A Digital-Cooperative Framework for Cross-border Railway Maintenance Decision Support

José Alberto Stradi
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By

José Alberto Stradi

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Thesis Committee

Prof. Dr. ir. Rolf Dollevoet,	TU Delft, chair
Dr. Alfredo Nunez Vicencio,	TU Delft, supervisor
Dr. Mahnam Saeednia,	TU Delft, advisor

Company supervisor:

Dr. ir. Arjen Zoeteman,	ProRail, advisor

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Preface

As a student of the Master in Civil Engineering focusing on Traffic and Transportation Engineering, I enrolled on an enriching academic journey from 2022 to 2024 at TU Delft. During this time, I studied the complexities of civil engineering systems, driven by an interest in roadway and railway engineering. I present this thesis with great enthusiasm and dedication. It proposes an innovative framework that combines digital solutions and cooperative approaches to facilitate railway maintenance operations in cross-border areas.

Maintenance strategies tailored to cross-border sections in railway infrastructure are practically absent from the academic literature, despite the specific challenges that make cross-border decision-making complex and unique. These challenges include a lack of data sharing between infrastructure managers in different countries, varying maintenance standards, and differing regulations. Dedicated research in this field is essential, as the absence of standardized methods hinders the achievement of EU targets for European Connectivity and the Green Deal, which aim to increase railway demand for international transport. Therefore, this thesis proposes a new framework that uses the latest developments in intelligent and digital railway infrastructure, condition monitoring, and cooperative approaches to address the key challenges in the decision-making process for cross-border maintenance. The framework consists of three key elements: first, a railway entity at the EU level with the authority and mandate to make maintenance decisions for cross-border regions; second, cooperative decision-making facilitated by the EU railway forum; and third, the implementation of digital railways using the latest developments in digital twin technologies.

This thesis is developed in the framework of the EU Project IAM4RAIL and has been made possible through collaboration with ProRail, an invaluable partnership that has given me access to real-world insights and expertise in the railway industry.

I hope that this thesis contributes to the advancement of knowledge in railway engineering and inspires further exploration and innovation in the realm of digital twin applications and cooperative decision-making for cross-border maintenance operations.

Jose Stradi
Delft, August 2024

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To my friends, thank you for your companionship, understanding, and words of encouragement during the challenging moments of this thesis journey. Your presence and humour have provided much-needed breaks and perspective.

Jose Stradi

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Abstract

The motivation for this research is rooted in the expected increase in demand for international train trips within the EU railway network, driven by policies promoting sustainable transportation solutions. Notable initiatives include the EU's Green Deal objectives and the commitment to achieve climate neutrality by 2050. Additionally, significant investments in rail infrastructure, such as the Trans-European Transport Network, the introduction of high-speed rail for international travel, and the reduction of barriers to promote international train travel, are contributing factors. This surge in demand requires a reliable railway network and improved management of temporary capacity reductions, particularly during maintenance operations at cross-border sections. Cross-border rail transport is essential for this strategy but faces significant challenges, including technical barriers, regulatory discrepancies, and coordination inefficiencies among infrastructure managers from different countries.

Despite its importance, academic literature on cross-border maintenance strategies is notably limited or non-existent. This thesis begins by describing the current situation of railway cross-border sections to identify the main challenges and existing coordination practices. It then proceeds to analyse these challenges through expert opinions gathered via a questionnaire. By highlighting the key issues and potential solutions, this research aims to fill the gap in the literature and provide a comprehensive framework for improving cross-border railway maintenance coordination.

This thesis also develops a digital and cooperative framework (DCF) to enhance cross-border maintenance decision support within the railway system of the European Union (EU), addressing the cross-border challenges holistically. It emphasizes the introduction of digital twin technology to meet the urgent need for infrastructure digitalization and coordination between the authorities and infrastructure managers in different countries, enabling the cooperative optimisation of the capacity of railway networks. The DCF consists of three components: the establishment of a European Railway Entity, the creation of a European Railway Forum, and the implementation of digital twin (DT) technology. The European Railway Entity aims to centralize coordination, streamline decision-making, and enforce standardized regulations across member states. The European Railway Forum focuses on fostering collaboration and knowledge sharing among stakeholders, facilitating continuous improvement in maintenance practices. The DT technology offers real-time data visualization, predictive maintenance, and advanced analytics to optimize maintenance operations and enhance infrastructure reliability, enabling an evidence-based decision-making process.

Each of the three components of the DCF is evaluated for its potential benefits and implementation challenges. The European Railway Entity can enhance the coordination and standardization of maintenance operations but may face resistance due to its hierarchical structure and potential conflicts with infrastructure managers whose national interests might be compromised for the sake of overall system performance. The European Railway Forum is cost-effective and practical, promoting voluntary data sharing and continuous improvement; however, suggestions and implementation involve complex procedures that require trust and the management of key confidential information. DT offers the greatest potential for innovation and future-readiness, but it demands a significant initial investment, robust data security measures, and the design of complex mechanisms to enable coordination between different DT platforms and protocols across countries.

