantly differently or that an abrupt increase can be seen, which could not be estimated from the previous data. Reasons for this can be a component failure as well as suddenly occurring, changed conditions. However, it can be excluded that a significant deterioration of the standard deviation occurs due to a tamping intervention. Therefore, it should be investigated separately by which influences such an increase of the deterioration occurs. For the objective consideration, these cases are not relevant and therefore they are not considered but implemented into the calculation process in course of the tamping task detection.

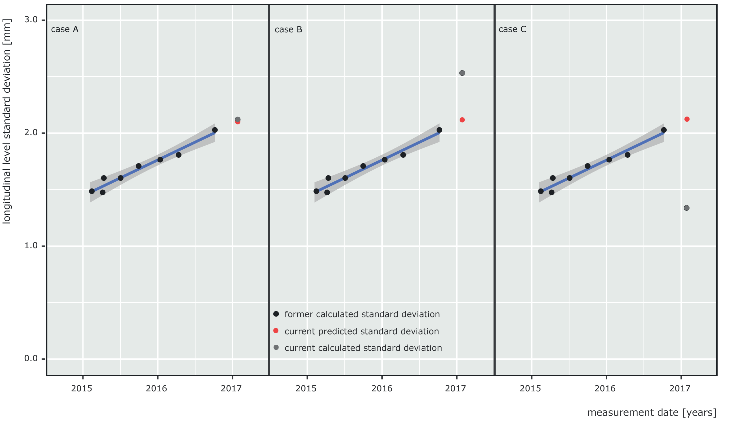

Figure 32 Case distinction to compare prediction and measured value.

Case C, in turn, means that the standard deviation has suddenly improved significantly against the trend from the past data. This circumstance can generally only be realised by a maintenance task, in the special case by a turnout tamping. But what does statistical significance mean? If maintenance would be recorded for all measurement runs where an improvement has taken place compared to the previous one, the number of tamping operations carried out would be clearly overestimated. Therefore, it is necessary to consider the scale of possible maintenance induced improvement as well as the potential deviation from a predicted value. At the end, it should be assumed with statistical certainty that a turnout tamping was carried out. Since the specification of an absolute improvement is not appropriate, a different methodology was developed.

4.3.4.1 Case discrimination based on a prediction interval PI

In addition to the standard deviation predicted from the past data, a prediction interval of the linear regression using Formula 9 is calculated.

$$Y_{U/L} = \hat{y} \pm t_{\frac{\alpha}{2};n-2} \cdot \sqrt{\hat{\sigma}^2 \cdot \left(1 + \frac{1}{n} + \frac{\left(x_{\hat{y}} - \bar{x}\right)^2}{SS_{XX}}\right)} \tag{9}$$

The parameter $t_{\frac{\alpha}{2};n-2}$ is a critical value of the t-distribution and can be taken from tables for $n-2$ degrees of freedom. $\hat{\sigma}^2$ stands for the standard error of the estimate and n for the number of observations. SS_{XX} describes the sum of the squares of the deviations of the data points from their sample mean and was implemented via Formula 10.

$$SS_{XX} = \sum_{i=1}^{n} {x_i}^2 - \frac{1}{n} \cdot \left(\sum_{i=1}^{n} x_i \right)^2 \qquad (10)$$

It is thus possible, based on a linear regression or a linear prediction, to calculate the upper and lower limits (Y_U and Y_L) within which, with a certain probability p, the predicted value will be located (Figure 33). A prediction interval is thus a kind of confidence interval which is used for predictions in regression analysis.

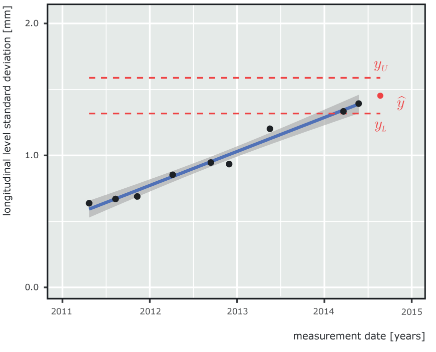

Figure 33 Case distinction to compare prediction and measured value.

If a value of the standard deviation is now predicted and additionally provided with the prediction interval, a verification whether a maintenance task has been carried out can be derived. The base is still the above-mentioned case distinction, the following considerations are only to be carried out if the real value of the standard deviation is significantly lower than the predicted one (case C). If the actual measured value is located within the prediction interval, which was calculated in the course of the prediction of just this measured value, it can be determined with a probability p, depending on how wide the prediction interval was chosen, that no maintenance was carried out. Therefore, a natural deterioration process occurs, which can be described by the data from the past. However, if the current measured value is situated outside (below) the prediction interval, this means that a significantly different behaviour can be expected from the past data and that maintenance has been carried out, otherwise this value could never have been reached. Of course, there is a probability of $1 - p$ that no maintenance was carried out despite the position outside of the prediction interval; for the present considerations this residual probability is accepted.

If a scenario is detected in which the measured and subsequently calculated value of the standard deviation is established outside and below the prediction interval, a tamping operation is automatically entered, the data series is clipped and the process is continued with a new start or repeated until the end of the data set is reached. By means of the implemented methodology, it is thus ensured that, based on statistical calculations, identical data is compared, thus creating a uniform base for the evaluation of tamping actions required in future. It is also possible to provide information about the maintenance work carried out by indicating probabilities. The choice of the width of the prediction interval is the only parameter to adapt this model to specific conditions.

4.3.4.2 Considerations about the width of the prediction interval PI

It was mentioned at the beginning that intensive research had made it possible to identify the tamping operations carried out in the past for twelve turnouts. Exactly these data are now used to calibrate the width of the prediction interval. In a first step, all tamping actions documented by the Austrian Federal Railways are entered into the routine. These data will not be adjusted or modified, as it can be assumed that machine operations, which were reported by the regional responsible staff, were actually carried out. In a second step, the model-based determination about the date of execution of past tamping operations was carried out, whereby a variation of the width of the prediction interval was realised. A small width of the prediction interval is equivalent to a statistically low confidence level and vice versa. Moreover, the width of the interval naturally also influences the detected tamping operations. A prediction interval of $p\%$ thus means that in $p\%$ of all considered measurements, the prediction is situated within this interval or that the standard deviation is located outside this interval in only $1-p\%$. This $1-p\%$ can therefore be regarded as a probability of error.

A graphical visualisation of this analysis is shown in Figure 34. The height of the grey bars corresponds to the number of tamping operations for the considered turnout, which were documented and reported by the Austrian Federal Railways. The bars coloured in the different shades of blue represent the number of tamping operations which could be determined by the described methodology, but with different widths of the prediction interval. It can be seen that the deviations between the two data sets considered are rather small. Especially the first bar, i.e. the situation with regard to turnout no. 1, is quite interesting. Three tamping operations could always be identified, whereas four tamping operations carried out by the infrastructure manager were reported. With a detailed analysis (small graph in Figure 34), it was found that this tamping, if carried out, led to a deterioration of the standard deviation, and it is therefore clear why no maintenance operation was set by the developed methodology.

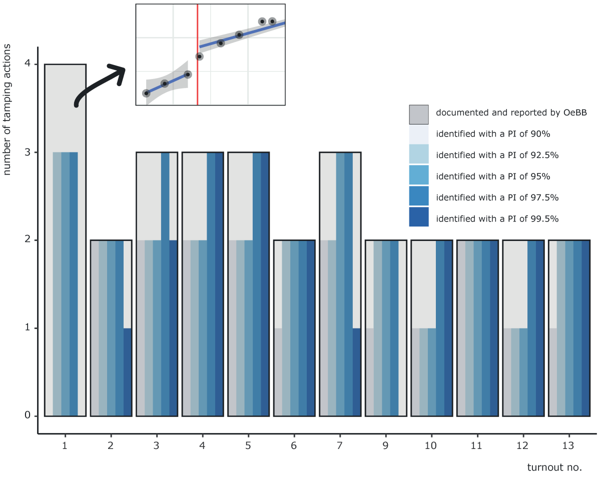

Figure 34 Identified tamping actions as a function of the prediction interval width.

The summary of all results from the twelve considered turnouts is shown in Figure 35. At this point it should be noted again that the methodology developed is exclusively a descriptive model. Such depicted tamping tasks, where an increase of the standard deviation is visible, can never be depicted or detected, since this is not a standard behaviour either. However, the method is very well suited for tamping operations which show an expected effect on the standard deviation, and thus the data gap can be closed with respect to the time of execution of past tamping actions.

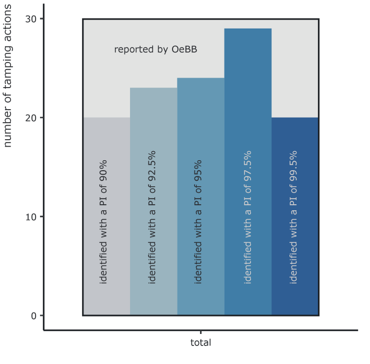

Figure 35 Results about the investigations according to the prediction interval width.

The methodology of the presentation (height of the grey bar corresponds to the confirmed tamping operations, and the height of the blue bars correlates with the number of tamping operations detected by the developed methodology) remains unchanged. It can be seen that for the considered twelve turnouts, an identification of the tamping operations carried out with a prediction interval of 97.5% leads to the highest conformity. Apart from the tamping operation of turnout no. 1, all documented tamping actions could be identified. Therefore the prediction interval for the identification of the tamping operations of all remaining turnouts is also determined with this percentage. All statements on tamping carried out refer therefore to an interval of 97.5%, or a probability of error of 2.5%.

In order to identify the tamping operations carried out, the developed methodology was applied to all 45 turnouts and thus the effects of a turnout tamping could be extracted.

The model was also tested using measurement data from open track related to the rail network of the Swiss Federal Railways (SBB). This was done in a cooperation project where the question of an optimal intervention level for tamping actions was investigated. In order to make this possible, it was primarily necessary to detect tamping operations carried out in the past, for which the developed methodology was used. It was found that the methodology described has limitations, especially if there are less than two measuring points or if an extremely high dispersion occurs. Nevertheless, the developed model could be successfully applied, and the identified tamping actions compared with internal documentation about maintenance activities. A very high agreement suggests that the methodology can also be used to identify tamping operations of open track.

Before the knowledge gained is combined and consolidated in a prediction model, the simplification made to describe tamping shall be validated via the homogeneous behaviour of a turnout. There is no question that this simplification for the description of tamping operations is absolutely justified. However, this does not mean that this simplification is also observable in reality.

4.4 Deterioration behaviour of different turnout areas

A turnout consists of many individual parts, which, in contrast to open track, are also designed to be partially movable (Figure 5). Due to the different lengths of the sleepers, due to the different number of rails per sleeper and due to the complexity of the overall system, turnouts have a varying stiffness over their length (J. Xu et al., 2016). There are also differences in the stiffness between the rails under consideration, which are also expressed by the different forces in the contact surface between rail and wheel (J. Xu et al., 2016).

Since it is assumed at this point that it is mainly the different stiffness ratio which influences the tendency of the turnout to geometrically deflect, the turnout itself is divided into three areas for further analysis, based on the knowledge gained (Figure 36):

- switch panel (2): The first area extends from the front of the turnout towards the first welding joint. On the one hand, the transition from normal sleepers to special turnout sleepers takes place, so a stiffness change can be expected (Loy, 2009). On the other hand, the intended switching machine, often located within a hollow sleeper, may cause a specific deterioration in performance.
- closure panel (3): The area between the first and second welding joint is characterised by turnout sleepers, which regularly increase in length, and by the different fastening positions of the rails (Loy, 2009). Within this area, no joints or high dynamic loads occur, meaning that a moderate deterioration of the geometric conditions is assumed in this area, and therefore a separate analysis is necessary.
- crossing panel (4): The solid common crossing area in combination with the wing rails mounted slightly apart leads to the highest stiffness in the system (Loy, 2009). Due to geometric discontinuities, this area has to be analysed separately. The section extends from the second welding joint to the rear of the turnout.

Even though this work focuses on researching the behaviour of turnouts, the track surrounding a turnout must not be completely ignored. Especially dynamic excitations, which occur in front of the turnout in the main traffic direction, can also be introduced into the turnout via dynamic effects. Thus, the environment of a turnout should always be considered. Based on this circumstance, two further areas are defined for later analyses:

- front transition panel (1): Insulated rail joints are usually located in the area near the turnout's front, which separate the turnout itself from open track. Due to the locally very limited stiffness increase, a high degree of deterioration must be expected (Quirchmair et al., 2019). Therefore this area will be analysed separately. A range of ten metre in front of the turnout is determined. It is assumed that insulated rail joints located further than ten metre in front of the turnout no longer have a relevant influence on the behaviour of the turnout itself.
- rear transition panel (5): Immediately after the last long sleeper, eccentrically arranged short sleepers with shortened sleeper heads are often located on the inner side. This results in a strong one-sided load with corresponding torsion of the track (Loy, 2009). For this reason, this area is also depicted separately. The last area is thus defined, beginning at the rear of the turnout, again with a length of ten metre. It is assumed that after this distance the effects described have subsided again.

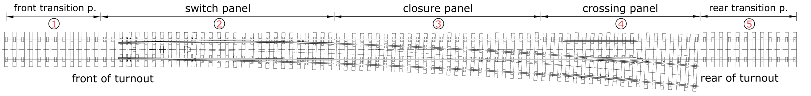

Figure 36 Designation of different turnout areas for further analyses.

Thus, five areas are defined in the environment of a turnout, which will be examined in detail in the following. The numbering of the individual areas necessary for further analyses is shown in Figure 36. All the area designations mentioned below refer to this. Here the main focus is on analyses which should show whether the differently defined areas change in a very different way with respect to the geometrical conditions. As already described in the previous chapters, the standard deviation of the longitudinal level is again very suitable for this purpose. Up to now, no excessive attention has been paid to the magnitude of this statistical parameter, since no comparison has ever been made within the analyses carried out. However, this is precisely what is important now. Since the areas have different lengths due to the geometry of the turnout, it must first be clarified which effect the length of the input data set has on the magnitude of the calculated standard deviation or how this effect can be eliminated and thus the comparability of the results can be ensured.

4.4.1 Influence of input data record length on the standard deviation

The calculated standard deviation depends on the length of the input data inasmuch as different areas are always analysed due to different observation lengths (Figure 37).

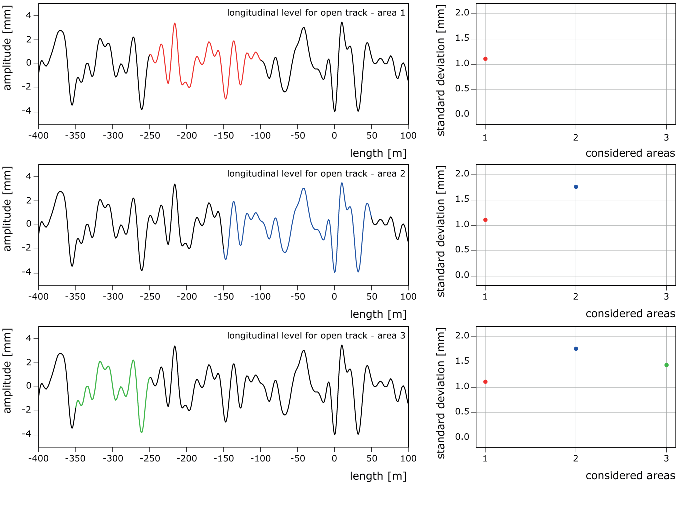

Figure 37 Influence of input data length on the longitudinal level standard deviation.

This means that the standard deviation can only be compared on the same base, i.e. with an identical length of the considered area. Now, however, the circumstance occurs that the areas of a turnout defined do not have the same length. The areas before and after the turnout have a length of ten metre. Related to a turnout with a branch radius of 500 m, the switch panel has a length of about 18 m, the closure panel is roughly 15 m long, and the area of the common crossing extends over a distance of almost 8 m.

The calculation methodology was adjusted to compare different lengths of the areas. A window width of 5 m is chosen. Within this fixed window, the calculation of the standard deviation is performed, whereby this window is located exactly at the beginning of each range in the first step. Subsequently, this fixed window is moved by one measuring point, and the standard deviation is calculated again. This process is repeated until the end of the window coincides with the end of the range. Finally, all calculated standard deviations are averaged to obtain a representative value for the entire range. This ensures that the calculated standard deviations of the differently long ranges are comparable, since the basic calculation is always performed on a window with a fixed width for all ranges, no matter how long a single range actually is. Only the number of standard deviations to be averaged varies.

4.4.2 Comparison of deterioration rates in differing areas

A summary of the results is shown in Figure 38. Here the rate of deterioration for each of the considered turnouts between two tamping tasks was calculated and presented in the form of box plots. The added violins summarise the results of all turnouts per area in a combined presentation and the numbers inserted in red and blue correspond to the mean value and median of this summary.

If the comparison of the two rails is made at the beginning, it is noticeable that the rail on which the common crossing is located has the highest deterioration rates, regardless of whether the median or the mean value is considered. This can be explained by the fact that the running edge is interrupted in the area of the common crossing, which results in an impact during the passage of a rail vehicle. This results in a higher deterioration in this area. This statement can also confirm the assumption made for the identification of tamping actions by considering the averaged longitudinal level signal between the left and the right rail. However, the difference between the deterioration rates, calculated based on the averaged longitudinal level measurement, and those of the two independent rails is not so high that averaging would distort the result too much and this adaptation would therefore be impermissible.

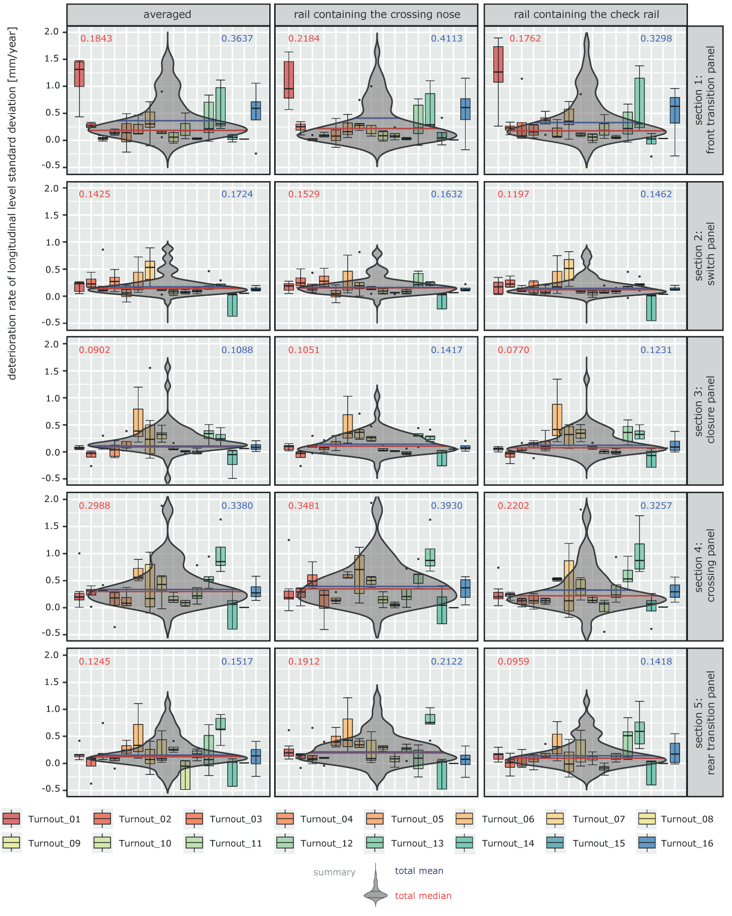

Figure 38 Longitudinal level standard deviation deterioration rates for different areas.