The proposed DCF is discussed in two case studies. The first case study consists of a generic case of a bridge for railways between two countries focusing on the implementation and assessing potential benefits and limitations of DT as a tool of the DCF. The second case study addresses the cross-border situation in the Netherlands, proposing an implementation plan and evaluating potential advantages and disadvantages. Additionally, the Emmerich–Oberhausen maintenance project on the cross-border section between the Netherlands and Germany is analysed. This case study highlights the benefits, and challenges of implementing the proposed DCF.

In conclusion, the proposed digital and cooperative framework, integrating the European Railway Entity, the European Railway Forum, and DT technology, aims to support maintenance decisions and address the current challenges in cross-border railway maintenance. This integrated framework seeks to improve operational efficiency, increase network reliability, and support the sustainability goals of the EU, ultimately making the railway system more attractive to users.

Table of Contents

Table of Figures

List of Tables

Chapter 1. Introduction

The introduction is divided into seven sections, which will give an outline of the thesis, from the research context and motivation to its societal impact. At the end of the chapter, a brief section describing the outline of the thesis is presented.

1.1 Context and Motivation

The EU is formed by 27 Member States and most of them have their own national railway network with different characteristics. In 2021, the total length of the railway lines in use in the EU is 202 596 km (European Commission, 2023). These lines in the EU can be used only for passengers, only for freight, or mixed traffic. According to the European Parliament; Council of the European Union (2012), a cross-border agreement is defined as any agreement between two or more Member States or between Member States and third countries intended to facilitate the provision of cross-border rail services.

Cross-border sections are segments of railway infrastructure that connect two different countries. Figure 1 shows an example of a cross-border section between The Netherlands (Country 1) and Belgium (Country 2). Within the railway network in Europe, there are more than 200 cross-border lines (#CrossBorderRail, 2024).

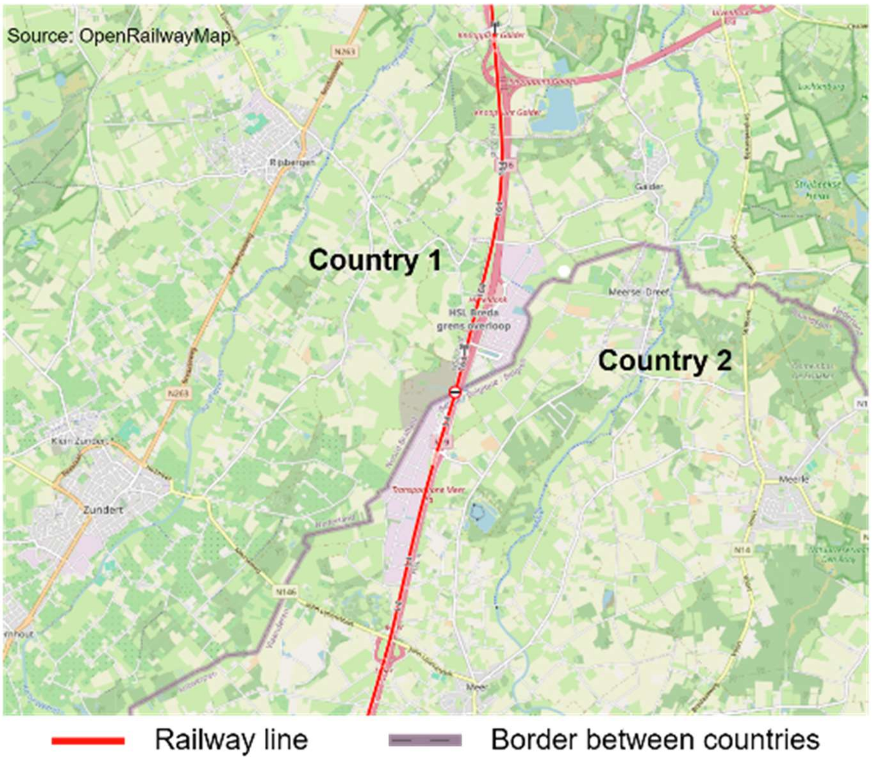


Figure 1. Example of a cross-border section (modified from source: OpenRailwayMap, 2024)

It is estimated that within the European Union (EU), road and rail transportation account for more than 63% of goods transport and almost 90% of passenger transport. These infrastructures ensure the daily mobility of people and goods while seeking to provide an efficient and safe service (Vieira et al., 2022). A significant portion of the EU population, up to 37.5%, lives in areas bordering one or more of the almost 40 internal borders (Lundgren et al., 2023). Klugman (2018) reported that 3.5 million people cross an internal Schengen border every day, with 1.7 million workers commuting across a border daily to work in another Member State. There were 4516 weekly long-distance cross-border trips (train pairs in both directions) in 2019, excluding infrequent services (European Commission, Directorate-General for Mobility and Transport, 2021). In 2022, passengers were carried 21 billion kilometres in international journeys (Jere et al., 2024).

In terms of rail freight transport, EU freight transport reached 397.6 billion tonne-kilometres in 2022 (Eurostat, 2023). Additionally, freight corridors have a big impact on the EU economy. For example, according to the European Commission—Directorate General for Mobility and Transport (2022), 138 billion tonne-kilometres of annual freight transportation occur along the Rhine-Alpine Corridor. The regions encompassing this corridor boast a combined Gross Domestic Product (GDP) exceeding €3.1 trillion, which accounts for 20% of the EU's total GDP. However, the modal split of freight transport is still one of smaller shares (5,4%) compared to other modes of transport (Jere et al., 2024). Regardless, the freight transport is expected to increase due to EU incentives promoting the use of rail transport. This highlights the importance of having and maintaining a reliable and robust transportation network in the EU.

The current focus on sustainable travel in EU policies is to improve the accessibility of public transport to make it an alternative to travel daily by car, within and between cities and regions and across borders (Ryan & Wretstrand, 2020). The modal shift to rail is a key pillar of the EU strategy to reach climate neutrality by 2050, and cross-border transport is critical to achieving the EU's Green Deal objectives (European Union Agency for Railways, 2022) as rail transport stands out as one of the most sustainable modes of transportation (see Figure 2).

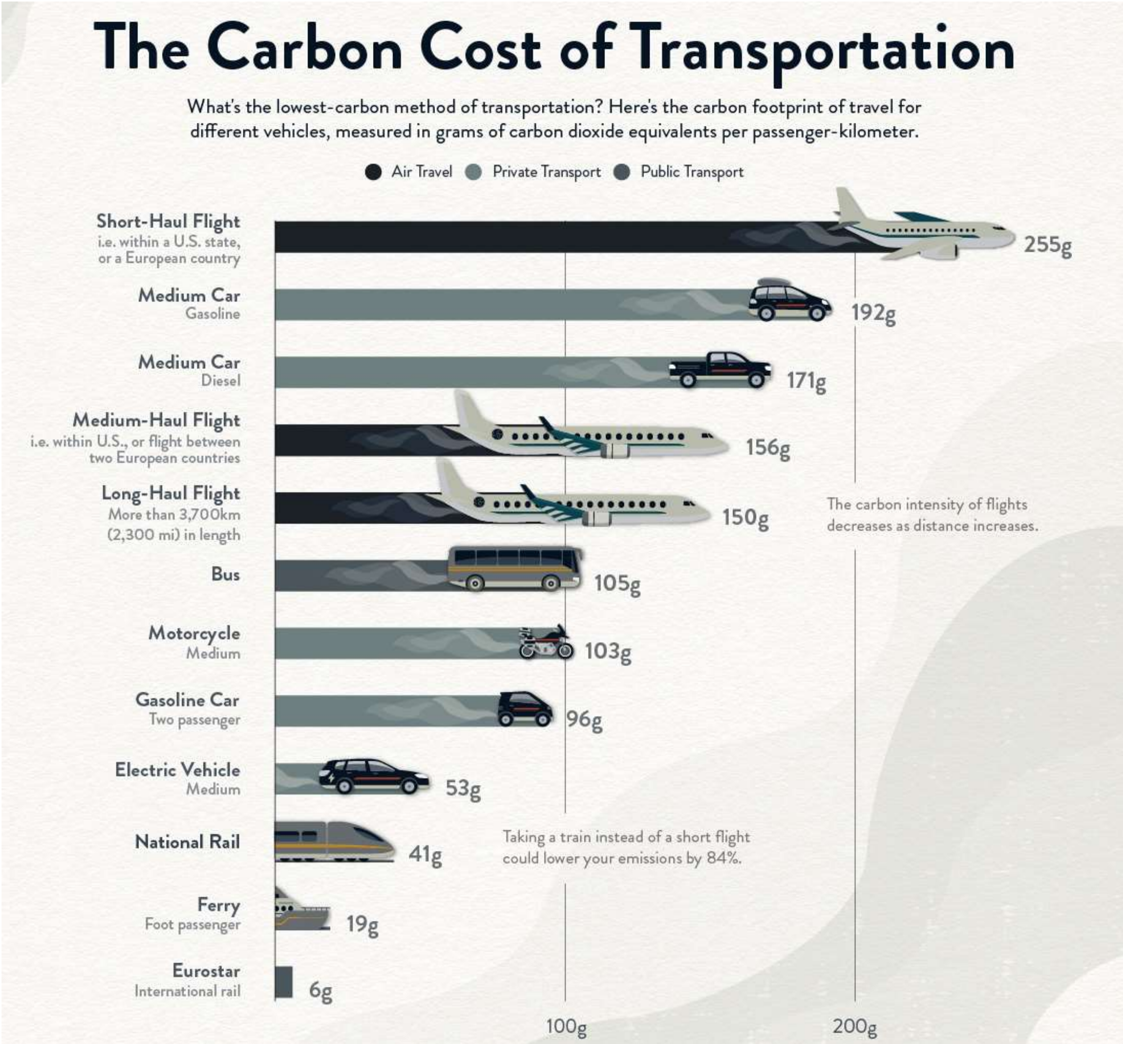


Figure 2. Emissions according to the mode of transport (source: Bhutada, 2022)

High-speed rail traffic is expected to double by 2030 and rail freight traffic by 2050 to make transportation sustainable, following the European Green Deal objectives (European Commission, n.d.). Other key factors for this expected increase in rail traffic include substantial investments in rail infrastructure, like the Trans-European Transport Network, the implementation of high-speed rail for international journeys, and efforts to reduce barriers to encourage international train travel. Therefore, it is essential to improve the rail network to create a more efficient and robust transport system that is reliable and attractive to users. This increasing demand for cross-border infrastructure and operations will require significant improvements and maintenance to ensure rail transportation remains a safe and dependable alternative.

Improving cross-border transport is important since it facilitates the movement of goods, utilising freight trains across the EU region, and establishes connections between cities in neighbouring countries. For passenger services, a robust and reliable cross-border rail transport system contributes to a modal shift from air travel to train travel. An example is the Night Train services, which link major cities throughout the EU, offering an environmentally friendly alternative to its competitor, short-distance flights.

The general situation in railway cross-border sections is complex because it involves the coordination of many stakeholders (from at least two different countries and even international entities). Each country involved has its own regulations and railway standards. Even more importantly, there is a difference in the priority they give to cross-border railway lines. In order words, each country focuses on its national interests first. Also, this interest changes periodically because different parties come into power.