When it comes to the question of which area deteriorates more rapidly in relation to the geometric conditions, a distinction can again be made between consideration of the mean value and the median. If the focus is placed on the mean value, the area in front of the turnout is the one with the highest deterioration rate. This section is closely followed by the crossing panel. However, if the focus is placed on the median, the situation is exactly the opposite. Here the common crossing area shows the highest deterioration rates, followed by the area in front of the turnout.

The fact that these two areas, regardless of the base on which the evaluation is made, emerge as those with the highest rates of deterioration can be argued by the induced hit. In most cases, an insulated rail joint is located at the beginning of the turnout.

If this joint is not properly maintained, the propagating wear causes an impact during the crossing, which in turn is decisive for the high deterioration rates. The same statement applies analogously to the crossing panel. Although the gap there, which subsequently leads to a hit, is geometrically necessary in today's standard turnout designs with a common crossing, this also results in a significantly faster deterioration than in other areas.

In summary, it can be observed that the hit, whether due to a worn insulated rail joint or due to the constructionally necessary gap at the common crossing, has an extremely negative effect on the geometric parameters of a turnout. Attention should therefore be paid to the wear of the components within these areas, so that the impact which occurs during train passage can be kept as low as possible. Among other things, the insulated rail joints have been identified as the cause of high deterioration rates. However, in this thesis the behaviour of insulated rail joints will be discussed in more detail below.

4.4.2.1 Jointed rail track analysis

To verify the fact that the deterioration rates of the track geometry are higher in the area of insulated rail joints, a jointed rail track is considered. The basic measurement data, i.e. the longitudinal level measurements, were in turn repositioned and synchronised using the methodology described in chapter 3. A window with a fix width of 20 DB was defined for the calculation of the standard deviation, whereby two areas with insulated rail joints and two surrounding reference areas (i.e. open track) were considered in detail (Figure 39) with reference to TwinPEAKs (section 3.4.1).

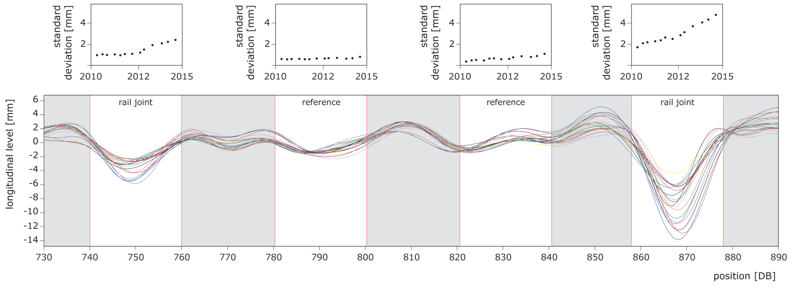

Figure 39 Analyses about the standard deviation deterioration of a jointed rail track.

Of course, there are minor differences between a rail joint and an insulated rail joint. However, a simple rail joint probably behaves most similar to an insulated rail joint. Moreover, jointed rail tracks have the advantage that their geographical location is known. Unfortunately, this is not the case with insulated rail joints. Therefore, the behaviour of a jointed rail track is examined more closely.

The lower illustration in Figure 39 shows the synchronised measurement signals. Within the small figures in the upper area the calculated standard deviation can be observed. If the change of the standard deviation of the two reference areas is considered, a very moderate deterioration over time can be seen. When looking at the two rail joint areas, a significantly higher deterioration rate, related to the identical observation period, is noticeable. The two joints are located at a distance of approximately 30 m from each other on the same track, which means that the applied load must be identical for both. Assuming that there are no excessive local differences according to the existing stiffness, this analysis indicates that the rail joints are not necessarily supercritical as long as the other boundary conditions, such as the necessary maintenance or care of such track areas, are not neglected. Otherwise, it would not be possible to explain the locally different behaviour.

Based on the results presented, it can therefore be assumed that in the case of insulated rail joints located in front of the turnout, an additional dynamic excitation of the turnout can take place, which is why the area in front of the turnout is analysed in more detail.

4.4.3 Behaviour of insulated rail joints and their effects on turnouts

For this purpose, the methodology described for calculating the standard deviation, again using the longitudinal level measurements as a base, is used. In order to better visualise the individual effects, the illustration as a colour plot was used and the standard deviation was calculated with a window width of three metre, moving over the entire turnout area.

Within the first evaluation (Figure 40), a very high value of the standard deviation can be seen especially in the period between 2005 and 2009 in the area of location -160. An insulated rail joint is located at precisely this position. Based on the standard deviation, it is assumed that the insulated rail joint was renewed in 2009. However, data on maintenance work carried out are not available for this period. The main traffic direction is from left to right, and it is very clear that the failure propagates in the main traffic direction over time, i.e. into the turnout. The impact at the worn insulation rail joint thus seems to be responsible for the inertial increase of the standard deviation, but the failure propagates into the turnout with increasing time. The periodic maxima within the standard deviation, visible at locations -140, -120 as well as -100 and -80, therefore always occur nearly at the same distance. This analysis thus gives the impression that the insulated rail joint is worn out, possibly due to inadequate maintenance, and that an increased deterioration rate of the standard deviation is therefore noticeable. Due to the main traffic direction, the failure is periodically applied to the turnout, and in regions at a distance of 20 DB (5 m), local maximum values within the standard deviation are also apparent. The cause of this behaviour could be the P_2-force (Hunt, 1986; Zarembski et al., 2001).

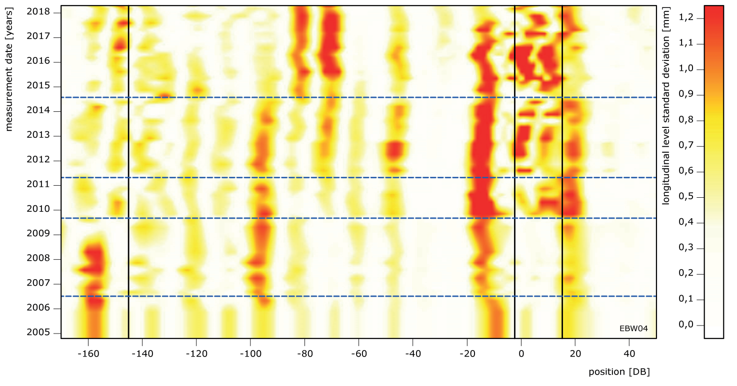

Figure 40 Critical area propagation - turnout no. 4.

The second analysis (Figure 41) shows a similar picture. At the beginning, a maximum of the standard deviation is visible near position -150. Again, an insulated rail joint is located there. In the course of time, the failure propagates into the turnout again, which leads to local maxima, but at much smaller intervals than could be observed in the previous analysis. These maxima are almost constant over the entire observation period and deteriorate much faster than in surrounding areas. Again, due to the reproductive patterns, it can be assumed that initially a worn insulated rail joint and the effect of the P_2-force are responsible for the high deterioration rates in the vicinity of the turnout's front.

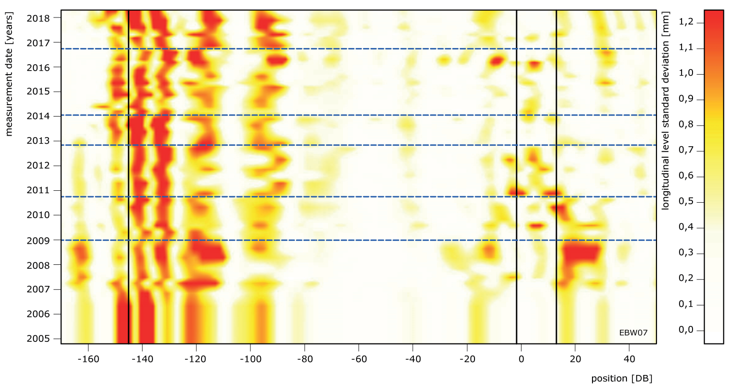

Figure 41 Critical area propagation - turnout no. 7.

By the way, it should be noted that maximum values of the standard deviation also occur more frequently in the area of the common crossing. This, can be seen as confirmation of the statement from Figure 38, according to which the insulated rail joint at the front of the turnout and the common crossing area emerged as the critical areas of a turnout.

In summary, it can be determined that, within the calculation of the moving standard deviation in the area of the turnout's front, local maxima can always be identified which seem to propagate with constant wavelengths, in the main traffic direction and thus into the turnout. Since areas of the considered turnouts show significantly lower rates of deterioration than those described near the beginning, it can be assumed that this high deterioration is due to a high wear at the insulated joint in front of the turnout. Of course, this analysis cannot be regarded as proof, but at least it can be concluded that it is quite useful and necessary to analyse areas in front of and behind the turnout in order to understand their behaviour.

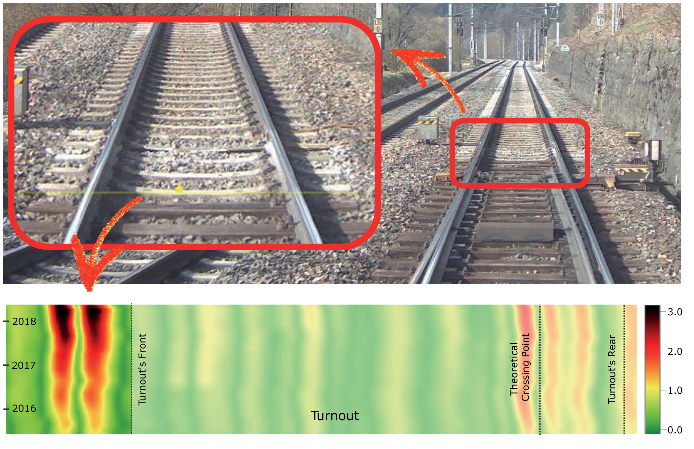

Figure 42 Example of insulated rail joint wear and ballast destruction.

As a final example to substantiate the formulated theory, a further analysis based on an identical calculation methodology is presented (Figure 42). Here, turnout no. 1. was analysed and the possibility arose to verify the gained knowledge by means of track photos. The colour plot provides information that two sections with maximum values of the standard deviation can be identified in the area of the turnout's front. A closer look at the track photo shows that these areas with a very high standard deviation already show a massive damage of the ballast, which is noticeable by white spots. This in turn is a sign of local over-stressing of the ballast, which in this case is again due to the already poor insulated rail joint. The problem can be worsened if there is a stiffness discontinuity nearby as shown in Figure 42. Thus it could be demonstrated once again that insulated rail joints can cause major problems in the case of insufficient maintenance, and that increased attention should therefore be paid to these areas. Furthermore, there would already be sufficient technical alternatives to control the behaviour of these areas.

On the one hand, the insulated rail joints could be avoided by changing the signalling system towards axle counters, which would remove discontinuity and thus a potential source of high deterioration. In addition, other constructions are also used in these critical areas, for example frame sleepers, adjusted under sleeper pads (Quirchmair et al., 2019) or joints with increased moments of inertia (Eisenmann & Leykauf, 1985).

However, the detailed analyses mentioned were more concerned with gaining knowledge or understanding the behaviour of turnouts than with the actual objective of this chapter. For this reason, the following section will again take up the basic objective and describe the creation of the tamping prediction model.

4.5 Prediction model for tamping tasks

The basic idea regarding the creation of models for the prediction of tamping actions is already known from the previous chapter and also shown in (Neuhold et al., 2020). Learning from past behaviour, assessing the current situation and predicting future behaviour - that's the way. However, this statement also implies that a separate model must be created for each turnout. Therefore, due to the limited number of analysed turnouts, no network-wide mean values of deterioration rates or intervention limits are used. Rather, the behaviour is assessed separately for each turnout and the necessity of a tamping task is derived from this. The knowledge gained so far, will be briefly summarised:

- On the one hand, the standard deviation of the longitudinal level, calculated over the entire turnout length, could be identified as the quality value which can describe the geometric situation with regard to turnouts very well.
- Using different models, the deterioration behaviour of the standard deviation was analysed, whereby the linear modelling provided the highest degree of determination, which is why the process is abstracted as a linear function.
- With the developed methodology for the identification of past tamping tasks, the effect of each individual action can be extracted and analysed in order to draw conclusions for the implementation of the tamping prediction.

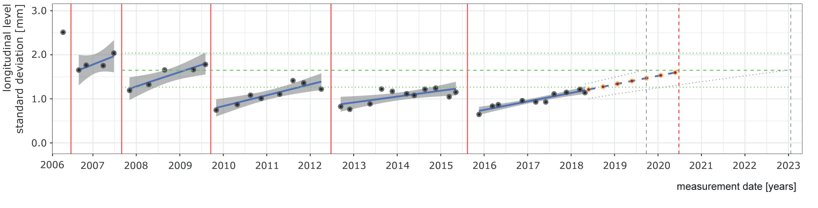

Figure 43 Principle method for predicting the next necessary tamping task.

Based on this knowledge, the creation of the prediction model is possible. Figure 43 visualises the process. For the considered turnout, measurement data are available up to the year 2018, which are shown by means of black dots. Using the developed methodology, the tamping actions (red vertical lines) in the years 2006, 2007, 2009, 2012 and 2015 could be identified and the linear regressions of the individual sections were calculated. Now the question arises at which point in time the next tamping operation is necessary. To answer this question, the linear regression of the last, still open section is continued. As mentioned at the beginning, the basic idea is to learn from past behaviour.

Therefore, a mean intervention level (dashed green line) is calculated as the mean value of all intervention levels. The point of intersection of this mean intervention level with the continued progression of the linear regression characterises the possible point in time for the next turnout tamping action (mid-2020 - dashed red vertical line). In order to take uncertainties into account, the prediction interval was calculated in addition to the actual forecasting and displayed as grey dotted lines. This step thus also makes it possible to determine an earliest (end of 2019) as well as a latest possible point in time (beginning of 2023) for the next tamping operation. Based on the past behaviour of the turnout, the next tamping operation can thus be inferred, whereby the asset managers are also given a certain amount of time to implement this tamping suggestion by taking the prediction interval into account.

The prediction based on a mean intervention threshold is only one possibility under which the forecast process can be implemented. Of course, age dependent threshold values for the standard deviation could also be defined, which could be easily integrated into the prediction model. There are almost no restrictions regarding this, and any boundary conditions can be defined in the model. However, defining a mean intervention level for prediction seems quite plausible, even though it is only one of many possibilities.

The developed methodology thus combines all the knowledge gained in a very clear manner. In turn, much emphasis was placed on this fact, as the vision is definitely an implementation of the developed models within the Austrian Federal Railways. It is known from the past that complex models are rarely implemented, because in most cases the understanding of these models is difficult, and therefore a very basic approach was chosen. At the end of the development of this methodology, a comparison between model and reality is made in order to validate the suitability of the model, at least by means of an observation. This is used to analyse the behaviour of turnout no. 9 in detail (Figure 44).

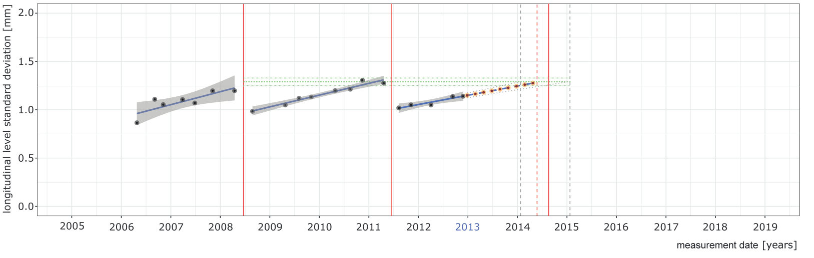

Figure 44 Predicting the next tamping task for turnout no. 9.

In this scenario, the year 2013 is set as the time of consideration. Again, all values of the standard deviation were calculated first, then the previously executed tamping tasks were identified and the necessary regression parameters determined. Based on the open interval, a regression is calculated and continued until this line intersects with the mean intervention level. In this example, the next necessary tamping task could be predicted for the second quarter of 2014 (dashed vertical red line).

Looking at the time of the performed tamping action (solid vertical red line), a difference of 86 days can be observed between the predicted and the performed tamping. The methodology thus seems to be well suited predicting future necessary tamping operations.

Now, however, the behaviour after the tamping operation carried out in 2014 should be discussed. For this purpose, the tamping action predicted and carried out in 2014 (Figure 44) is assumed to be given, and the methodology is repeated with the existing measurements until the end of 2015 (Figure 45). It can be seen that the algorithm would predict the next necessary tamping operation for mid-2016.

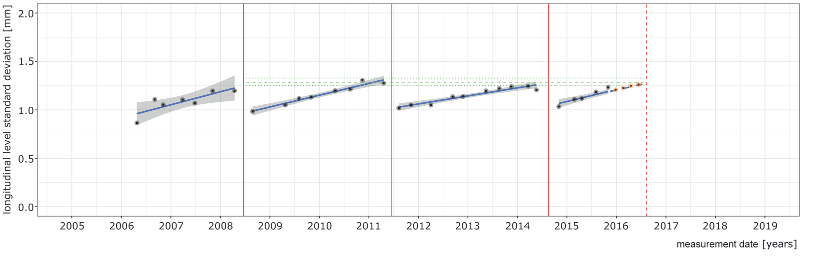

Figure 45 Predicting an additional tamping task for turnout no. 9.

Now, all measurement data are included to generate a holistic statement about the actual behaviour (Figure 46). Obviously, no tamping operation was carried out in reality at mid-2016, although the reasons for this could not be reconstructed. It can only be concluded that the model would have predicted a tamping action.

The slope of the regression line for the last six measurement points (Figure 46) differs therefore significantly from the slope of the other four approximation lines. The much higher deterioration rate indicates that the predicted tamping operation is absolutely correct and necessary, and that this maintenance would have prevented an excessively high level of the standard deviation. This example also shows that the methodology for the prediction of tamping actions can forecast more than only the following tamping task.

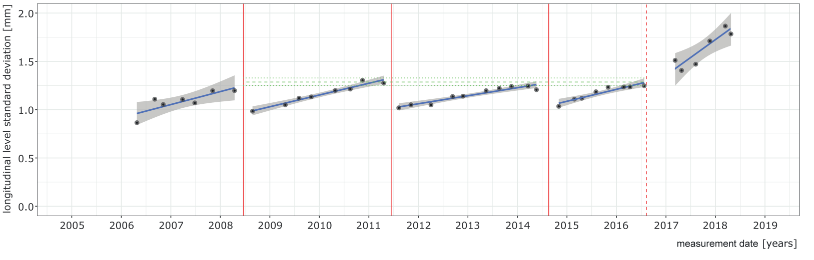

Figure 46 Comparison between the prediction and the real behaviour for turnout no. 9.

Of course, the limiting factor of the described methodology must not be ignored. The main point is that the calculation of a prediction interval (Formula 9) can only be carried out with a minimum of three measurements.

This implies that the methodology is only applicable to newly installed turnouts to a limited extent, as the data base may be insufficient in relation to this. Indeed, it should not be necessary to decide about the necessity of tamping in the first year for newly installed turnouts anyway.

Based on all the findings, it was thus possible to show how tamping tasks can be predicted for a certain period of time, based on the behaviour of the turnout under consideration. Neither network-wide analyses nor statistical observations are necessary for implementation; the methodology also works very well with turnout-specific parameters as input data, so local effects of a turnout are always taken into account. Nevertheless, it should be emphasised again that the prediction based on a mean intervention level is only one possibility, which, however, was considered to be quite reasonable using the available data base.

4.6 Conclusion

First, the causes of the geometric change as well as possibilities for related maintenance were discussed. As tamping is the most frequent maintenance task with regard to the geometric parameters of a turnout, this process was briefly explained by means of an illustration.