According to the European Union Agency for Railways (2022), although the interoperability of the EU railway system is improving, technical and operational barriers at cross-borders still hamper international rail connections and the modal shift to rail. There is a substantial potential for time savings at cross-borders by solving technical and operational issues. Additionally, solving these issues will improve the quality of the cross-border services (of freight and passengers), helping to avoid a modal shift from trains to other alternatives.

Problems related to cross-border transport are becoming more significant, according to Gamon & Naranjo Gómez (2019). These problems can be divided into three main groups:

- The first group concerns technical aspects (existence of various signalling and power systems, and vehicle types). For instance, the Betoweroute, connecting the Netherlands and Germany, involves a shift in both signalling systems, transitioning from the European Train Control System (ETCS) to Punktförmige Zugbeeinflussung (PZB, translated from German as "intermittent automatic train running control"), and power systems, switching from 25kV to 15kV. This implies that the rolling stock used has to be compatible with both systems or that the locomotive will change at the border.
- The second group is related to the differences in the documentation (e.g., instructions on traffic and signalling).
- The third group is associated with the use of different languages by train drivers, traffic controllers, and other people involved in the transport process (Gamon & Naranjo Gómez, 2019). It is important to mention that there are also other types of problems associated with cross-border transport, such as the different interests of the involved stakeholders in terms of investment and operations. For example, in a situation involving two neighbouring countries sharing one rail line, one invests more than the other in the maintenance of the railway.

One of the key areas demanding immediate attention to improve cross-border rail transport lies in the maintenance operations of the rail infrastructure. These operations have, as a consequence, temporary capacity restrictions (TCRs) in the railway system. The optimisation and coordination of these maintenance operations are critical to minimise capacity restrictions within the system as they reduce the number of disruptions and delays between countries.

In this context, the digitalisation of railway infrastructure becomes a need for infrastructure managers as it enables efficient operation management and assessment of the condition of the railway infrastructure. Through digitalisation, infrastructure managers can use advanced technologies to monitor assets in real-time, predict maintenance needs, and optimise resource allocation. Moreover, digitalisation facilitates the implementation of applications and tools aimed at enhancing coordination among different stakeholders involved in cross-border transport. For example, the integration of digital twins into railway operations could provide real-time insights and simulations, allowing for better decision-making and improved coordination among stakeholders.

After a brief overview of the context in railway cross-border sections, the main motivation for this thesis is to reduce the impact of TCRs in these sections by introducing a digital and cooperative framework. This framework aims to increase the capacity of the EU railway network to meet future demands and support the achievement of environmental goals.

As previously stated, cross-border railway sections face multiple multidisciplinary challenges, including technical, regulatory, and coordination issues. By implementing a new framework, this thesis will aim to address these challenges holistically, ensuring a more efficient and effective approach to support railway maintenance decisions.

Furthermore, promoting a framework that utilizes digital tools to optimize railway system performance will assist infrastructure managers reach their digitalization objectives. This digital and cooperative approach not only enhances the capacity and reliability of the rail network but also aligns with broader goals of sustainability and technological advancement within the EU.

1.2 Problem Statement

One of the main goals of infrastructure managers is safe train operation of rail traffic with maximum performance. Railway maintenance operations are essential for ensuring safe train operations by maintaining all system components in good condition. However, as previously mentioned, these maintenance operations generate TCRs in the railway network. Since TCRs cannot be avoided – they are even a means to achieve these goals– the planning of TCRs should be stable and cost-efficient (RailNetEurope, 2022).

The coordination of maintenance work is an essential part of asset management for infrastructure managers. This is already a challenge within one country due to the stochastic nature of the degradation of the infrastructure and the interaction of different stakeholders, among many other factors. The complexity increases when coordination is required across different countries. In such cases, incomplete information about the rail system and a focus on national services create barriers to the operation of cross-border services.

The lack of coordination of maintenance operations between the main stakeholders affects cross-border rail services. For example, a route connecting two regions or countries experiences closures due to preventive maintenance at least twice a year or for extended durations. This extended closure results from a lack of communication between infrastructure managers, leading to a situation where the route could potentially be closed just once a year or for a shorter time. So, effective coordination of maintenance activities is critical to achieving this goal not only at a national scale but also among infrastructure managers across different EU countries.

This research project aims to study **how to reduce the impact of maintenance operations on cross-border railway lines**.

1.3 Research Gaps

There is limited literature on challenges faced by cross-border infrastructure and transport, thus there is a significant gap in the understanding of the coordination and maintenance of such infrastructure, particularly between neighbouring countries (see Figure 3).

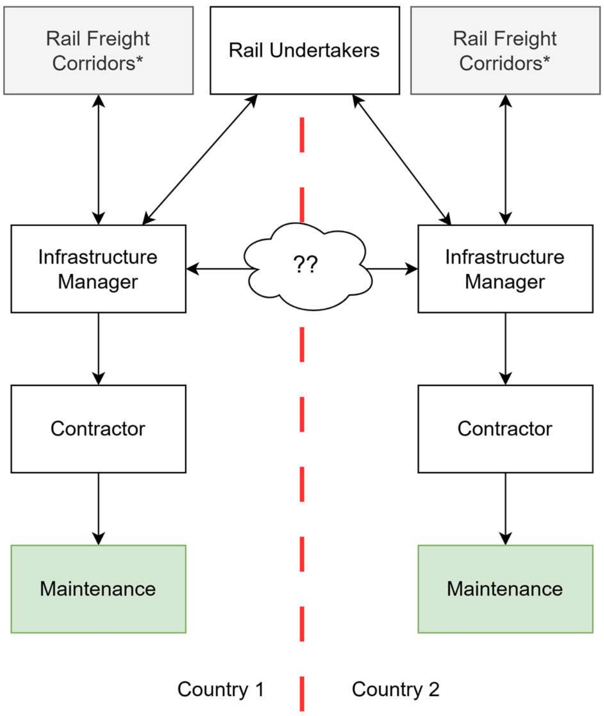


Figure 3. Communication and coordination gap in rail maintenance operations

Research Gap 1: Coordination and Maintenance Practices

There is a lack of research on how coordination and maintenance of cross-border railway infrastructure are managed between neighbouring countries. This gap raises questions about the efficiency and effectiveness of current practices. The lack of research on these practices means that there is insufficient knowledge to develop strategies that could enhance coordination and reduce the impact of maintenance operations on international railway services.

This thesis will address this gap by conducting a descriptive analysis of the current coordination and maintenance practices between infrastructure managers of different countries. It aims to provide an analysis of the current situation of cross-border maintenance operations and their challenges as well as propose solutions to reduce the impact of these operations.

Research Gap 2: Digital Twins in Cross-border Rail Maintenance

While digital tools and technologies have been increasingly used in various sectors to improve efficiency, there is limited research on their application in railways, especially in coordinating maintenance of cross-border sections. The potential of digital twins, data-sharing platforms, and real-time monitoring systems to enhance coordination is in their early stages and shows great potential.

Without understanding the benefits and implementation challenges of these digital tools, infrastructure managers may miss opportunities to optimize maintenance operations and improve the reliability of cross-border railway services. This thesis will propose a framework that uses digital twins to improve the coordination of maintenance operations as one of the components to reduce their impact.

By addressing these gaps, the current thesis will contribute to the field by providing insights and solutions to enhance the coordination of cross-border railway maintenance operations.