Subsequently, investigations were presented which dealt with a representative quality value to describe the geometric situation. The standard deviation of the longitudinal level in the wavelength range D_1 could be determined as a suitable statistical parameter. The consideration concentrates on the turnout area, i.e. starting at the front of the turnout and ending at the rear of the turnout. Once the characteristic values had been determined, further investigations focused on determining the best possible description of the deterioration process. For this purpose, a linear and an exponential deterioration model were compared based on 15 turnouts, and their adaptation was assessed using the coefficient of determination. From this analysis, a linear deterioration resulted in the model for further investigations.

Based on this knowledge, an attempt was made to answer the question of past tamping activities. As there are not enough reliable records regarding past maintenance actions in turnouts within the Austrian Federal Railways, a method was developed to identify past tamping actions. For this purpose, linear regression was applied, and it could be determined based on past behaviour whether a certain value of the standard deviation results from a normal (predictable) behaviour or whether maintenance was carried out. Thus, a possibility could be created to detect tamping actions carried out in the past by differentiating the cases of the considered standard deviations and taking into account a prediction interval. It was also possible to extract the effect of each tamping task and thus ensure a uniform starting point for all further investigations.

For modelling tamping actions, the entire length of the turnout was assumed to be homogeneous in a first step, since all analyses carried out also referred to this area. For this reason, investigations were still carried out about the possibly deviating behaviour of individual turnout areas in relation to their geometric deterioration. For this purpose, the turnouts themselves were subdivided into three areas. It was found that the common crossing area as well as the area prior to the turnout deteriorate faster than all others.

As the reason for the higher deterioration in the crossing nose area, the hit could be identified. Subsequently, insulated rail joints could be identified as the trigger for high deterioration rates especially at the turnout's front. In summary, insulated rail joints could in any case be identified as critical areas, since a failure in front of the turnout is entered into the turnout in the course of time due to dynamic effects, and thus a significantly faster deterioration of the geometric conditions within the turnout results.

Finally, the collected knowledge was combined within the prediction model of necessary tamping tasks and a methodology was derived from it. This method is based on a linear regression and takes into account all local effects. The successful operation of the methodology could be shown and a comparison between the model and reality could be made.

Research question 2

Is it possible to adapt or process the existing measurement data of the track recording car in order to extract information for turnouts? What would a possibly necessary reworking process look like?

Answer to research question 2

With regard to the geometrical change of turnouts over time, this question can definitely be answered with yes. Of course, the post-positioning process for the measurement data described in chapter 3 is a basic requirement for this. However, information about the current geometric conditions can be obtained from the measured data by calculating the standard deviation of the longitudinal level. By detailed consideration of the progress, the necessity of future tamping actions can be predicted. These data also allow for the identification of information about tamping operations carried out in the past, which also allow for more detailed analysis of the effect of tamping actions in context to turnouts.

Research question 3

Do these measurements provide sufficient information on the geometric conditions under loading to deduce turnouts' behaviour? Is it possible to derive maintenance activities from these data?

Answer to research question 3

This question can also be answered in the affirmative. By observing the standard deviation, the behaviour of turnouts can be concluded very well. Through the development of a model for the identification of past tamping actions, it could also be proven that these data are able to describe the effect of maintenance activities, in this context the effect of tamping actions. The question of the deduction of necessary tamping tasks can also be answered with yes, as the relevant modelling was explained at the end of the present chapter and demonstrated based on an example.

5 INNOVATIVE ANALYTICAL METHODS TO ASSESS THE BALLAST CONDITION

The following chapter contains methods, results and text passages, some of which have already been published (Fellinger et al., 2019; Fellinger, Neuhold, & Marschnig, 2020; Fellinger, Wilfling, & Marschnig, 2020a, 2020b). Text passages of the same wording are appropriately marked.

Figure 9 already showed the high economic importance of ballast cleaning in context to maintenance tasks. However, a relevant prediction model for the necessity of ballast cleaning is always based on knowledge about the current condition of the ballast. Therefore it is necessary to move away from purely geometric considerations towards the derivation of a component condition. The geometrical situation within turnouts can be described very well by means of the standard deviation of the longitudinal level (chapter 4). Purely geometrical wear and tear can thus be compensated by maintenance activities such as tamping. It is also possible, based on the evaluations already shown (Figure 43), to identify different sections within a time series, all of which are limited by an executed tamping action. A deterioration process which is repeatedly interrupted by maintenance activities can thus be recognised.

However, a fundamentally different approach is required for the research of methods to describe an individual component or the component condition. In general, this cannot be described by an existing measurement signal, or it is not possible to calculate a statistically significant value of a measurement signal and to relate it to a component condition.

For these reasons, it is necessary to develop more specific analyses. Since the goal is still the extraction of additional information from existing measurement signals, smart evaluation methods must be developed to ensure the derivation of a component condition from standard measurement data. For this reason, the methods which have already been developed will be discussed in the introduction, which more or less allow a condition description for open track or for turnouts. Concerning this matter, general boundary conditions for the objective modelling will be derived from the conclusions.

5.1 Methods and data sources for ballast condition description

As a result of an extensive literature study, many methods and data sources were identified which could be used to describe the condition of the ballast. It is not primarily relevant whether these methods require new data or not. Within this section only an overview of already researched methods and data sources in this context should be given.

5.1.1 Visual inspection for open track and turnouts

One of the most widespread methods used to generate information about the overall condition of an asset is the visual inspection. Although, the inspection staff is located in the danger zone of the track and performs a subjective assessment of the overall condition as well as the condition of individual components (Wilfling et al., 2020). In addition, safety-critical limits are measured with regard to the geometry. However, these are irrelevant for the present considerations. The main advantage of this method is that the inspection staff have a complete overview of the condition on site and can thus assess the overall situation.

It is therefore also possible to gain an impression of the current condition of the ballast. A disadvantage is the subjectivity of the description about the condition and the high manual effort. Furthermore, the ballast can only be characterised on the surface, an assessment of deeper layers is impossible within the scope of the visual inspection. Although it is therefore possible to generate statements about the near-surface ballast condition within a visual inspection, these data are definitely not suitable for the creation of prediction models about a necessary ballast cleaning. For this reason, the aim is to automate the turnout inspection process (Rusu, 2015) and to examine the technological possibilities associated with this (Wilfling et al., 2020).

5.1.2 Ballast excavation and ballast sieve analysis

Only based on data from the visual inspection it is not possible to describe the actual condition of the ballast. A further development of this idea are ballast excavations.

For this purpose the track has to be closed because ballast has to be removed, but it is theoretically possible to get a more detailed impression of the ballast condition in deeper layers by means of this method. A particle-size distribution curve of the removed ballast is generated, which can be compared with that of the delivery ballast (Klotzinger, 2008).

Theoretically, the excavation of ballast offers a very accurate way of assessing the condition of the ballast, both in turnouts and for open track. For this purpose the ballast is removed between two sleepers within a track closure either manually or with the help of an excavator. The ballast sample is then taken to the laboratory and divided into two samples:

- first sample: ballast surface layer (i.e. directly beneath the sleeper)
- second sample: ballast bottom layer (i.e. between the surface layer and subgrade)

The ballast is analysed, and a size distribution is determined according to normatively regulated procedures (Austrian Standards Institute, 2012). The percentage of fine stones (< 22.4 mm) in the sample allows conclusions about the condition of the ballast and its elastic properties (ÖBB Infrastruktur AG, 2011; Kuttelwascher & Zuzic, 2013). A proportion of this fraction of more than 25% is an indicator of an insufficient ballast condition (Knoll, 2019). On the one hand, this method is a very objective procedure. On the other hand, the results of different investigations can be easily compared with each other. A disadvantage of this method is the fact that the track has to be closed during sampling, as the removal of the ballast takes a long time and is therefore rather cost-intensive. In addition, the homogeneity of the ballast bed is usually no longer ensured after ballast excavation, which is why tamping should be carried out afterwards.

5.1.3 Ballast condition description by ground penetrating radar

In contrast to taking ballast samples, ground penetrating radar (GPR) is an automated and non-destructive method which can be used to determine the condition of the ballast. GPR is a widely used technique that allows the user to investigate relevant features of the subsoil by studying the propagation of an electromagnetic field (Ciampoli et al., 2019). The measuring equipment can be mounted on an inspection or measurement vehicle, allowing the condition of the ballast to be determined at speeds of more than 100 km/h. Based on this measuring principle it is possible to assess the ballast condition and to calculate a pollution index of the ballast. The advantage of this method is clearly the reproducibility as well as the objectivity of the evaluations produced and the fact that it is a non-destructive analysis method.

The disadvantage, however, is that the railway network under consideration must be measured separately with this device and the data processing and evaluation procedures are extremely complex (Eriksen et al., 2011). Furthermore, these data are only available related to the OeBB rail network for 1,500 km, measured twice (Landgraf, 2016). These data unfortunately do not appear to be sufficient as a base.

5.1.4 Innovative analysis of measurements from the track recording car

All methods and data considered up to now have certain disadvantages, which is why none of them have yet become established. Innovative approaches are analyses based on measurement data, whereby two different methods can be distinguished. On the one hand, such model can be based on innovative data in connection with complex analysis methods. On the other hand, there are methodologies which use innovative analyses in combination with existing measurement data or data available over a long period of time.

5.1.4.1 Determination of ballast geometry by automatically generated data

The idea behind this methodology is to derive the ballast geometry from measurements of the ballast profile and calculations of a geometry index (Sadeghi et al., 2019). These calculations are based on data from a rotating laser, which is attached at the front of the track measurement car. In course of the analysis, a comparison is made between the real ballast profile and that from the planning stage. From the differences between target and actual values, conclusions can be drawn about the stability of the ballast bed and the maintenance tasks required in this respect. This method can be used to identify areas where a shortage of ballast occurs, thus enabling the correct maintenance action to be initiated in time. However, it is not possible up to now to qualify the actual ballast condition easily. This is due to the fact that the ballast is deteriorating and new ballast is added within tamping tasks, wherefore further research is necessary.

5.1.4.2 Determination of ballast condition through innovative data analysis

By means of wavelength analyses, an attempt is made to assign different failure characteristics to different components (Landgraf, 2016). A calculation of simple statistical parameters is not enough. Rather, further analysis options have to be considered, which allow for condition evaluations that are not possible at first glance or by a pure amplitude consideration of the measurement signals (Raju, 2017). For this reason, various models have been established, which are all based on spectral and wavelength analyses. Thus, error characteristics of the track geometry can be linked to a damage pattern by applying the fractal analysis (Hyslip, 2002; Hyslip & Vallejo, 1997).

Again based on the longitudinal level measurements provided by the track recording car and by using wavelength analyses, a method was developed which describes both the actual condition of the ballast and the condition of the substructure (Hansmann, 2015). By applying the fractal analysis, the longitudinal level signal is divided into three wavelength ranges. The first range extends from 1 m to 3 m, the second from 3 m to 25 m and the third includes all wavelengths between 25 m and 70 m. By analysing the fractal number within the middle wavelength range, the ballast condition can be described (Landgraf & Hansmann, 2019).

By adapting the described analysis method, it was possible to investigate deterioration models of the ballast in relation to turnouts. In this case, the longitudinal level measurements of the Danish track measurement car served as input. Based on the calculation of the fractal dimension in combination with other statistical methods, a model for the description of the ballast deterioration was developed (Barkhordari et al., 2020). However, the aim of this method was not to describe the actual condition of the ballast, but rather to examine the deterioration process of the ballast itself.

Based on already presented ideas, a method will be developed at a later stage, which, on the one hand, is of course based on existing track measurement car data and, on the other hand, tries to characterise the current ballast condition by wavelength analyses. Thus, the first step is the implementation of a method which allows for the characterisation and differentiation of good and poor ballast condition by means of track recording car data.

5.2 Power density spectra based on longitudinal level signals

It has already been explained that a precise description of the ballast condition requires wavelength-specific analyses. Thus, in a first step it is necessary to split the longitudinal level signal into its individual frequency and wavelength components. In this context, the methodology of power density spectrum calculations is considered in more detail, whereby the terms frequency and wavelength are used synonymously. On the one hand, this can be explained by the fact that in the railway industry the term wavelengths is used rather than frequency, and, on the other hand, that the conversion from frequency to wavelength is very comfortable for the existing measurement signals due to their processing.

$$PSD_f = \frac{2 \cdot D_x}{L} \cdot \left[\sum_{i=0}^{L} \left\{ a_i \cdot \cos\left(\frac{2 \cdot \pi \cdot i \cdot f}{L} \right) \right\} \right]^2 + \left[\sum_{i=0}^{L} \left\{ a_i \cdot \sin\left(\frac{2 \cdot \pi \cdot i \cdot f}{L} \right) \right\} \right]^2 \qquad (11)$$

The spectral power density indicates the frequency-related power of a signal in an infinitesimal frequency or wavelength range. If the spectral power density is specified over the frequency, a power density spectrum (PDS) is obtained. The integral over all frequencies or wavelengths gives the total power of a signal (Meyer, 2014). For resent considerations, the power density spectrum is calculated based on Formula 11, where D_x is the sampling rate, L is the length of the input data set, a is the input data itself and f is the frequency under consideration.

The division of the total power density by L, i.e. by the length of the input data set, represents a necessary adaptation, since otherwise the comparability of different lengths of the input data sets, based on power density spectra calculations, would not be possible. However, this normalisation should eliminate this effect and thus make it possible to compare power density spectra regardless of the length of the input data. This step can be understood in analogy to the topic discussed in section 4.4.1 with reference to the standard deviation. An exemplary power density spectrum of a longitudinal level measurement is shown in Figure 47 (a). This implementation makes it possible to split up the input signal into its individual wavelength components and to calculate and graphically display the power present in the signals of each infinitesimally small wavelength range. Thus, the basic requirements for wavelength-specific analyses are given, which is why within a next step, the detailed process from wavelength analysis to the determination of the ballast condition is shown.

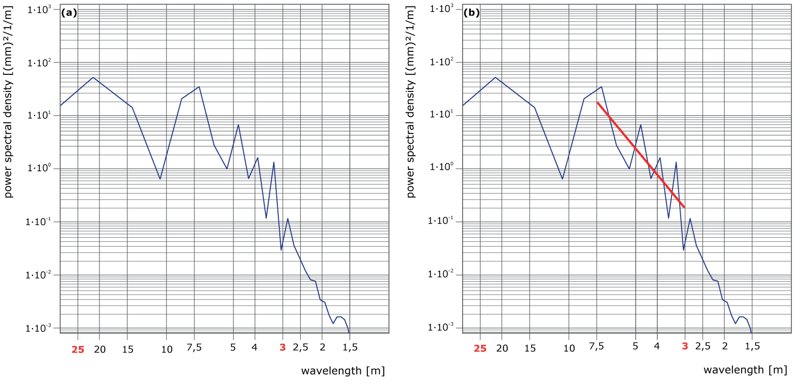

Figure 47 Power density spectrum curves based on longitudinal level measurements.

5.2.1 Properties of the chosen power density spectra calculation

Since this is perhaps not a very common form of data analysis, the properties of power density spectra will be briefly discussed. The basic idea of a power density analysis is the division of a signal into individual wavelength ranges. To illustrate this, the power density of different input signals (Figure 48 left), each with defined wavelengths, was calculated and displayed (Figure 48 right). The signal range coloured in red is representative of the input signal passed into the calculation. It can be seen very clearly that the calculation method works and that exactly those wavelengths within the power density spectra can be recognised which were present within the sinusoidal signals.

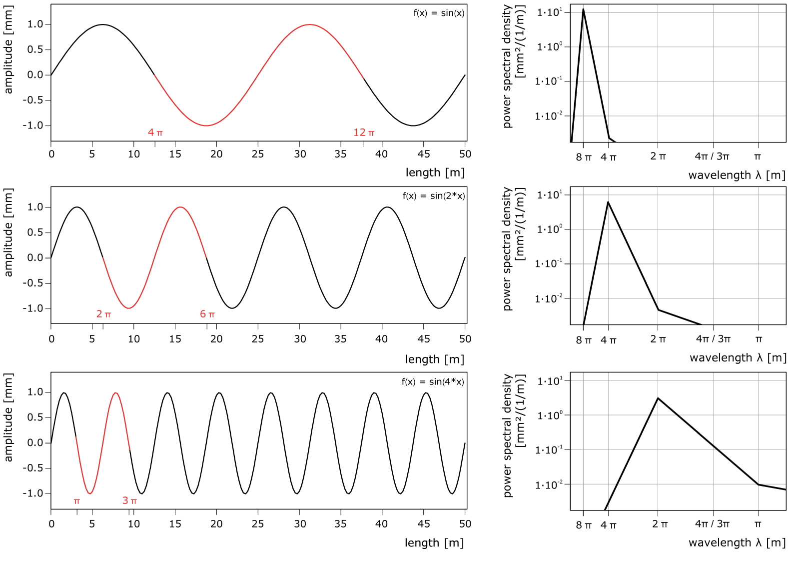

Figure 48 Results of power density calculations for different input signals.

Furthermore, mathematically superimposed sinusoidal signals were used to test whether the intended normalisation of the power density to the length of the input signals worked (Figure 49). The input data are again shown on the left, and the results of the power density calculation on the right-hand side. The coloured areas of the input signals correspond to the power densities shown in the same colour on the right.

A comparison of the three cases shows that the length of the input data has no influence on the level of the calculated power density and that the standardisation works. On the one hand, the comparability of different input data set lengths which is necessary for power density calculations, can be confirmed.

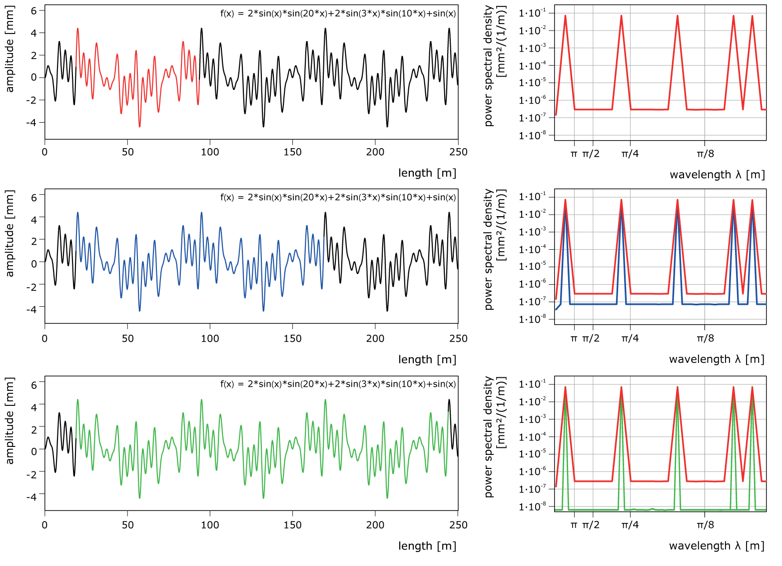

Figure 49 Result comparison of different data lengths power density calculations.

On the other hand, the possibility arises to compare different areas of a turnout based on their ballast condition, no matter over which length these areas extend.

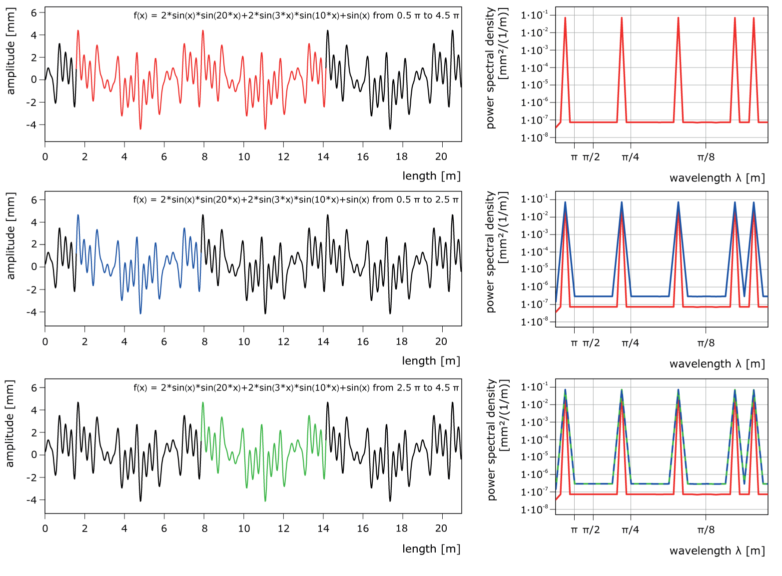

Figure 50 Result comparison of averaged power density calculations.