1.4 Research Objectives and Questions

After defining the main research problem and the gaps, the research objectives and questions are presented in the following sub-sections.

Research Objectives

The main objectives of this research are to:

- Describe the barriers and needs of the railway cross-border services in the EU.
- Evaluate the current situation of the coordination of maintenance works between neighbouring countries in the EU.
- Generate a framework to reduce the impact of maintenance operations on cross-border railway lines in the EU.
- Generate a flowchart for potential digital twin implementation in cross-border maintenance operations.

Research Questions

The main research questions of this thesis are:

Research Question 1: What is the current situation regarding cross-border maintenance of the railway lines in the EU?

Research Question 2: How can the current coordination mechanisms be improved to reduce the impact of cross-border maintenance operations?

Research Question 3: To what extent can a digital and cooperative framework help improve the maintenance operations in cross-border lines?

1.5 Scope of this Thesis

This research aims to improve the support maintenance decisions and coordination between involved parties to mitigate their impact rather than optimising rail network timetables (according to maintenance operations). The study will focus on the railway system within the European Union in lines that connect at least two countries. Fright-dominated and mixed rail traffic lines will be analysed.

The thesis proposes a digital and cooperative framework to enhance the coordination of rail maintenance operations between neighbouring countries. It includes a detailed flowchart for implementing digital twin technology in cross-border maintenance operations. Additionally, the thesis offers a comprehensive analysis of the current challenges related to the coordination of maintenance operations in the cross-border sections of the EU.

The study will only focus on improving coordination in the maintenance phase of cross-border rail infrastructure. It will not cover the maintenance technique itself or the details of how to perform the actual work. Moreover, the coordination within the preliminary stages of the project, such as the design and construction, will not be part of the scope of this project. The case study will focus on preventive rail maintenance rather than reactive, as preventive can be subjected to coordination between the involved stakeholders.

Finally, this research will not aim to develop a digital twin model as the time required to build such a model will surpass the time budget for this research. Additionally, the thesis will provide an overview of the potential cost-benefits of implementing the DCF and its components. However, it will not include a detailed cost analysis of this application.

1.6 Contribution

The main contribution of this thesis is the development of a framework to support maintenance decisions in cross-border sections. This framework incorporates the use of digital twin technology, an innovative tool for coordination between countries. By enabling real-time monitoring and predictive maintenance, digital twin technology facilitates better decision-making and more efficient maintenance operations. Furthermore, this thesis contributes to the digitalization of infrastructure within the EU by providing an implementation flowchart for digital twins specifically tailored for cross-border sections, aligning with broader objectives of modernization and optimization in the transport sector.

This thesis represents as an initial exploration of railway cross-border sections within academic research, addressing a significant gap in the literature. Currently, there is limited academic focus on the unique challenges and complexities of maintaining cross-border railway infrastructure. By providing a detailed analysis and proposing practical solutions, this thesis aims to pave the way for further studies and advancements in this critical area.

1.6.1 Societal Impact

The main positive impact of this research is its contribution to an effective use of cross-border railway capacity. In other words, cross-border railway lines will have more available time for freight and passenger transport due to the more effective allocation of maintenance planning. Improving the coordination of maintenance operations in the cross-border regions will also help the EU reach the agreements of the Green Deal by improving the reliability of the railway system, subsequently incentivising freight transport and extra transnational passenger services such as the Night Train. Additionally, it aims to improve communication among stakeholders, particularly between infrastructure managers of neighbouring countries, thereby improving the coordination of maintenance operations.

One of the advantages of having a reliable cross-border transport network is that it can incentivise commuting between cities around the border. This also generates an advantage for businesses: companies have access to a larger number of suitable candidates for jobs, and jobs can be better matched with people's skills. (Klugman, 2018)

One negative impact of increasing cross-border rail operations is that the railway infrastructure will degrade quicker as it improves the use of the capacity of the railway network. Additionally, the increased use of the railway system will create more noise and vibrations for the people living nearby the railway tracks.

Sustainable Development Goals (SDGs)
This project aligns with the Sustainable Development Goals (SDGs) set by the United Nations, specifically Goal 9 and 11. SDG Goal 9 focuses on building robust infrastructure, encouraging sustainable

industrialisation, and fostering innovation (United Nations, n.d.). Meanwhile, SDG Goal 11 aims to make cities and human settlements inclusive, safe, resilient, and sustainable (United Nations, n.d.).

By improving the coordination of cross-border maintenance operations, this research project will contribute to achieving Target 9.1, which focuses on the development of high-quality, dependable, sustainable, and resilient infrastructure, including both regional and transborder elements (United Nations, n.d.). This goal is accomplished by improving the availability and reliability of the railway system, as it will incentivise freight transport and transnational passenger services, such as the Night Train.