Finally, it was investigated how an averaging of spectra calculated over different lengths behaves in comparison to a power density calculation implemented over the entire length (Figure 50). The output was again the identical superimposed sinusoidal signals, which were already shown in Figure 50. First, the power density of the red coloured input data was calculated. Then the input signal was divided into two areas, and the power density of each part (blue and green) was calculated (middle and bottom in Figure 50).

It could thus be shown that it is possible to average different power density spectra with respect to the length of the input data sets and that this leads, after averaging, to identical results for the calculation of the power density over the entire length.

The expectations regarding the properties of the power density spectra on which all further analyses are based have thus been confirmed and, through a precise analysis of the calculation methodology, the limits of application could be identified, or the opportunities presented. In the next step, the transition from very abstract power density spectra to the real ballast condition is necessary.

5.3 From wavelength analyses to the ballast condition

At this point a connection between the spectral power density, on the one hand, and the ballast condition, on the other hand, has to be established. Research has already dealt with the use of power density calculations for turnouts and, demonstrated a possible optimisation of various maintenance activities (Minbashi, Bagheri, Golroo & Arasteh, 2016). However, the application of this methodology to describe the condition of the ballast has not yet been carried out for turnouts, in contrast to open track. By implementing the method of fractal analysis on the vertical track geometry, it could be shown that changes in the wavelength range of 3 m to 25 m are often accompanied by an inadequate ballast condition and that therefore, by evaluating the changes in this wavelength range, a conclusion about the ballast condition is possible (Landgraf & Hansmann, 2019). With regard to the possible application of power density spectra in the railway industry (Hamid et al., 1983), a wavelength range between 1.5 m (5 feet) and 7.6 m (25 feet) was identified as significant for track deterioration. Based on today's boundary conditions with respect to the existing measurement data, a wavelength range between three metre and 7.6 m is thus defined for further analyses. For measurement system reasons, the small wavelengths below 3 m are in any case no longer included in the currently determined longitudinal level measurements (Table 2).

Figure 47 (a) shows that the power density curve of a longitudinal level measurement in the wavelength range mentioned shows partly very strong fluctuations, which is why the possibility of recording the change must be considered more carefully. The aim is, as mentioned at the beginning, to evaluate the roughness of the longitudinal level measurements. For this reason, the curve of the power density spectrum in the wavelength range which turned out to be significant is approximated by a linear function (Figure 47 (b)). Based on the methodology for calculating the power density for each individual frequency (Formula 11), the power density curve in the representative wavelength range between 3 m and 7.6 m is referred as PDS^* in the following. The regression line $\widetilde{PDS}$ to the extracted part of the power density curve PDS^* is determined by Formula 12.

$$\widetilde{PDS} = \alpha + \beta \cdot f_i^* \tag{12}$$

Although, the coefficients α and β are determined by the least squares method (Formula 13 and Formula 14).

$$\beta = \frac{\sum_{i=1}^{n}\left(f_i - \bar{f}\right) \cdot \left(PDS_i^* - \overline{PDS_i^*}\right)}{\left(f_i - \bar{f}\right)^2} \tag{13}$$

$$\alpha = \overline{PDS^*} - \beta \cdot \bar{f} \tag{14}$$

The ballast condition index BCI can thus be calculated by the first derivative of the linear regression function $\widetilde{PDS}$ (Formula 15).

$$BCI = \frac{d(\widetilde{PDS})}{df} \tag{15}$$

A change within the power density in the wavelength range mentioned changes the slope of the regression line which approximates the power density curve. For this reason, this criterion is defined as an indicator to describe the roughness of the input measurement data and thus the condition of the ballast. The different coefficients of determination R^2 of the linear regressions are not considered. No criterion could be identified which demonstrably influences the correlation coefficient between the linear function and the power density and which would therefore provide further necessary information. Since the linear function thus has more the purpose of simplifying or abstracting the power density curve in a certain wavelength range, a further consideration of the coefficients of determination is not necessary. The observation of this gradient over time is therefore seen as a possibility to gain valuable information about the development of the ballast condition.

Thus, the basic idea of already implemented analysis methods is taken up, combined with partly new approaches, and thus an attempt is made to implement possibilities for the description of the ballast condition in turnouts.

5.3.1 Ballast cleaning as link between model and reality

Following on from the specifications presented with regard to the fundamental methodology, a defined point in time or circumstance must be found at which the ballast condition is known in order to establish a link between the ballast condition index BCI and the ballast condition in reality, for which four different scenarios were considered:

- When turnouts are renewed, the ballast is usually also renewed. This point in time could therefore serve as a reference for the ballast condition index. However, a large number of, in relation to their age and therefore to their ballast condition, interesting turnouts were renewed in periods without available measurement data (before 2005). Therefore, this point in time is not useful as a reference.
- Another possibility would be to use the ballast quality determined during a ballast excavation as a reference. Since this type of ballast condition identification is very complex and cost-intensive, data on ballast samples taken from turnouts are unfortunately rare, for which reason this data source should be excluded.
- The use of GPR data would of course be possible. This would in turn allow for a very objective and reliable link between the actual ballast condition and the ballast condition index using power density calculations. Unfortunately, these data are not available for the entire rail network under consideration, neither on a network-wide basis nor as time series, so this data source cannot be applied or considered either.

The only way to define a reference case in which a known ballast condition prevails is therefore to consider maintenance activities which have an effect on the ballast condition. If the ballast condition is insufficient or the ballast itself shows excessive wear, ballast cleaning can be performed as maintenance (Zuzic & Wörgötter, 2015).

Since this type of maintenance is extremely time-consuming and cost-intensive (Wilfling et al., 2020), it can be expected that such an action is only ordered and carried out if the ballast condition is extremely poor. In addition, the quality of the ballast is recorded, checked and evaluated after cleaning. It can therefore be assumed that the condition of the ballast after ballast cleaning is correspondingly good. Thus, for the purpose of referencing the ballast condition index, all cleaning tasks in turnouts carried out in Austria with the URM 700 ballast cleaning machine are analysed and used as reference cases for calibration.

5.3.2 The ballast condition before and after a ballast cleaning task

A total of 15 turnouts (Table 1) are thus available for further evaluation. In a first step, the turnout area within the corresponding longitudinal level measurements in the wavelength range D_1 is extracted per measurement run using the methodology already presented. These data are then used as input for calculating the power density. Based on this, the power density curve in the wavelength range between 3 m and 7.6 m is approximated by a linear function and the gradient of this line is regarded as a representative value for assessing the condition of the ballast. Since the ballast cleaning as a maintenance task has already been defined as a reference case, four values each before and after this maintenance action are averaged in order to counteract the occurring scattering. By comparing the respective values before and after ballast cleaning, the condition of the ballast can be characterised (Figure 51 (a)). The values before the ballast cleaning are equated with a poor ballast condition and vice versa.

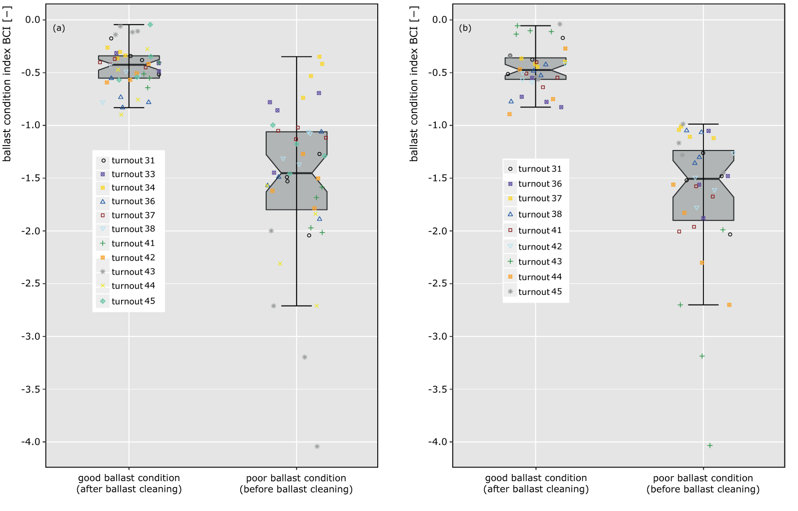

Figure 51 Ballast condition index before and after ballast cleaning.

It can be noted that the ballast condition index before (poor ballast condition) and after (good ballast condition) ballast cleaning can be divided into two independent groups. Even if there are overlaps between the two groups, the calculated index can be used to distinguish between good and poor ballast condition. By applying a Shapiro test, the hypothesis of an existing normal distribution could be discarded, resulting in the Wilcox test being carried out subsequently, thus proving the statistical independence of the two groups. This fact can also be seen from the notches of the boxplots in Figure 51 (a).

Since this is a purely descriptive approach, the overlap of the two areas is also understandable. Within this area, turnouts are located, where a ballast cleaning was carried out, although this would not have been necessary under certain circumstances, or turnouts where no ballast cleaning was carried out, although such a maintenance activity would have been necessary. It should be noted that this method of analysis is an innovative procedure. The decision as to whether ballast cleaning was necessary for the 15 turnouts under consideration was taken on a completely different base, for which reason, on the one hand, the overlapping area is logical and, on the other hand, the suitability of the method for describing the condition of the ballast can also be classified as very positive. A sensitivity analysis was carried out to derive a statement about the overlapping area.

5.3.3 Area allocation with reference to the real ballast condition

For this purpose, those turnouts where the ballast condition index is located in the area of overlap were removed from the evaluation. The resulting findings are visualised in Figure 51 (b). After elimination of the corresponding indices, there is a slight shift in the area of good ballast condition as well as within the other group, but in principle the result is stable. This analysis will be the base to define range limits for different ballast conditions. Furthermore, this sensitivity analysis showed that the influence of the turnouts temporarily removed from the analyses has almost no effect, and therefore the methodology applied appears to be suitable with respect to a descriptive approach.

The results illustrated in Figure 51 (b) serve as a base for defining range limits in relation to the ballast condition index. For the time being, a subdivision into four different groups has been made, but a later adaptation is possible at any time:

- The first range (perfect ballast condition) starts at the minimum of all evaluations, which is 0 due to the calculation method. Taking into account the variance, the lower limit of the first range is restricted by the 25th percentile of the data series of a good ballast condition. This means that the ballast condition, which is located in the upper 25% of the reference turnouts, can be classified as faultless. The absolute limit values for this range are therefore 0.0 and -0.35 respectively.
- The second range begins seamlessly at the end of the first, with a ballast condition index of -0.35, where the ballast condition can be described as appropriate. Toward the lower end of this range, it is limited by the upper end of the boxplot of the data series about poor ballast condition. This specification can be justified by the fact that it makes sense to add 25% of the calculated indices to a good ballast condition. The absolute values for this range are therefore defined as -0.35 and -1.25 respectively.

- However, since ballast cleaning is a very expensive procedure with a long preparation time, it seems sensible to introduce a kind of attention zone. The condition of the ballast in this area can be classified as poor. If the values are within this range, it is necessary to plan a ballast cleaning. The third area is again limited by the 25th percentile of the data set before ballast cleaning and thus by a ballast condition index of -1.25. At the lower end, the limitation was set to the median of the same data set (BCI = -1.5).
- Finally, the area below a ballast condition index of -1.5 remains. This range was deliberately chosen with 50% of the values of the data set before ballast cleaning, since it is not absolutely necessary to clean the entire turnout immediately at the first signs of a poor ballast condition. The last range includes a BCI between -1.5 and -4.0, i.e. the lowest value that could be determined within this investigation.

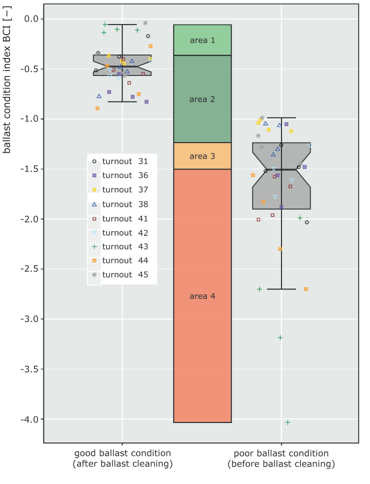

Figure 52 Ballast condition index area definition.

The entire division of the areas is visualised again in Figure 52. This information can now be used to apply the developed methodology to certain turnouts where no ballast cleaning has taken place. It is thus possible to classify their ballast condition on the base of the currently assigned limits. In summary, however, it can already be stated at this point that the analyses of the first 15 turnouts have clearly shown that the ballast condition can be classified by the slope of a regression line to the curve of the power density spectrum in the defined wavelength range.

5.3.4 Ballast condition after cleaning compared with a renewal

Interesting in relation to the ballast quality is of course a comparison between a newly installed and a cleaned ballast, which can also be regarded as a validation of the method.

By reason of the evaluation methodology, all influences are naturally included in the ballast condition index. Due to the fact that the longitudinal level measurement signal is the base for these analyses, it cannot be excluded that the condition of other components such as the sleepers and especially the subsoil also influences the result. For this reason, it can be assumed that the ballast condition index of a new ballast is lower than the index of a cleaned one. The results of the analysis are shown in Figure 53 and thus confirm the assumptions. It is quite interesting, that the BCI of the new ballast is scattered only within a very narrow range, whereas the index of the cleaned ballast shows very large variations.

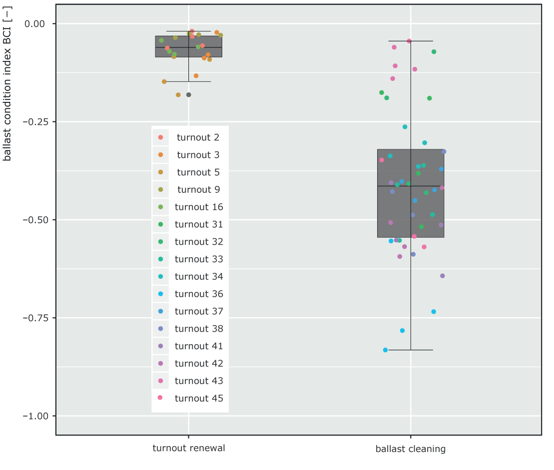

Figure 53 Ballast condition index comparison between new and cleaned ballast.

Due to the complex behaviour of turnouts, more attention is paid to ensure that the subsoil is in good condition. For this reason, in general the subsoil is renewed in the course of a turnout renewal. During a ballast cleaning task, the subsoil generally cannot be improved. Therefore the assumption can be made that the differences shown in Figure 53 are due to a significant extent to the subsoil or its condition. Proof of this cannot be provided at this point, but the evidence does strongly suggest that this proposition is correct. In this context it is also noticeable, that the ballast condition index after a ballast cleaning extends into the second range (Figure 52 – area 2: corresponding ballast condition). More detailed analyses should be carried out to confirm these results, on the one hand, and to identify optimisation potential or the real cause for the shown differences, on the other hand.

5.4 Validation of the ballast condition assessment results

The ballast condition was calculated for all 45 turnouts considered in detail and will now be validated. However, it is difficult to find the necessary data base. If there were objective recordings of the current ballast condition, the developed methodology would be obsolete. Nevertheless, an attempt was made to obtain data to verify the developed methodology.

The local responsible staff for turnouts were interviewed and asked to identify turnouts for which ballast problems were proven to prevail. In some regions it was possible to find such turnouts, which were of course included in the list of the considered turnouts (Table 1). In this context, although in the majority of cases only a visual assessment of the ballast condition was carried out, the expertise and experience of the persons who carried out these assessments should not be underestimated.

In summary, a subjective assessment of the ballast condition could be derived for the remaining 30 reference turnouts based on the condition grade 1 (very good to good ballast condition), 3 (poor ballast condition) and 5 (extremely bad to critical ballast condition). For validation purposes, it was subsequently necessary to compare these with the calculated ballast condition index. Therefore, the first two sections of the ballast condition index were combined under condition grade 1; grade 3 corresponded to the third section, and grade 5 to the last. The comparability of the two evaluation methods with regard to the ballast condition is given in the best possible way, and the results are visualised in Figure 54.

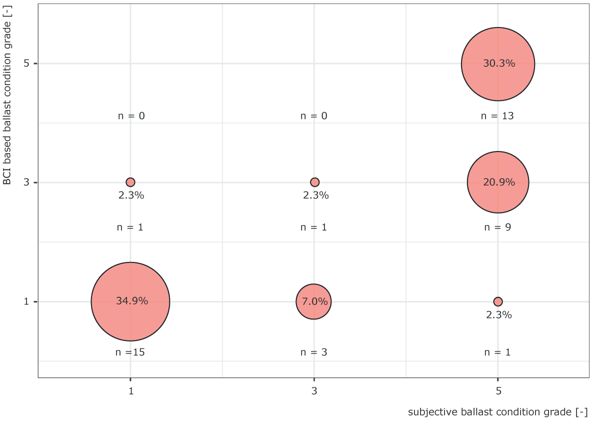

Figure 54 Comparison of subjective and data-based ballast condition grade.

It is immediately noticeable that the entries within the diagonal, i.e. those turnouts for which an identical statement about the ballast condition could be deduced based on the different evaluation methods, form the majority with 67.5% (29 turnouts). A relatively large proportion of the remaining turnouts, 20.9%, have a subjective ballast condition grade of 5 and a measured, data-based ballast condition index of 3. This result can be explained by the fact that it can sometimes be very difficult to assess the condition of the ballast accurately during visual inspection, as the boundaries are fluid. The remaining part of all considered turnouts (11.6%) shows no correspondence between the different variants of the condition description. Overall, this analysis showed a high degree of correlation between the subjective assessment of the ballast condition (based on a ballast excavation or data from the subjective visual inspection) and the objective assessment based on the ballast condition index. This confirms the results of the BCI and shows that the analysis of power density spectra can be practically applied to assess the ballast condition.

5.5 Investigations about the development of the ballast condition

Similar to the development of the standard deviation over time, knowledge about the type of deterioration is also necessary to describe the condition of the ballast. The procedure is to be understood analogously to the one described in section 4.3.2. The development of the ballast condition index over time was calculated, and subsequently attempts were made to approximate this by means of various functions. In this context, a linear, a quadratic and an exponential function were chosen to serve as base, and the quality of the adaptation was assessed by the coefficient of determination R^2. The corresponding visualisation is shown in Figure 55.

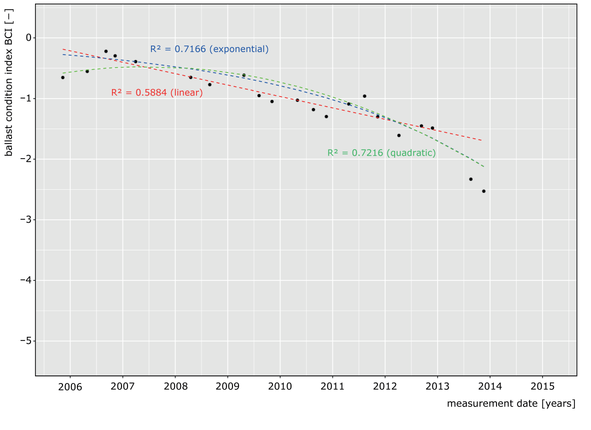

Figure 55 Adjustment of the ballast condition index deterioration models.

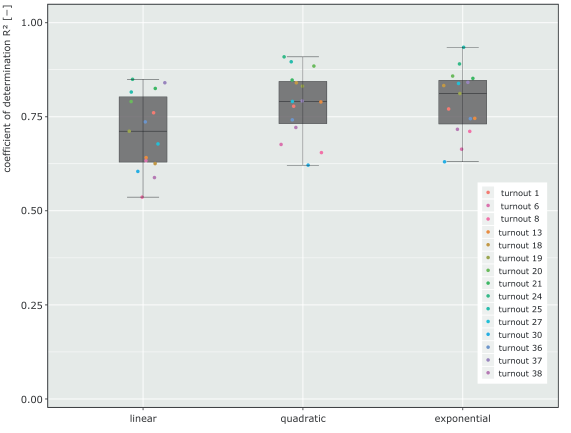

Figure 56 Comparison of different BCI deterioration models.

Within Figure 55, a graphical comparison of the different regression models is shown. It can already be seen that the exponential as well as the quadratic models adapt very well to the real process of deterioration, whereas the linear model shows some deviations. A similar situation can be seen within the observation of 15 turnouts (Figure 56). Modelling with an exponential and a quadratic function has the highest coefficients of determination; the linear function cannot keep up in this respect. As a result of this and the fact that component deteriorations are often modelled using exponential approaches, this form is determined by the development of the deterioration of the ballast condition over time and is used for further investigations. However, when considering the different turnouts, it has been shown that the development of the ballast condition, especially in the first years after renewal, is very linear and only with increasing age / increasing load, a strong tendency towards an exponential trend can be identified. This circumstance has to be investigated further in the context of a comprehensive deterioration analysis.

5.5.1 Ballast deterioration analysis across turnouts

Without paying attention to specific superstructure parameters and other properties of the different turnouts, an overall picture of the ballast condition should be determined. It is clear that within this consideration certain variations will occur, but it should be possible to derive a tendentious trend. It is also clear that the 45 turnouts which are combined within this evaluation cannot generate a comprehensive deterioration function. Nevertheless, an attempt should be made to establish a tendentious progression and a statement about the most probable form of deterioration. This also raises the question about the most appropriate reference parameter which should be used to represent and compare the ballast condition for different turnouts.

5.5.1.1 Reference parameter for analyses spanning multiple turnouts

Up to now, all deterioration processes, whether related to the standard deviation or to the ballast condition index, have been considered as a function of the asset's age. This is perfectly good, as up to now only asset-specific results and conclusions have been obtained. Furthermore, the asset age is a useful reference parameter, since all economic models considered in detail in this thesis are based on the asset age (and take into account the load experienced over time via load classes). Now, however, different turnouts should be compared, meaning that the asset age cannot be used here anymore. Rather, a reference parameter must be chosen which also takes into account the total load that a turnout has experienced over time.

In this context, the cumulative load appears to be the most appropriate reference parameter. On the one hand, the age of the turnout is implicitly taken into account (the older the turnout, the higher the cumulative load), and, on the other hand, the daily load - and thus implicitly the location of the turnout is also taken into account (the higher the daily load, the higher the line class and the higher the cumulative load). Thus the cumulated turnout load actually represents an ideal reference parameter for comparing different turnouts.

However, the fact that there is no information available in Austria about the cumulative load of turnouts is problematic in this context.

Thanks to an innovative combination of different data sources, it was recently possible to obtain information about the main traffic direction of turnouts (Figure 13). A model was developed for open track and for a similar problem to calculate the cumulative load for various conditions (Hansmann, 2015). Unfortunately, no such data or models exist for turnouts regarding the actual load, so a very simplified model is assumed (Formula 16).

$$CTL = 0.8 \cdot t \cdot DTL \qquad (16)$$

CTL stands for the cumulative total load of the currently considered turnout, t describes the time period since the renewal in days, and DTL is the actual daily total load of the turnout in gross tons. A graphical representation of this very simplified model is shown in Figure 57. The relevant DTL value for the considered turnout is known or can be determined by the Austrian Federal Railways. The asset age t can also be determined from inventory data. The preliminary factor of 0.8 pictures the average growth of the traffic load over the whole observation period. If this preliminary factor were not taken into account, the conclusion would be that the daily load did not change during the period considered.

This assumption is even further away from reality than the providence of the factor 0.8. Of course, discussions or confirmatory investigations can be made about the value of the preliminary factor as well as the actual progress of the daily turnout load.

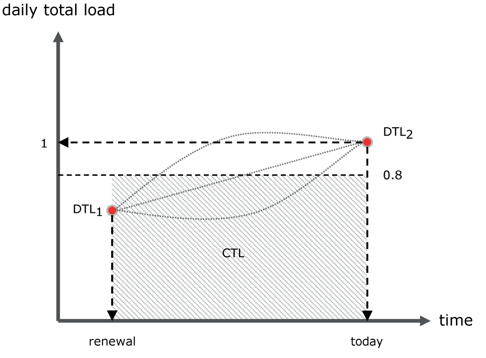

Figure 57 Cumulative total load calculation model.

Probably, a more in-depth investigation would show that different pre-factors would result, since different turnouts can be expected to cause different growth in traffic load over time. Likewise, by applying the model shown, it is assumed that there has been no change in the boundary conditions during the entire period of operation and therefore a linear growth can be assumed. This also represents an approximation to a certain extent, but compared to the data otherwise available, this is still the only way to compare turnouts with different daily loads. However, as no further data are available, this very simple model is used and applied. Due to the fact that the application is done for all turnouts, the tendency of the load assumption is definitely sufficient.

5.5.1.2 Overall progress of the ballast condition

Based on the cumulative load separately determined in this way for each turnout, an overall trend of the ballast condition as a function of the cumulative load can be shown (Figure 58). For this purpose the cumulated load was summarised in groups of 25 million gross tonnes each, and the corresponding values of the ballast condition were presented as boxplots. The group width of 25 million gross tonnes corresponds to a time span of about 1.5 years with a daily load of 46,000 gross tonnes. For analyses covering several turnouts, this seems to be sufficient, considering that four measuring runs are usually carried out per year, and thus the ballast condition index can also be calculated four times.

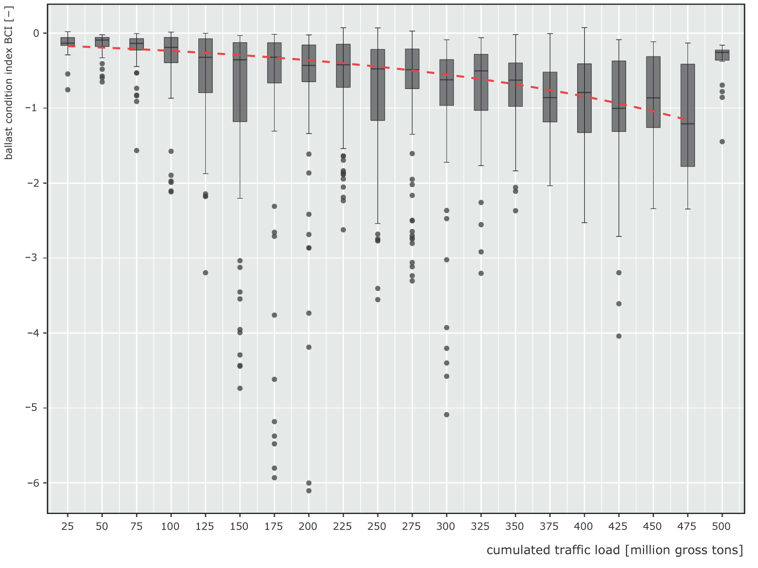

Figure 58 Summarised ballast condition index development over the cumulated load.

An exponential function was determined for the approximation, which refers to the medians of the box plots of each individual data series, i.e. of each individual load class. All turnouts that are considered shortly after renewal show a rather linear progress of the ballast condition index. Only from a cumulative load of approximately 250 million gross tonnes onwards an over-linear and thus exponential behaviour can be recognised, which, when applied to the entire area under consideration, leads to a coefficient of determination of 94.2%. From a turnout age of roughly 15 years at a constant average load of 46,000 gross tonnes (corresponding to the point at which the linear changes to a more exponential curve), the ballast condition deteriorates in an over-linear manner. Of course, within this analysis there are, in some cases, very large variations, which appear due to the parameter diversity or the descriptive methodology of the model. The ballast condition indices of those turnouts, which show a cumulated load of about 500 million gross tons, cannot be explained. The number of turnouts in this group is little and thus cannot be taken into consideration within statistical analyses. In this respect, even deeper analyses on a broader data base would be necessary.

However, a basic statement can be derived from Figure 58: The condition of the ballast deteriorates linearly over a very long period of time, whereby a tendency towards an over-linear deterioration is recognisable from a certain cumulative load.

If this point in time can be predicted as precisely as possible in the future and thus in any parameter-specific, or even turnout specific case, then ballast problems can be identified very early, and the necessary maintenance tasks can be planned with a correspondingly long preparation time.

Since a holistic view of the ballast condition index, based on all turnouts available for analyses, has now been prepared, the opposite approach will be pursued in the following. Therefore, the following consideration will again refer to one turnout only; and, in this context, it will be investigated whether there are differences with regard to the ballast condition in the different areas within a turnout.

5.5.2 Ballast condition description for different turnout sections

The fact that an impact loading, i.e. a high force impact into the ballast superstructure, caused by dynamical loads, leads to a high deterioration of the ballast condition and to ballast breakage has already been formulated (Berghold, 2016). It could also be shown by means of Figure 38 that a higher deterioration of the geometric parameters can be expected in areas where a hit can occur (common crossing area as well as at the insulated rail joints in front and after the turnout). In the following, again based on the already argued separation of a turnout into different areas (Figure 36), it will be examined whether similar statements are also permissible for the ballast condition.

For this purpose the longitudinal level of the respective areas was extracted and provided as input into the calculation methodology described above. The admissibility of this approach can be confirmed by the considerations in section 5.2.1. A visualisation of this is given in Figure 59. The development of the ballast condition index over time can be seen above. The representation positioned in the respective lower left corner provides information about the area currently under consideration.

Figure 59 (a) shows the progression of the ballast condition, calculated for the entire length of a turnout. The coloured horizontal lines represent the limit values of the different ballast condition indices defined in section 5.3.3. It is very clearly visible that a deterioration of the ballast condition is visible, but the values are situated in a non-critical area near the limit between area 1 and area 2. It can therefore be assumed that there are currently no ballast problems and that ballast wear is still limited.

Now the examination of the ballast condition is carried out for each individual sub-area of the turnout. Figure 59 (b) shows the development of the ballast condition for the area between the front of the turnout and the first welding joint.

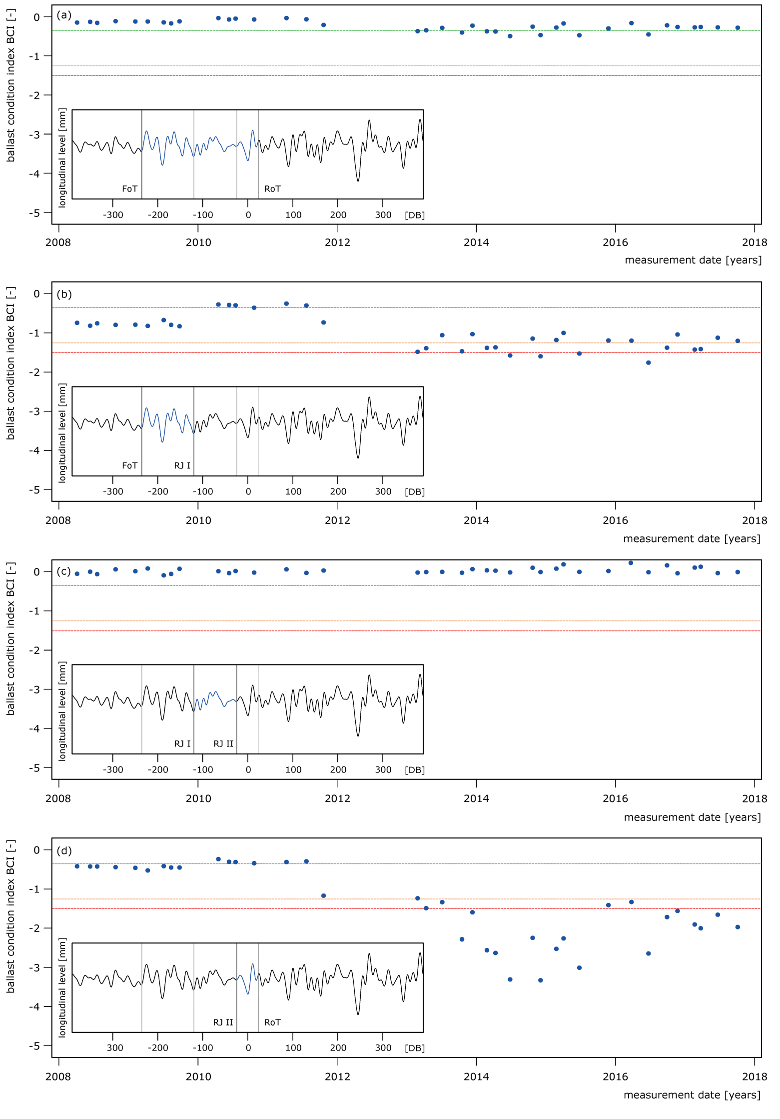

Figure 59 Ballast condition development for different turnout areas.

It is very clearly recognisable that, in this area, the ballast condition, at least from the year 2013 onwards, is in a poor / critical range and that ballast problems definitely prevail, without being able to identify this circumstance in the overall consideration of the turnout (Figure 59 (a)).

The reason for the poor ballast condition is again assumed to be the presence of a moderately maintained insulated rail joint at the front of the turnout and the propagation of the fault into the turnout.

On the contrary, Figure 59 (c), which visualises the analyses of the closure panel, shows no abnormalities. These results correspond very well with those related to the geometrical parameters. This area is therefore also uncritical in relation to the ballast condition.

A completely different picture emerges again when looking at Figure 59 (d), which describes the development of the ballast condition in the common crossing area. Here, too, it can be seen that an extremely distinct deterioration of the ballast prevails. Again, from 2013 onwards, it can be expected that there will be problems with the ballast, some of which will be immense, whereby the ballast condition can no longer be lifted into an uncritical area at all. All these statements can be made for the common crossing area, although the overall view of the turnout has shown a deterioration, but, by no means, such a critical condition.

This detailed investigation is concluded by the analysis of the area in front and after the turnout, which is shown in Figure 60. These areas are not included in the analysis shown in Figure 59. However, it is assumed that knowledge of the ballast condition in these areas allows for an explanation of the development of the ballast condition within the turnout.

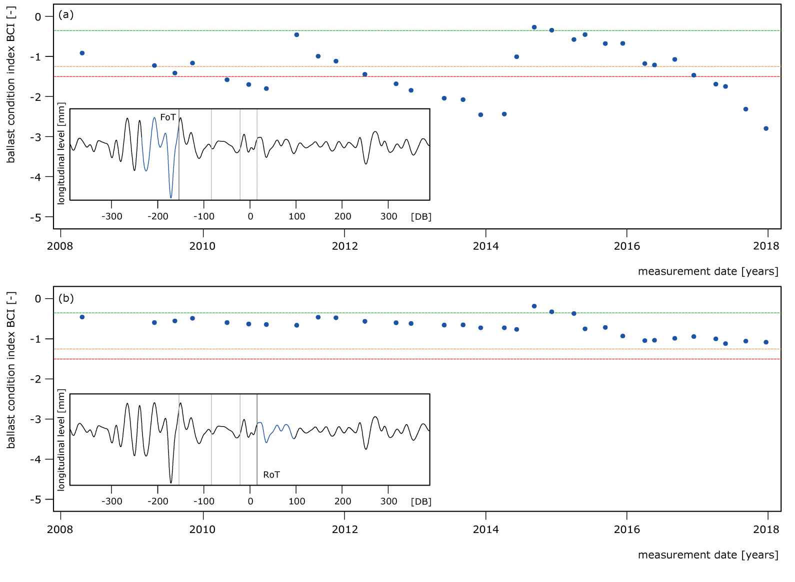

Figure 60 Ballast condition development before and after the turnout.

The upper graph (Figure 60 (a)) shows the analysis for the front of the turnout. For the first time within a ballast condition analysis, the effect of maintenance work can be seen. As this is again the area of an insulated rail joint, it is assumed that the improvements in the years 2011 and 2014 can be explained by a complete exchange of this joint including the replacement of the ballast underneath. However, it is now clear where the high degree of ballast deterioration in the first area of the turnout comes from. This originates from the area in front of the turnout, meaning that the theory or assumption established in section 4.4.2 can be confirmed at least a little further.

As expected, the rear of the turnout (Figure 60 (b)) shows a very homogeneous progression without any peculiarities, although a certain trend towards worn ballast is also discernible.

In summary, it can be established that, with the developed methodology for describing the condition of the ballast, it is possible to characterise not only entire turnouts but also individual sub-areas of them. It could be shown that observations of the ballast condition over the entire length, which do not give any indication for the assumption of ballast problems, smooth the result in part to such an extent that locally limited critical areas may not be identified.

Of course, this statement must be put into the context of the entire turnout. With regard to asset management, the question is whether a ballast cleaning is necessary or not. If this maintenance activity is carried out, the ballast of the entire turnout is, of course, cleaned, and not only individual sub-areas. Nevertheless, in some cases a small-scale ballast replacement is executed in old turnouts to squeeze out additional service life. However, in this thesis a ballast cleaning action of the total turnout is taken into consideration as this type of work is often treated as a standard maintenance action. Thus, also the necessity for additional maintenance actions such as small-scale ballast replacement can be assessed under certain circumstances. However, a closer look at the limits to be applied to the different areas would still have to be taken in this context, but the basic possibility of applying this method to smaller areas has been shown and proven.

5.6 Ballast cleaning prediction model

The last step within this chapter is the development of a prediction model for a possibly necessary ballast cleaning, which will combine and link all the knowledge gained so far.

The statement already made according to the prediction of necessary tamping operations applies here analogously. It does not seem to make sense at all to predict the necessity of ballast cleaning based on network-wide average values. For this purpose the total number of analysed turnouts would be too small, and, in addition, ballast cleaning is a complex activity, which is why a specific consideration of a turnout is always necessary anyway. Therefore, the behaviour must be assessed, a progression derived from the past, the current condition evaluated and thus the need for ballast cleaning concluded.

First of all, the knowledge gained so far, which is necessary for model generation, will be briefly summarised:

- On the one hand, it was possible to develop a methodology which, based on wavelength analyses as well as certain simplifications or approximations, allows the condition of the ballast to be assessed over the entire length of the turnout and a time progression to be derived from this.
- Using various models, the deterioration behaviour of the ballast condition was analysed, with exponential modelling providing the highest degree of determination, meaning that the deterioration process is abstracted as an exponential function.
- By knowing the time of application of ballast cleaning tasks, their effect could be evaluated, and the gained knowledge can be used for model development.

Based on these findings, a prediction model was developed to verify whether a ballast cleaning will be necessary for specific turnouts in the foreseeable future or not. The relevant graphical representation is visualised in Figure 61. For later validation, not all existing measurement data were included in the analysis, but rather the year 2011 was chosen as the reference point and thus all measurement data (black points) available up to this date were considered. Based on this, an exponential function was used to describe the probable development of the ballast condition over time. As mentioned in section 5.3.3, the third range (poor ballast condition), which is limited at the top by the orange line and at the bottom by the red horizontal line in Figure 61, is some kind of attention area. For this reason, the point of intersection of the deterioration function with the upper limit of this area is defined as the point when the need for ballast cleaning should already be recognised, and all schedules for the earliest possible maintenance deployment should begin.