Enhancing the accessibility, availability and reliability of rail transport in cross-border regions will incentivise transnational passenger services. This can contribute to a modal shift from car or plane to train, as the train presents itself as one of the most sustainable modes of transport. This will help to achieve Target 11.2, which aims to provide access to safe, affordable, accessible, and sustainable transport systems for all (United Nations, n.d.).

1.7 Thesis Structure

This thesis is divided into seven chapters. The outline of the thesis and a brief description of each chapter are provided in the following figure:

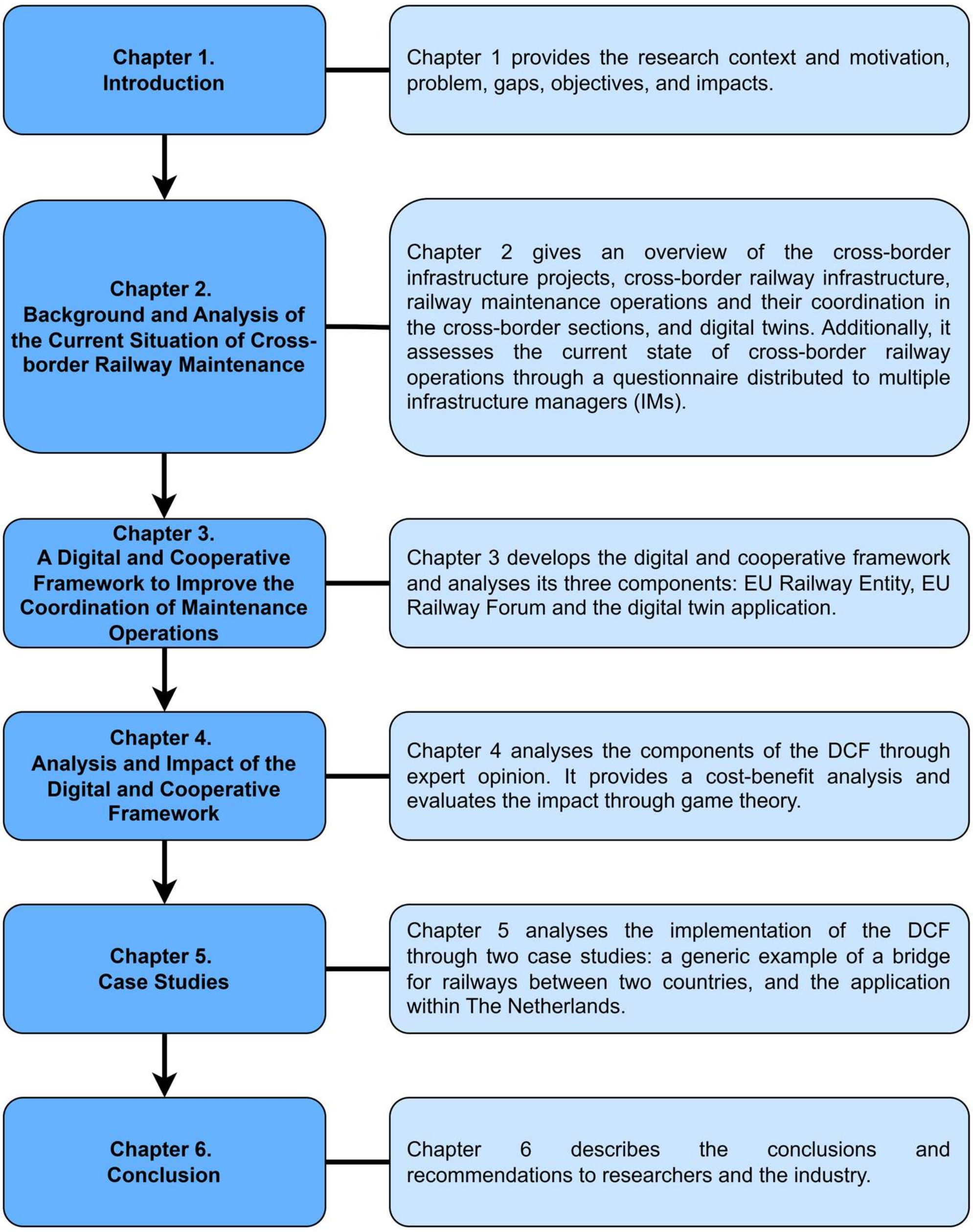


Figure 4. Outline of the thesis and brief description of the chapters of the thesis

Chapter 2. Background and Analysis of the Current Situation of Cross-border Railway Maintenance

This chapter contains four main sub-topics: an overview of the EU cross-border infrastructure projects, railway infrastructure, railway maintenance operations in cross-border sections, and digital twins. It is important to remark that the academic literature found on railway cross-border sections is very limited.