In the example shown here, this is the year 2014, so it would have been possible to predict as early as the year 2011 that the ballast condition would fall into the critical range in 2014. The planning activities could also have been initiated at that time. With regard to maintenance planning, it would have been possible to gain a lead of almost three years using the model, and three years would have been sufficient to plan a ballast cleaning task.

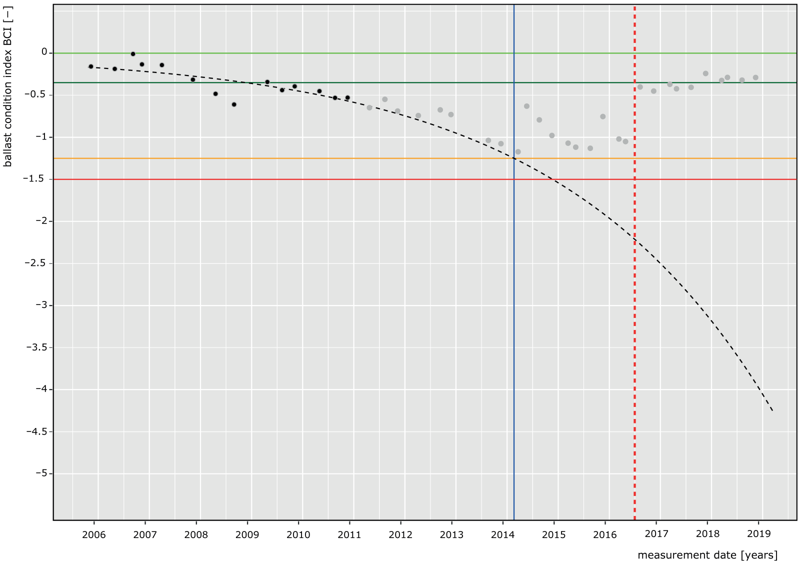

Figure 61 Model based prediction of a ballast cleaning task.

Of course, in the end or rather for the validation of such models, the comparison with the real behaviour is necessary. This comparison is also shown in Figure 61. In the example considered, a ballast cleaning was actually carried out in 2016 (dashed vertical line shown in red). The comparison between the actual measuring points and the development predicted by the exponential function shows an extremely small deviation, which means that the prediction quality can be classified as extremely precise.

Apparently, the responsible persons for turnouts recognised approximately in 2014 that there were ballast problems with regard to the considered turnout. In relation to the long preparation time, another action was taken to maintain the turnout at least in the meantime. At this point, it can only be assumed that these were tamping operations with an extremely high proportion of new ballast. Otherwise, no maintenance activity is known that would bring the ballast condition index back into the first range (at least in the short term and unfortunately not sustainably).

Nevertheless, a comparison between reality and the prediction model shows a good agreement and confirms the suitability of the calculation method for describing the ballast condition. Once again, a combination of findings, which are largely based on measurement data, and knowledge of system-related interactions, has enabled a very manageable model to be developed and validated for the description of the ballast condition and for the derivation of the necessity of a maintenance activity.

5.7 Conclusion

At the beginning of the chapter, the necessity of a ballast condition description and the possibility of a conclusion about the requirement for ballast cleaning in an economic context or with regard to life cycle costs were discussed once again. Moreover, the clear methodical difference between the description of geometrical parameters, which can be derived directly from measurement signals, and the evaluation of a component condition, which can be identified by means of partly complex and innovative analysis methods, were explained.

Based on this comparison, various data sources and methods were presented, which are currently used or could be used to draw conclusions about the current condition of the ballast. In the end, the main statement concentrated on the methodology of fractal analysis, which is also capable of drawing conclusions about the current condition of the ballast from longitudinal level measurements of the track recording car. Since turnouts, however, have to be treated significantly differently from the characteristics of open track, a different analysis method was developed, although thematically very similar to fractal analysis.

Power density spectra make it possible to subdivide input signals into their wavelength ranges and, by looking at different ranges, to determine the corresponding changes over time. On the one hand, the theoretical background of the basic calculations was explained in detail and the properties of the calculation methodology were demonstrated by means of theoretical considerations and practical examples. On the other hand, certain components of the fractal analysis, such as the linear approximation of certain wavelength ranges within the respective representative curves, were extracted and adapted for use in power density calculations. Thus, a methodology could be created which, based on longitudinal level measurements, makes it possible to describe the ballast condition in a turnout.

Since the slope of the approximation line to the power density curve in a wavelength range between 3 m and 7.6 m is perhaps not primarily associated with the current ballast condition within a turnout, a very broad validation was shown.

In this context, 15 turnouts were considered where ballast cleaning was carried out, so that a very poor ballast condition can be assumed in this regard. The analysis was also based on the assumption that a very good ballast condition prevails after ballast cleaning. Based on these assumptions, it could be shown that, with the calculated ballast condition index, it can be distinguished between a good and a poor ballast condition, and that the differences in this respect are statistically significant. In addition, four areas within the ballast condition index could be defined, and the corresponding ballast condition described verbally.

Based on these results, the quality of the ballast between a turnout renewal and a ballast cleaning task could be compared. In addition, it was possible to compare the results of the ballast condition assessment by the ballast condition index with the results of visual inspections or ballast excavations, whereby a very high degree of agreement between the two methods could be demonstrated.

For later modelling, it was necessary to investigate the manner in which the condition of the ballast deteriorates. For this purpose, a linear, a quadratic and an exponential deterioration approach were compared, whereby the exponential model was characterised by the highest degree of determination and was thus used for the model formation. In this context, an attempt was also made to develop a ballast deterioration model for overall turnout considerations. Due to the small number of analysed turnouts, the informative value is limited, but certain basic tendencies can still be derived from it, and a possibility for the comparative consideration of different turnouts with different basic conditions could be presented.

The possibility of describing the ballast condition for shorter turnout areas, analogous to the standard deviation calculation, was also considered. It could be shown that with a slightly adapted methodology, areas with poor ballast condition within turnouts can be identified, whereby the overall evaluation would not allow any conclusions to be drawn in this respect. It could thus be shown that even small-scale ballast problems can be detected and, if necessary, predicted.

Finally, the collected findings were combined within the model generation for the prediction of future necessary ballast cleaning tasks, and a methodology was derived from this, which is based on an exponential regression and takes into account all local effects of the considered turnout. The function of the methodology could be shown, and a comparison between the model and reality could be made. The model for the prediction is simple, but nevertheless all relevant influencing parameters can be taken into account.

The final point in this chapter is again a reflection on the formulated research questions (section 2.5). The second question dealt with the topic of generating additional information from the available measurement data:

Research question 2

Is it possible to adapt or process the existing measurement data of the track recording car in order to extract information for turnouts? What would a possibly necessary reworking process look like?

Answer to research question 2

This question can now be answered in full, since a partial answer was already possible within the considerations about the tamping prediction. With regard to the evaluation of the condition of the ballast, this question can now also be answered with a definitive yes. Of course, as could be shown in detail, a process of data preparation, validation and modelling is necessary to extract the required information. However, it must not be forgotten at any time that the basic data are available anyway, and that the additional information about the ballast condition and the need for ballast cleaning is thus provided free of charge, i.e. without further measurement data or the need for new measurement systems. Against this background, the expenditure mentioned above again appears to be quite justified.

Research question 4

Do smart analysis methods also allow for component-specific condition monitoring? Is reality described with sufficient accuracy?

Answer to research question 4

Yes, the procedure was explained in detail based on longitudinal level measurements and the condition of the ballast. It is possible, for example, to derive indicators for describing the condition of the ballast from longitudinal level measurements. These indices can then be used to identify the need for maintenance activities at an early stage or to describe critical areas more precisely. There are also other ideas for deriving further condition indicators for other components from existing measurement signals. However, these ideas will be discussed in more detail in the course of the outlook (chapter 7).

6

LIFE CYCLE MANAGEMENT AND ITS IMPLEMENTATION FOR TURNOUTS

The central decision in asset management must be made between renewal and maintenance (Marschnig & Veit, 2012). Thus, two different scenarios are compared whereby the aim is always to identify the economic service life. In case of an equivalent replacement the optimum point in time for a turnout renewal is reached when the total annual costs reach a minimum. From a purely economic point of view, this means not more than that the depreciation which decreases due to an extension of the service life is compensated by the costs of additional maintenance. The mathematical formulation for calculating the economic service life for an equivalent reinvestment (Veit, 2019) is given by Formula 17.

$$\frac{dD}{dt} = \frac{\frac{dM}{\alpha} + \frac{dCOH}{\alpha}}{dt} \tag{17}$$

D stands for depreciation, i.e. the investment costs divided by the actual year of service life, $\frac{M}{\alpha}$ for the maintenance costs per year, and $\frac{COH}{\alpha}$ for the cost of operational hindrances COH per year (both calculated over the entire service life). As long as depreciation decreases more than maintenance costs and COH increase, the optimal time for reinvestment has not yet been reached, and the renewal of an asset does not make sense, based on an economic point of view. If the reduction of depreciation is equal to the increase of maintenance and operational hindrances costs, the economic service life of a turnout is reached as then the annuity function would increase again.

A wide variety of models have become established. A universally applicable method in this context is the annuity monitoring (Veit, 1999). This method can therefore be used to determine when it is useful to renew an infrastructure component, based on economic considerations. As railway infrastructure deals with costs only (no revenues), the annuity represents the average annual dynamic costs; their calculation has already been described in section 2.4.2. This method will be used in the following to move towards a specific asset management for turnouts. First, however, the asset to be investigated, must be determined.

6.1 Asset and boundary condition definition

All turnouts listed in Table 1 are available for selection with regard to the turnout considered as an example. Since both the application of the methodology for the prediction of a tamping actions and the application of the methodology for the prediction of a possible necessary ballast cleaning shall be shown, the consideration of a turnout on concrete sleepers is suitable. With this type of turnout and under certain circumstances, a ballast cleaning could be expected (Wilfling et al., 2020).

However, this circumstance restricts the selection to 32 turnouts. The actual question of asset management is concerned with determining the optimal time for reinvestment, which is why the following consideration should focus on turnouts approaching the end of their expected service life. If a minimum age of 20 years is assumed, 24 turnouts are still available for selection. The daily load as well as the speed at which the turnout is passing through should be relatively high, so that a reliable statement about the occurring wear can be deduced within a short period of time.

Thus, the selection is limited primarily to turnouts with a branch radius of 1,200 m. From the remaining possibilities, turnout no. 27 - a straight turnout with a branch radius of 1,200 m, a common crossing, mounted on concrete sleepers, with a 60E1 rail profile and a daily load of around 65,400 total gross tonnes, installed in 1994 - was selected for demonstrating the application of asset management methods.

The specification of the system to be considered in detail is thus complete and the general conditions are again clearly summarised in Figure 62. All maintenance activities mentioned in section 2.4.1, which have to be specified below, have also already been included.

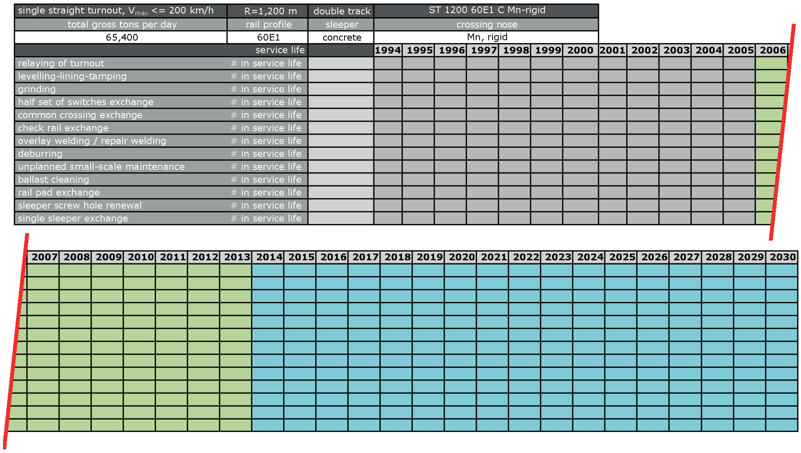

Figure 62 Project specific boundary conditions and asset definition.

6.2 Maintenance frequencies for filling the working cycle

Filling the working cycle with the necessary maintenance tasks is the next necessary step. Therefore, a subdivision of the timeline must be made according to the available data:

- The first section covers the period from the installation to the year from which measurement data are available (2006). Since no measurement data and no information on maintenance activities performed are available in this period which would make it possible to fill the working cycle, network-wide mean values or expert knowledge must be used which have been provided to create standard working cycles (section 2.1.2). This time range is highlighted in grey in all following figures.
- The second section, immediately following the first, covers the years 2006 till 2019, but not all the available data will be used to draw a comparison between the model and reality. In this context, the predictions are calculated starting in 2013. Within this period, measurement data out are available, which can be used to fill the working cycle. This time period is highlighted in green in all the following figures.
- The third and thus last section begins in 2014 and is open at the back. Since the year 2013 has been defined as the current point in time, all necessary maintenance activities to fill the specific working cycle must be predicted. Since models for prediction are not available for all maintenance activities, network-wide averages are used again for certain maintenance activities. Corresponding indications will be given later. The end of this area remains open for the time being, as this represents the final result, i.e. the total service life. This temporal range is highlighted in blue.

At this point, reference should be made once again to Figure 9, which reflects the order of the individual cost items, both based on unit costs and on life cycle costs. Using the ordered life cycle costs, the individual maintenance activities are discussed in detail below, and an attempt is made to fill the working cycle for each task.

6.2.1 Relaying of a turnout

Relaying of a turnout is an investment action; indeed it is absolutely necessary to consider it, especially in context of subsequent economic calculations. The reinvestment date is entered at the beginning of the life cycle. Since only one life cycle is represented, there are no further entries within this line.

6.2.2 Ballast cleaning

With regard to this maintenance activity, the temporally different approach is applied for the first time. Within the first period between 1994 and 2005, it can be assumed, based on network-wide evaluations, that no ballast cleaning took place. This statement can be made with a high degree of certainty, as this area only extends over ten years, and precisely this area is at the beginning of its life cycle, which is why a ballast cleaning can be classified as very unlikely in this context. The first section of this line therefore remains empty. More interesting in this context is the second section, which is assessed based on measurements.

6.2.2.1 Ballast cleaning already carried out

Using the developed methodology, an assessment of the ballast condition was carried out for the period between 2006 and 2013 (Figure 63). Based on the degradation of the calculated ballast condition indices, it can be concluded that no ballast cleaning took place in the period under consideration. At this point, reference is made again to Figure 51 where the effect of ballast cleaning can be seen indirectly. Such a high improvement of the BCI cannot be seen in relation to the ballast condition index in Figure 63, which is why the second time period within the working cycle and in relation to the ballast cleaning also receives no entry.

6.2.2.2 Prediction of a possibly necessary ballast cleaning task

The need for ballast cleaning in the third time period must be determined based on a prediction. In this context, the developed model (section 5.6), based on the input data already presented, is again applied. The result of the prediction is visualised in Figure 63.

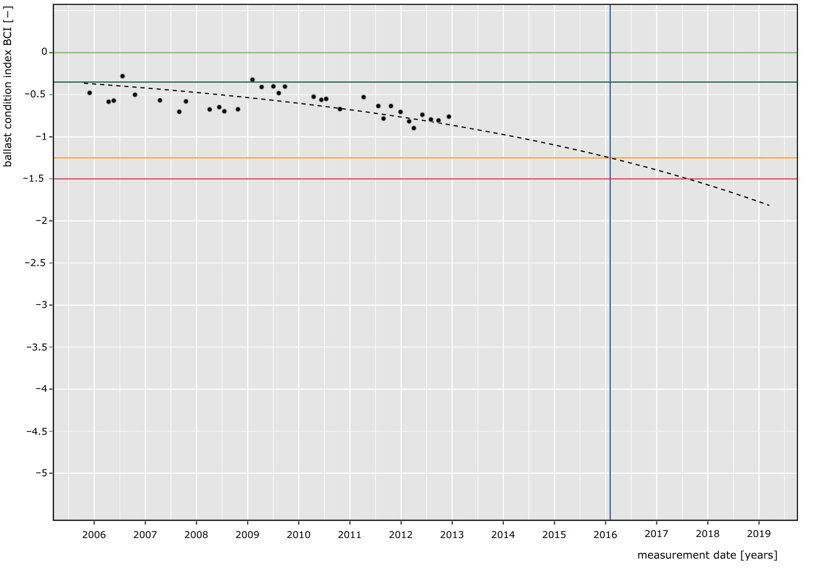

Figure 63 Ballast cleaning prediction for the considered turnout.

The exponential modelling allows for an intersection with the beginning of the attention area in 2016 to be identified. Thus, this point in time is initially regarded as the time for a necessary ballast cleaning. This task is therefore deposited in the working cycle in the referring year. This means that the line of ballast cleaning can be filled from 1994 to 2016. A further provable derivation of statements is not possible based on the existing model. Of course, it could be assumed that the ballast is again in perfect condition after the ballast cleaning and thus again fulfils its function for the period of the next 22 years without any problems.

However, this is an optimistic assumption as older turnouts cause higher stresses into the ballast due to a higher degree of dynamics of the entire system, so that this circumstance is countered later by a sensitivity analysis. However, this analysis can only be carried out at the end, which is why it is primarily assumed that no further ballast maintenance will be necessary after the cleaning in 2016. The filling of the corresponding line in the working cycle is thus completed.

6.2.3 Levelling - lining - tamping

The next most important maintenance task under consideration is tamping. With regard to this activity, the temporally different approach is again applied. In the first area, i.e. from 1994 to 2005, network-wide averages for this turnout type are used. The relevant standard working cycle has a tamping interval of four years, which is deposited into the specific working cycle of the considered turnout. Afterwards, i.e. within the period between 2006 and 2013, measurement data are used again, as no information on tamping operations carried out is available.

6.2.3.1 Already carried out tamping actions

Using the methodology developed in section 4.3.4 for the identification of tamping actions which have been carried out in the past, the filling of the working cycle could be further advanced. The model (Figure 64) provided tamping tasks carried out in 2006, 2008 and 2011. These three actions can thus be integrated into the working cycle, which means that only the consideration of the third time period is still outstanding.

6.2.3.2 Prediction of the next necessary tamping task

As in the case of ballast cleaning, the time for the next tamping operations, starting in 2014, is described using the developed prediction model, which was explained in detail in section 4.5. The results from the application are shown in Figure 64.

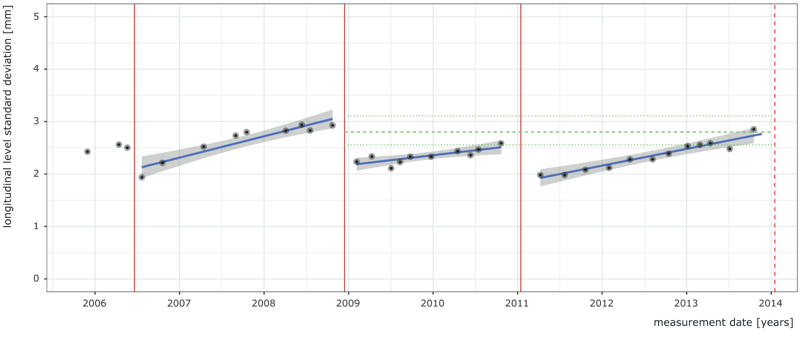

Figure 64 Tamping task prediction for the considered turnout.

It can be seen that the next tamping task would have to be carried out in 2014 based on the behaviour from the past. This point in time is relatively close between the second and third area in terms of time. The execution is stored in the working cycle in the year 2014.

6.2.3.3 Comprehensive consideration of maintenance tasks

However, the assumption about the need for tamping tasks in the future can be somewhat limited. A ballast cleaning was already predicted for the year 2016 in section 6.2.2. If now the results of the two prediction models are combined, it can be deduced that after the cleaning task, the ballast condition is again very good and thus a tamping interval identical to that at the beginning of the service life will be necessary. Thus, at least a certain restriction with regard to the frequency of the tamping operations necessary in the third area could be realised and, starting after the ballast cleaning in 2016, a tamping interval of 4 years is again assumed and stored within the working cycle. Of course, due to the existing uncertainties, this assumption must also be validated by means of sensitivity analyses at the end of the calculations. Thus, the line of tamping actions could be completely filled for the time being. The current partly filled working cycle is shown in Figure 65.

single straight turnout, V_{max} <= 200 km/h	R=1,200 m	double track	ST 1200 60E1 C Mn-rigid
total gross tons per day	rail profile	sleeper	crossing nose
65,400	60E1	concrete	Mn, rigid

	service life		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
relaying of turnout	# in service life	1	1	-	-	-	-	-	-	-	-	-	-	-	-
levelling-lining-tamping	# in service life	9	-	-	-	-	1	-	-	-	1	-	-	-	1
grinding	# in service life														
half set of switches exchange	# in service life														
common crossing exchange	# in service life														
check rail exchange	# in service life														
overlay welding / repair welding	# in service life														
deburring	# in service life														
unplanned small-scale maintenance	# in service life														
ballast cleaning	# in service life	1	-	-	-	-	-	-	-	-	-	-	-	-	-
rail pad exchange	# in service life														
sleeper screw hole renewal	# in service life														
single sleeper exchange	# in service life														

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
relaying of turnout	-	-	-	-	-	-	-	-	-	-	-	-
levelling-lining-tamping	-	1	-	-	1	-	-	1	-	-	-	-
grinding												
half set of switches exchange												
common crossing exchange												
check rail exchange												
overlay welding / repair welding												
deburring												
unplanned small-scale maintenance												
ballast cleaning	-	-	-	-	-	-	-	-	-	1	-	-
rail pad exchange												
sleeper screw hole renewal												
single sleeper exchange												

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
relaying of turnout	-	-	-	-	-	-	-	-	-	-	-	-
levelling-lining-tamping	-	1	-	-	-	1	-	-	-	1	-	-
grinding												
half set of switches exchange												
common crossing exchange												
check rail exchange												
overlay welding / repair welding												
deburring												
unplanned small-scale maintenance												
ballast cleaning	-	-	-	-	-	-	-	-	-	-	-	-
rail pad exchange												
sleeper screw hole renewal												
single sleeper exchange												

Figure 65 Specific working cycle with predicted maintenance tasks.

Up to now, the filling of the working cycle could almost exclusively be based on models developed. However, all of these models have already been applied, which is why no more models are yet available for the remaining maintenance activities. For this reason, network-wide mean values are used for the remaining activities and these are entered into the working cycle. Nevertheless, the individual tasks will be discussed below, as this provides a good opportunity to present ideas, which measurement data or models could be used to describe or specify the necessity of the remaining maintenance activities.

6.2.4 Crossing nose exchange

Network-wide analyses suggest a service life of the common crossing of twelve years for the given loading. This interval is deposited in the working cycle, which results in a total of two crossing nose exchanges within the entire life cycle.

A crossing nose replacement is usually necessary if an abrupt component failure occurs or if the occurring wear is no longer acceptable. The first situation cannot be depicted within such examinations, which is why the focus is clearly placed on the detection of crossing nose wear. For this purpose, it would be possible to measure wear using templates within the visual inspection (Rainer, 2013) in order to be able to derive necessary maintenance activities under certain circumstances. Moreover, additional measurement data from the track recording car EM250 could also be used to generate a prediction model. In this context, the rotating laser, which is attached at the front of the measurement car, seems to have a high potential. Investigations of the Austrian Federal Railways have already shown respectable results (Figure 66). Even forward-looking technologies such as fibre-optic sensing (FOS), i.e. the recording and electronic analysis of acoustic signals recognised by fibre-optic cables in the vicinity of railway installations, seem to have the potential to describe the existing wear at the common crossing (Vidovic, 2020). Whether a relevant derivation of prediction models about a crossing nose exchange is possible will be shown in the future.

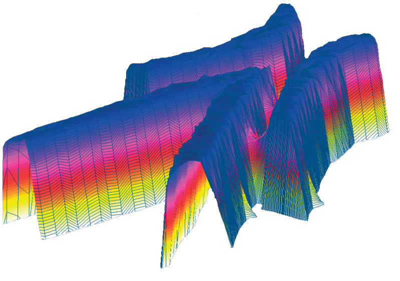

Figure 66 Common crossing wear description by using laser scan data.

6.2.5 Half set of switches exchange

With regard to the load class and the boundary conditions of the turnout, the half set of switches have to be replaced every 20 years, which is deposited within the working cycle. With regard to the possibility of describing wear and tear and deriving models, there could again be different approaches. Knowing that the half set of switches is replaced mainly due to wear, a possible data source could be the rail profile measuring system (section 3.2.4).

Here the measurement of the rail profile is done by lasers, which is why it should be possible, from a purely technical point of view, or even under certain circumstances by making minor adjustments to the measuring system (Schmid, 2013), to measure the profile of the switch panel and subsequently also the existing wear. From these data a prediction model could be derived to forecast the time for a replacement of the switch panel or the half set of switches. Of course, the results of the visual inspection would also provide a possible data base for the development of a corresponding wear and maintenance model. As already mentioned several times, the lack of a central maintenance data collection makes this task very difficult.

6.2.6 Sleeper exchange

The replacement of sleepers as a maintenance activity is in any case justified with regard to turnouts with wooden sleepers. This maintenance activity is generally not necessary for concrete sleeper turnouts. The statistical evaluations for turnouts within the current load class and under the given boundary conditions also show that no sleeper replacement is necessary. Therefore, the corresponding line in the working cycle does not receive an entry.

In relation to possible data sources for the creation of a prediction model, the track measurement car must again be mentioned first. For open track it could already be shown that the current condition of the sleeper can be deduced from gauge measurements using wavelength filtering (Landgraf, 2016; Lillin et al., 2018). Of course there are different geometrical conditions in turnouts, which have an effect on the gauge measurement, but the basic idea (possibly with minor adjustments) should also be applicable with regard to the description of the condition of turnout sleepers.

Of course, the visual inspection, with all its advantages and disadvantages, should be mentioned again at this point as a possible data source for creating a description model about the sleeper condition.

6.2.7 Grinding

It is known from network-wide considerations that a constant grinding interval of six years is applied for the given boundary conditions, which is why this activity is entered five times within the whole working cycle due to the lack of a prediction model.

This could be remedied by a detailed analysis of the so-called SOF measurement signals. These measurements were created by scanning the rail surface with a laser chord which is clamped at three points. The signal is available every 5 mm, whereby initial analyses have already shown the high potential with regard to the detection of squats.

Therefore, it should be possible, using in-depth analyses, first, to integrate the signal into the positioning methodology (chapter 3), second, to detect the defects on the rail surface which trigger a grinding action and third, to be able to derive the necessity of future grinding tasks from this. Acceleration measurements at the axle box could in principle also enable the derivation of such a model, nevertheless the current storage as a root mean square value (RMS) of this measurement signal prevents such investigations.

6.2.8 Other maintenance activities

Due to their value, low cost or low implementation frequency, the remaining maintenance activities are considered together. A sleeper screw hole renewal is, in turn, particularly relevant for wooden sleepers and is therefore not included in the present working cycle. The statements made with regard to the sleeper condition about the possibility of a description based on measurement data apply accordingly.

The rail pad exchange does not play a significant role with regard to the straight section of turnouts; and evaluations have also shown that no rail pad exchange has to be expected for the given boundary condition. With regard to the description of a possible rail pad wear, the rail inclination measurements could provide information about the current condition and possibly allow for a model derivation. However, more detailed investigations in this respect are necessary in any case.

With regard to the remaining maintenance activities such as overlay welding, check rail exchange, unplanned small-scale maintenance and deburring, no measurement signals are known which would allow for the deduction of a wear model. The proportionate costs do not primarily speak in favour of a detailed consideration of these activities, although neglecting them is not advisable. With regard to the working cycle to be filled for the considered turnout, one exchange of the check rail after 25 years, two overlay welding actions as well as deburring of the turnout every two years is deposited within the standard working cycle.

The small-scale maintenance, which is exclusively represented by an underlying statistical distribution anyway, is represented with 50% of its total costs in the first third of the life cycle, 100% of the costs in the second third and 150% of the small-scale maintenance costs in the last third, in order to take into account component deterioration. The working cycle thus completed in conjunction with the summary of the boundary conditions is finally shown in Figure 67 and thus subsequently provides the base for calculating the annuities and, by extension, all subsequent economic considerations.

single straight turnout, V_{max} <= 200 km/h	R=1,200 m	double track	ST 1200 60E1 C Mn-rigid												
total gross tons per day	rail profile	sleeper	crossing nose												
65,400	60E1	concrete	Mn, rigid												
	service life		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
relaying of turnout	# in service life	1	1	-	-	-	-	-	-	-	-	-	-	-	-
levelling-lining-tamping	# in service life	9	-	-	-	-	1	-	-	-	1	-	-	-	1
grinding	# in service life	5	-	-	-	-	-	-	1	-	-	-	-	-	1
half set of switches exchange	# in service life	1	-	-	-	-	-	-	-	-	-	-	-	-	-
common crossing exchange	# in service life	2	-	-	-	-	-	-	-	-	-	-	-	-	1
check rail exchange	# in service life	1	-	-	-	-	-	-	-	-	-	-	-	-	-
overlay welding / repair welding	# in service life	2	-	-	-	-	-	-	-	-	-	-	1	-	-
deburring	# in service life	17	-	-	1	-	1	-	1	-	1	-	1	-	1
unplanned small-scale maintenance	# in service life	37.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1
ballast cleaning	# in service life	1	-	-	-	-	-	-	-	-	-	-	-	-	-
rail pad exchange	# in service life	0	-	-	-	-	-	-	-	-	-	-	-	-	-
sleeper screw hole renewal	# in service life	0	-	-	-	-	-	-	-	-	-	-	-	-	-
single sleeper exchange	# in service life	0	-	-	-	-	-	-	-	-	-	-	-	-	-

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
relaying of turnout	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
levelling-lining-tamping	-	1	-	-	1	-	-	1	-	-	-	-	-	1	-	-	-	1	-	-	-	1	-	-
grinding	-	-	-	-	-	1	-	-	-	-	-	1	-	-	-	-	1	-	-	-	-	-	-	-
half set of switches exchange	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
common crossing exchange	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
check rail exchange	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
overlay welding / repair welding	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
deburring	-	1	-	1	-	1	-	1	-	1	-	1	-	1	-	1	-	1	-	1	-	1	-	-
unplanned small-scale maintenance	1	1	1	1	1	1	1	1	1	1	1	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
ballast cleaning	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
rail pad exchange	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
sleeper screw hole renewal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
single sleeper exchange	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 67 Filled working cycle as base for economic considerations.

6.3 Economic considerations

The methodology of annuity monitoring is based on the working cycle (Figure 67), as already explained in section 2.4.2. Within depicting the annuity function, specific annuities are calculated for a service life of one year, two years, and so on.

By considering the minimum within the annuity curve, conclusions can be made about the optimal time for a reinvestment. At the beginning, the calculation of the annuities for the reference scenario takes place, i.e. exactly the case which is currently represented in the working cycle (Figure 67). The relevant result of the annuity monitoring is visualised in Figure 68, whereby the calculation always takes place with an imputed interest rate of 0% (i.e. static) and once with an imputed interest rate of 5% (dynamic). This is to show the stability of the results. The imputed interest rate cannot be determined exactly for such a long period of time, or changes in the business environment may occur, which is why both variants are calculated and compared. For investment decisions, the dynamic calculation delivers a more critical statement, since the costs of capital commitment are taken into account. For following analyses regarding individual maintenance activities, the result of the static calculation is considered more critical, since the financial input of additional maintenance tasks is lower due to the dynamic calculation, compared to the static one.

The case under consideration represents a rather optimistic basic scenario. It is assumed that the ballast condition after the predicted ballast cleaning in 2016 is comparable to that at the beginning of the service life. Therefore, after the ballast cleaning, the tamping interval from the beginning of the service life can also be deposited.

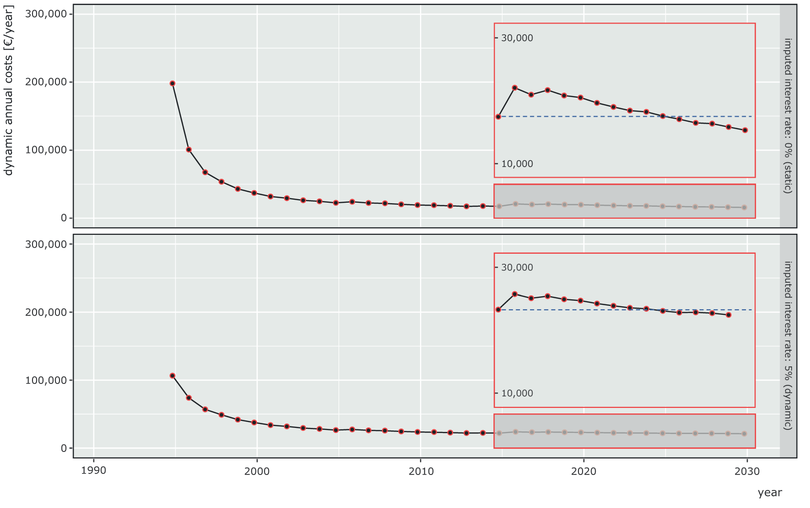

Figure 68 Annuity curve of the considered reference case.

In Figure 68, the ballast cleaning can be recognised as a sudden increase within the annuity curve in the year 2016. Under the described boundary conditions, the year in which the annuity falls below the level of 2015 (year before a ballast cleaning is necessary) can be determined, thus making ballast cleaning economically viable. This point in time is reached in the year 2025, regardless of which imputed interest rate is used as a base for the calculation. It can therefore be summarised that the economic viability of ballast cleaning can only be guaranteed if the turnout has a required remaining service life of more than ten years or that this maintenance task can extend the service life by more than ten years. If this is not the case, from an economic point of view, reinvestment of the turnout is preferable to ballast cleaning in 2016. However, assuming that no intensification of maintenance activities is necessary after the ballast cleaning, it can be concluded that if the maintenance can achieve a remaining service life of less than ten years, the economic efficiency of this major maintenance task is no longer given. Conversely, it can also be concluded that a turnout reinvestment is preferable to the possible ballast cleaning action, always assuming that maintenance activities at the same frequency are necessary after ballast cleaning.

Now the question can still be asked about the probability that the turnout will last another ten years after the ballast cleaning. With a strategic service life of 36 years for the given boundary conditions and the ballast cleaning carried out in 2016, there is still sufficient service life remaining, meaning the annuity can again fall below the level of 2015, resulting in lower annual costs for the entire turnout.

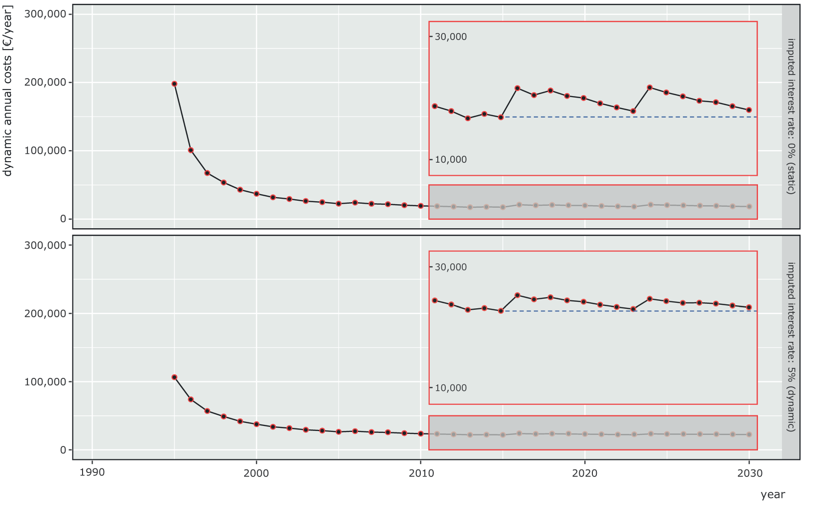

Figure 69 Annuity curve in case of a second necessary ballast cleaning in 2023.

In order to provide concrete evidence in this respect, a further scenario is considered. If an extension of the service life by ten years is necessary to justify the economic efficiency of a ballast cleaning task, it is no longer given if another ballast cleaning task becomes necessary within this period. This scenario can be seen in Figure 69 by depositing a second ballast cleaning in 2024. It can be seen that the annuity will, under the assumed boundary conditions, never fall below the level of 2015 within the framework of the strategic service life.

It can thus be shown that, in the event of an additionally required ballast cleaning within the first ten years after the initial ballast cleaning, the annuity will no longer fall below the level of 2015. Thus, in the case of a second necessary ballast cleaning, the profitability of the first one is also no longer given and the best solution from an economic point of view in this case would be a turnout reinvestment in 2015. It must not be disregarded that a rather optimistic basic scenario is still considered. Due to the increasing wear of components, it will probably not be possible to avoid an intensification of maintenance activities, which is why it can be assumed that an additional ballast cleaning, which may be necessary under certain circumstances, will become necessary at an earlier stage. This circumstance also suggests that the first ballast cleaning is no longer economical if a second maintenance activity of this type becomes necessary.

6.4 Sensitivity analyses

Sensitivity analyses are performed to account for uncertain input data and to take account of the fact that the reference case represents a rather optimistic scenario. With this method the influence of the frequency of maintenance activities can be visualised in detail.

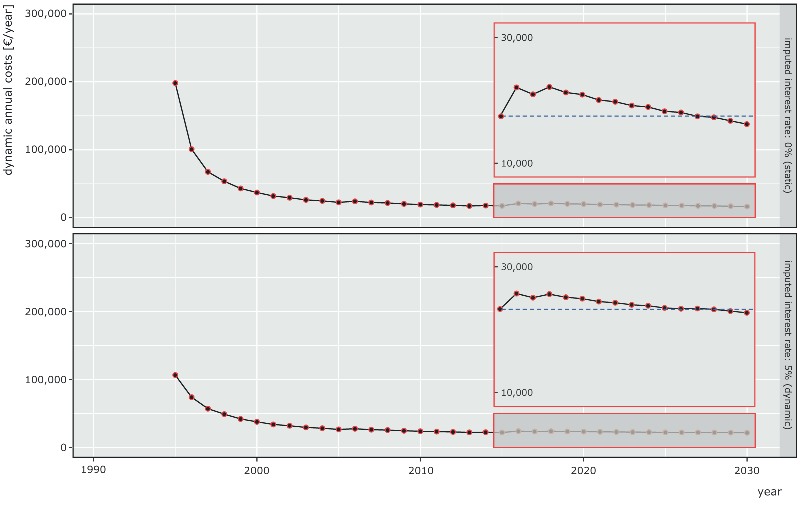

Figure 70 Sensitivity analysis about the tamping interval after ballast cleaning.

First of all, the issue of the tamping interval after ballast cleaning is considered. In the reference case, the inertial one, i.e. the one from the beginning of the service life, was deposited in the working cycle. In order to validate the effects of this assumption, the tamping interval is halved and therefore the number of necessary tamping actions is doubled. The relevant result of the annuity curve is shown in Figure 70. In comparison to Figure 68 (annuity curve of the reference case), it is immediately noticeable that the necessary remaining service life, to ensure the economic efficiency of ballast cleaning, increases from ten to 13 years, with only little influence of the imputed interest rate.

In summary, it can therefore be stated that the tamping interval after ballast cleaning has a considerable influence on the economic efficiency of ballast cleaning itself, but halving the tamping interval is also an extreme assumption. Even if it is not claimed that such a scenario is realistic, this sensitivity analysis was able to show the important influence of the tamping interval after ballast cleaning on the economic efficiency in a meaner way. If the tamping interval is only adjusted to a lesser extent, this also results in a lower additionally required remaining service life, but the meaning remain unchanged.

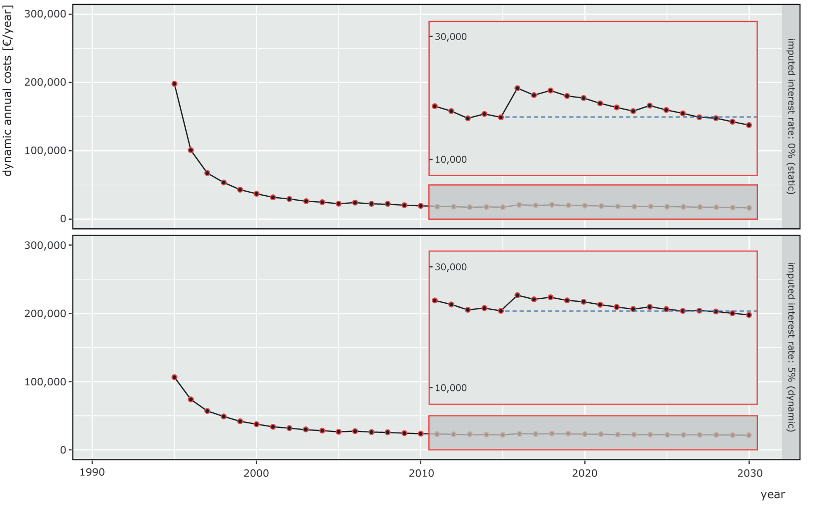

Figure 71 Annuity curve for a second common crossing exchange in 2024.

In terms of costs, the common crossing exchange is also of considerable size. As mentioned in Figure 9, the unit costs for a common crossing exchange are higher than all others, except those of a ballast cleaning. Thus, the statement of the sensitivity analysis presented below can also be understood analogously for all other maintenance activities, since the consideration of a core replacement covers a major maintenance task. For this reason, further investigations have to be carried out. The ballast cleaning is again deposited in the working cycle in 2016, which would again correspond to the result shown in Figure 68. The sensitivity with regard to a common crossing exchange is taken into account by including an additional replacement in 2024 into the working cycle. The results are shown in Figure 71.

However, a common crossing replacement in 2024 would mean an increase in the annuity. By the end of the strategic service life, the annuity level is anyway less than in 2015, which is why a common crossing exchange within this period would be economically justifiable in addition to the ballast cleaning. Under the analysed conditions, a common crossing replacement does not trigger a turnout reinvestment in any case.

It can therefore be stated, always taking into account the underlying conditions and assumptions, that the models developed to predict necessary tamping actions or ballast cleaning tasks in combination with economic approaches can determine the optimal time for reinvestment. In this example, where the year 2013 was defined as the point of observation,

- the ballast cleaning is economically reasonable, if a remaining service life of at least ten years after this maintenance task can be expected. Otherwise, a total renewal of the turnout would be the better option.
- it could be shown, that the tamping cycle after cleaning has an effect on the necessary service life for justifying the cleaning task. Even if an extreme scenario was considered, the influence of the tamping interval could be proven and an necessary service life for ensuring the economic viability of ballast cleaning from 13 years could be calculated.
- the analysis showed that an additional common crossing exchange, as a large cost block within the maintenance activities, has no influence on the optimal point in time for reinvestment and can therefore be carried out at almost any time necessary.
- it was possible to show that if the common crossing exchange has no influence, other singular maintenance activities and their frequencies cannot have any influence either, thus ensuring the optimal reinvestment date.

Although the date for the reinvestment is not available as an absolute year based on the procedure in this example, the exact time of a reinvestment can be determined and validated for this specific turnout, depending on the necessity of an additional ballast cleaning. The results shown are of course to be understood as exemplary. All input parameters can vary, so the specific results are only valid for the case under consideration. However, the underlying methodology can be applied to all boundary conditions.

6.5 Conclusion

At the beginning of this chapter, the basic ideas or issues in asset management were reviewed, and the most important methods for economic evaluations, especially in the railway sector, were discussed, and certain topics from chapter 2 were repeated.

In the further course of the proceeding, a turnout was defined, which was used to demonstrate the developed models and subsequently to illustrate the link with the economic point of view. The main focus was put on the corresponding load, the execution by means of concrete sleepers and a corresponding asset age. Finally, a turnout was selected from the list (Table 1) and planned for further investigations.

Once the boundary conditions such as the design of the superstructure, the load class, the main traffic direction and similar aspects have been defined, the next step was concerned with filling the working cycle. For this purpose, all maintenance activities, which have already been described in detail in section2.4.1, as well as their frequencies over the entire life cycle were entered.

In this context, it was necessary to differentiate between three time periods in the working cycle with regard to the existing data:

- In the first range of the timeline, no measurement data are available, and the entries of the working cycle are based on network-wide average values or statistical evaluations for the considered turnout type.
- The second time period provides the possibility to derive information about executed maintenance tasks based on measurement data.
- The third time period is in the future, in relation to 2013, the year of observation, which is why the working cycle has to be filled with predictions or, again, with network-wide mean values in case of missing prediction models.

The second time period was particularly interesting, as the time of the next tamping action and the necessity of a ballast cleaning task could be determined based on the prediction models developed and thus integrated into the working cycle. For all maintenance activities, for which no models about the maintenance prediction could be developed in the context of this thesis, suggestions were made about possible data sources or evaluation methods, in order to be able to fill these knowledge gaps in the future. Very innovative approaches were also presented, which could not be examined in detail with regard to their suitability.

Based on the completely filled working cycle, the transition from technical considerations to economic assessments using annuity monitoring took place. At the beginning, the reference case with the predicted maintenance activities was calculated and analysed in detail. By means of a very focused consideration it was determined that in principle the ballast cleaning has such a high influence on the annuity that a renewal would be preferable instead. For the case analysed, the economic efficiency of ballast cleaning could be confirmed for a service life extension of at least ten years. As the necessity of a second ballast cleaning cannot be predicted, this scenario was calculated as proof. It has been shown that in the case of a second ballast cleaning, which is necessary within the first ten years after the internal cleaning task, also the first one is not economically reasonable.

As the relevant prediction horizon would be very far in the future, it is not possible to name an exact year. Nevertheless, the end of the service life could be clearly determined based on technical and economic aspects. Within sensitivity analysis, on the one hand, the tamping interval after the ballast cleaning was halved, and the economic consequences were evaluated. If this case occurs, the ten years until the ballast cleaning is economically viable increases to 13 years. On the other hand, the effect of an additional common crossing exchange was examined, as this maintenance activity represents the largest cost block after ballast cleaning and tamping, in relation to the unit cost. Comparative analyses have shown that an additional common crossing replacement does not influence the basic statement.

It can be stated that by combining the technical models for predicting necessary maintenance activities with economic approaches, it is possible to determine the time for reinvestment of a turnout and to consolidate this statement also economically with sensitivity analyses.

Of course, the simplifications or assumptions underlying the economic calculations should not be lost. It is obvious that it is almost impossible to consider all interactions in detail. It would also be necessary to develop further prediction models for other maintenance activities, especially with focus on a common crossing exchange as well as on the half set of switches exchange. Nevertheless, due to the simplifications made and the basic conditions, it was possible to show that a description of the condition and the derivation of necessary maintenance activities is possible based on measurement data. These measurement data do not have to be determined separately or specifically, they are available anyway over a period of about 15 years. In combination with economic models, a very important step towards the asset management implementation for turnouts could be shown. While it was previously almost impossible to derive statements about the optimal point in time for a turnout reinvestment with an acceptable accuracy, the implementation of asset management for turnouts can be advanced by combining newly developed condition description models and proven economic approaches. This should be understood as a major step towards sustainable and economically optimised life cycle management in the sense of the holistic asset management approach.

Research question 5

Is it possible to combine technical models and economic aspects to predict the optimum time for a maintenance activity or a turnout replacement?

Answer to research question 5

Basically, yes! In this chapter, the possibility of linking the developed prediction models with economic evaluation methods was shown and also applied. To give a selected example, it was possible to determine both the economic appreciation of a maintenance task as well as the optimal time for a reinvestment. Of course, some simplifications have been made, as further prediction models would also be necessary. In principle, however, the process could be shown, and the power and potential of the developed methods could be demonstrated.

Research question 6

Is there a need for a separate additional turnout measurement car? Which data are missing nowadays?

Answer to research question 6

The question of whether an independent turnout measuring car is necessary should tend to be answered with no. Of course, a measuring car specially designed for turnouts offers much better and much easier possibilities to obtain well prepared and meaningful data. However, the data of the track measurement car EM250 are available in time series back to the year 2005 and thus constitute a valuable asset, which still needs to be researched in the future and from which various models could be derived. Also, with regard to the additional data sources mentioned in the present chapter for the creation of prediction models for maintenance activities, which have not been considered up to now, the measuring car itself could be attested great potential.

7

SUMMARY, CONCLUSION AND OUTLOOK

This work started with the basic idea of developing an asset management methodology or a related system for turnouts. The focus was not necessarily only on theoretical considerations. Rather, the final aim was to create a possibility to actually implement the desired system within the Austrian Federal Railways. A very abstract and simple graphical summary of these visions is shown in Figure 72, i.e. the possibility of making a turnout completely describable by means of existing measurement data. It became clear very quickly at the beginning of this thesis that the most fundamental things, namely meaningful measurement data, were the reasons why the very first and certainly most important step was aimed at the preparation of measurement data.

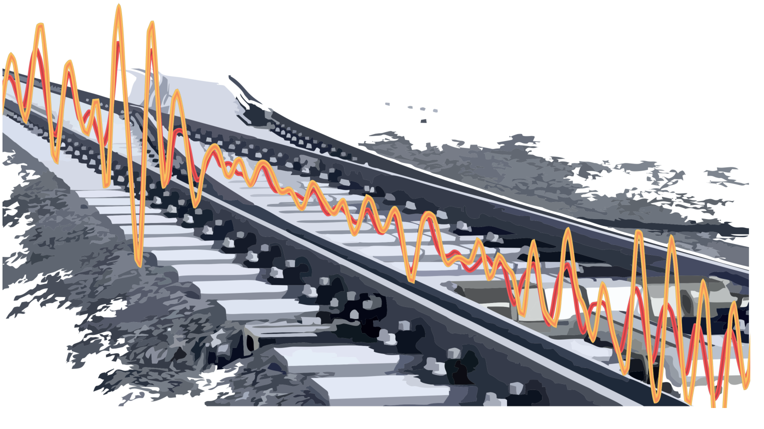

Figure 72 Vision of a turnout which is completely describable by measurement data.

In the following, the individual chapters are again discussed and summarised in detail, and the most important results are highlighted. Particular attention is paid to the research results achieved in a wider context and to assessing the impact of this research on the railway sector.

7.1 Turnouts, management strategies and life cycle considerations

The aim of the second chapter was, on the one hand, to provide the theoretical background with regards to life cycle considerations and, on the other hand, to give an overview of asset management in general, as these topics form the base for all further considerations. The methodology of standard elements developed at the Institute of Railway Engineering and Transport Economy at Graz University of Technology was extensively presented, and their application possibilities discussed. The facilities, which are considered in detail within this thesis, also had to be specified and described further. For this purpose, the turnout, including its technical functional principles and components, was explained, an analysis of the existing situation in the OeBB rail network was carried out, and thus conclusions were drawn about the types to be considered in detail.

A comprehensive presentation of all necessary maintenance activities again paved the way from purely technical to technical-economic considerations. The chapter was closed with an overview of economical methods for evaluations in the railway sector. Based on the acquired and processed knowledge, research questions could finally be derived, which have to be answered within the scope of this thesis.

The focus of this work is thus, on the one hand, the adaptation of existing methods for the economic evaluation, which is necessary for turnouts. These methods have already been successfully applied to open track of the Austrian Federal Railways and are now supposed to be further developed for turnouts as well. The biggest obstacle is the knowledge about future maintenance requirements - predictive maintenance. Thus, primarily descriptive models will be developed which allow for a prediction of maintenance activities in order to finally combine these models with the already existing economic approaches. The final result is a contribution to the implementation of an asset management system for turnouts, based on the general conditions in Austria and based on the data of the Austrian Federal Railways.

7.2 CoMPAcT - data source and their preparation for turnouts

For the development of such descriptive models, data are primarily necessary, so the first part of this chapter deals with possible data sources for the description of turnouts. Since the full potential of already existing data should be exploited, measurement data from the track measurement car EM250 of the Austrian Federal Railways were defined as a reference for further considerations. After a review of the various measurement systems and the data acquisition behind them, it was necessary to ensure that these measurement data were suitable for describing turnouts. This implies that a clear identification of the turnouts in the measurement signals is possible and that all measurement data are synchronous, both within one measurement run and within time series considerations. By comparing different methods, an algorithm, CoMPAcT, could be developed which ensures the required characteristics and raises the quality of the existing measurement data to a new level, which facilitates a data-based analysis of turnouts.

Within the intensive measurement data processing, fundamental problems regarding measurement data could be solved, beyond those relating to the special adaptations for turnouts. Up to now, the issue of post-positioning or the proof of synchronicity could not be fully provided, or it was not (or only to a limited extent) possible to calculate the displacements necessary for synchronicity. By combining these developed solutions with the possibility of automatically identifying the turnout in a measurement signal, a complete system for measurement signal location and measurement signal synchronisation is developed, whose field of application is not limited to turnouts. For example, the positioning algorithm for describing the growth of single failures as well as for linking the data of the track measurement car with various other data sources such as axle box acceleration measurements could be applied and proved. The developed methodology is currently in the implementation phase at the Austrian Federal Railways.

7.3 Investigations about geometrical properties of turnouts

Based on the measurement data processed in this way, the current chapter aims to develop a model that enables the prediction of tamping operations for turnouts. For this purpose, the process of tamping was explained in more detail at the beginning, and measurement signals were searched which could depict the effect of tamping. Based on longitudinal level measurements in the wavelength range D1, two deterioration models of the geometric parameters of a turnout were compared, a linear and an exponential one. Since both models allow for an almost equally good adaptation to the real calculated data, the linear deterioration model was given priority due to its simplicity, and all further investigations were based on this knowledge.

Since no data on tamping operations for turnouts in Austria in the past are available, a methodology was developed to identify tamping actions for turnouts by considering the longitudinal level measurements carried out in time series back until 2005. Thus, it was possible to extract the improvements of tamping and to predict the necessity of the next tamping task for turnouts based on the behaviour in the past. The model is not based on network-wide mean values or simplifications, but rather on learning from the past, a description of the present and, derived from this, a prediction of the future. With this model it is possible to forecast the next time a tamping operation will be required from a technical point of view.

The methodology for the identification of tamping operations carried out in the past, in particular, represents a very innovative concept. The basic idea behind it is relatively simple: It is assumed that the geometrical parameters of a turnout will behave the same in the future, as could be observed in the past. If this does not occur, maintenance must be carried out. The model is as simple as it is effective and functional, making it possible, for example to determine tamping actions in the past for open track of the Swiss Federal Railways, thus closing a large gap in the data management of maintenance activities. In addition, by identifying the relevant geometric parameters in turnouts, it was possible to identify areas of increased deterioration rates and to investigate the cause of this. From this knowledge, it would be possible in the future to derive proposals for new designs with regard to turnouts, for example, thus protecting the overall system and contributing to an overall optimisation in this context.

7.4 Innovative analytical methods to describe the ballast condition

This chapter is mainly concerned with the possibility of deriving the condition of individual components from the existing measurement signals. Since ballast cleaning is a very cost-intensive and therefore very important maintenance activity within the framework of asset management, it is necessary to develop models to describe the current condition of the ballast. For this purpose, purely geometric considerations are no longer sufficient, and therefore wavelength analyses of the longitudinal level measurement signals were investigated. By means of power density spectra calculations, the input signals are split into their individual wavelengths, and subsequently the range between 3 m and 7.6 m is investigated in detail.

For approximation, this range is estimated by a linear function in the power density spectrum, and the slope of this straight line serves as an indicator for the current condition of the ballast by indirectly describing the roughness of the longitudinal level measurement. Based on 15 performed ballast cleaning operations in turnouts, a referencing of the determined values took place, which created a possibility for differentiating between a good and a poor ballast condition by means of the longitudinal level measurements in the wavelength range D_1. By comparing different deterioration models, the exponential model could be identified as the one with the highest coefficient of determination, which is why this approach forms the base for the subsequently developed ballast cleaning prediction model.

The developed methodology for describing the condition of the ballast represents a very innovative approach, as it is possible to derive a statement about a component condition using measurement data which exist anyway. Only by knowing this condition it is possible to derive maintenance activities and to verify their necessity and optimal timing. It is also possible to examine the ballast condition of different areas within a turnout and make comparative statements. In the process, areas with increased ballast wear could be identified and the cause investigated. Again, this allows the derivation of future design changes to counteract excessive ballast wear at an early stage.

The two maintenance prediction models mentioned so far are required for an asset management method for turnouts, although many other maintenance activities would also require a prognosis. The data base for this is created with the entirety of processed measurement data, so the most diverse models can be created, validated and implemented using this data.

7.5 Life cycle management and its implementation for turnouts

The conclusion is derived from probably the most important chapter, for which a combination of the technical prediction models and the economic models for annuity monitoring allows calculating the economic service life nor by pure technical or pure economic considerations. Thus, an association of technical necessity with economic effects was produced. By means of a selected exemplary turnout, the prediction of the next tamping action as well as a necessary ballast cleaning were demonstrated first. After these input data were available, and the working cycle could be filled, different scenarios were evaluated and compared using the annuity monitoring methodology. It was possible, among other things, to generate results about the economic viability of the technically necessary ballast cleaning, to evaluate uncertain input data and to critically vary the frequency of different maintenance tasks.

As early as during the discussion of the different maintenance activities in this chapter, some ideas for further research work could be presented. On the one hand, underlying data sources were mentioned and, on the other hand, approaches for predicting different maintenance activities were presented. Thus, the process away from maintenance based on fixed time intervals to preventive or proactive maintenance can be realised step by step, and the developed models can always be immediately subjected to an economic cross comparison. Only by employing such a procedure a step towards a system optimum can be initiated, which is not possible either by the singular optimisation of individual components without considering the mutual interactions.

7.6 Final remark

Of course, a complete asset management is not possible in conjunction with the presented findings, but the most important maintenance activities in terms of costs can be evaluated both technically and economically. The possibility of determining the optimal point in time for reinvestment was also demonstrated, albeit with certain limitations / simplifications. This possibility was definitely not available before, so through this work an important contribution to sustainable asset management in relation to turnouts is guided, and thus technical models combined with economic approaches can lead to a new perspective.

The importance of this combination, especially with regard to the railway system with very high investment and follow-up costs, on the one hand, and very long service lives of mostly more than 35 years, on the other hand, was demonstrated. Only by means of a technical and economic consideration can, for example, the economic efficiency of a technically necessary ballast cleaning be evaluated and thus the most reasonable decision in asset management be made. In this way, all technical necessities can be verified from an economic point of view, and decisions can always be substantiated by considering both fields of expertise, thus avoiding wrong decisions.

It's unwise to pay too much, but it's worse to pay too little. When you pay too much, you lose a little money - that's all. When you pay too little, you sometimes lose everything, because the thing you bought was incapable of doing the thing it was bought to do. The common law of business balance prohibits paying a little and getting a lot - it can't be done. If you deal with the lowest bidder, it is well to add something for the risk you run, and if you do that you will have enough to pay for something better.

John Ruskin 1819 - 1900

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