2.1 Cross-border Infrastructure

According to the European Investment Bank (2023), "cross-border infrastructure projects are fixed-asset investments that physically link two or more countries via infrastructure, including digital infrastructure, enabling the flow of people, goods, commodities, or data. A key factor that differentiates cross-border infrastructure projects from typical projects within a single country is their scale and complexity, as they very often span difficult terrain across borders and involve two or more countries instead of just one."

Cross-border infrastructure projects are central to the completion of the European Union's internal market because they enhance connectivity and reinforce economic and social cohesion (European Investment Bank, 2023). These projects are divided into different areas: electricity, gas, telecom, road, and rail. Figure 5 shows the location of the different projects financed by the European Investment Bank between 2010 and 2022.

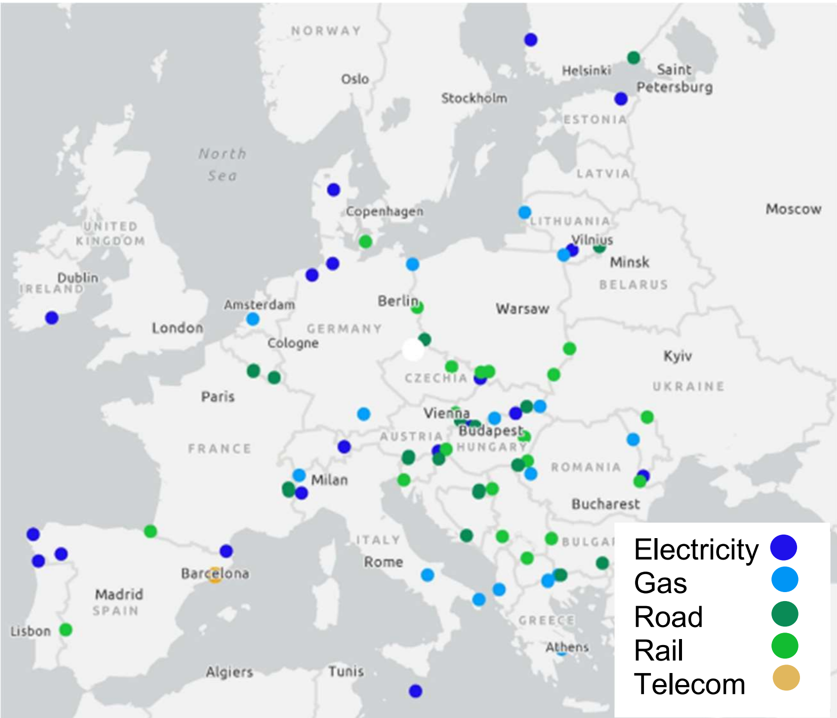


Figure 5. Cross-border infrastructure projects (modified from source: European Investment Bank, 2023)

As stated by the European Investment Bank (2023), this institution granted €20 billion for cross-border infrastructure projects over the period from 2010-2022. As seen in Figure 6, the railway and electricity sectors were the sectors with the most money allowed (around €6 billion each).

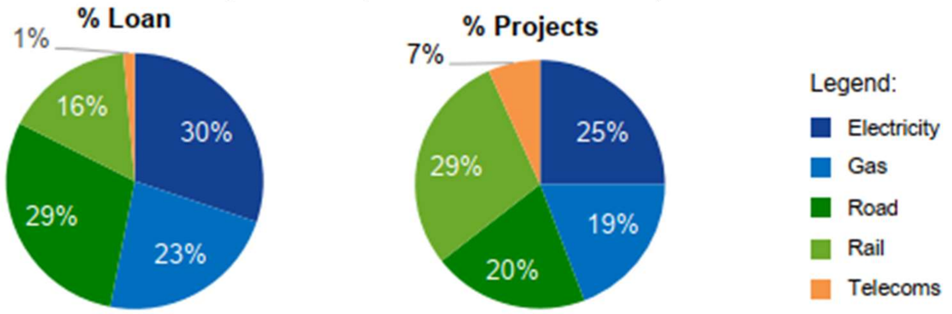


Figure 6. Contribution of each sector to cross-border infrastructure projects approved and signed by the EIB between 2010 and 2022 (source: European Investment Bank, 2023)

2.1.1 Challenges for the Cross-border Infrastructure

Developing an infrastructure project is a complex process as it involves the participation of multiple stakeholders throughout the life cycle of the project. When two or more countries are participating, the level of complexity increases as the number of stakeholders also increases. It is important to mention that each country has a different economic and political interest, and they tend to prioritize national interest over a more European one.

The nature of cross-border projects implies the need for effective and continued regional coordination to facilitate project planning, preparation, and implementation, as well as coordination among funding sources. This is not easy, because different sets of regulations and laws exist, but also cultural and/or language barriers (European Investment Bank, 2023).

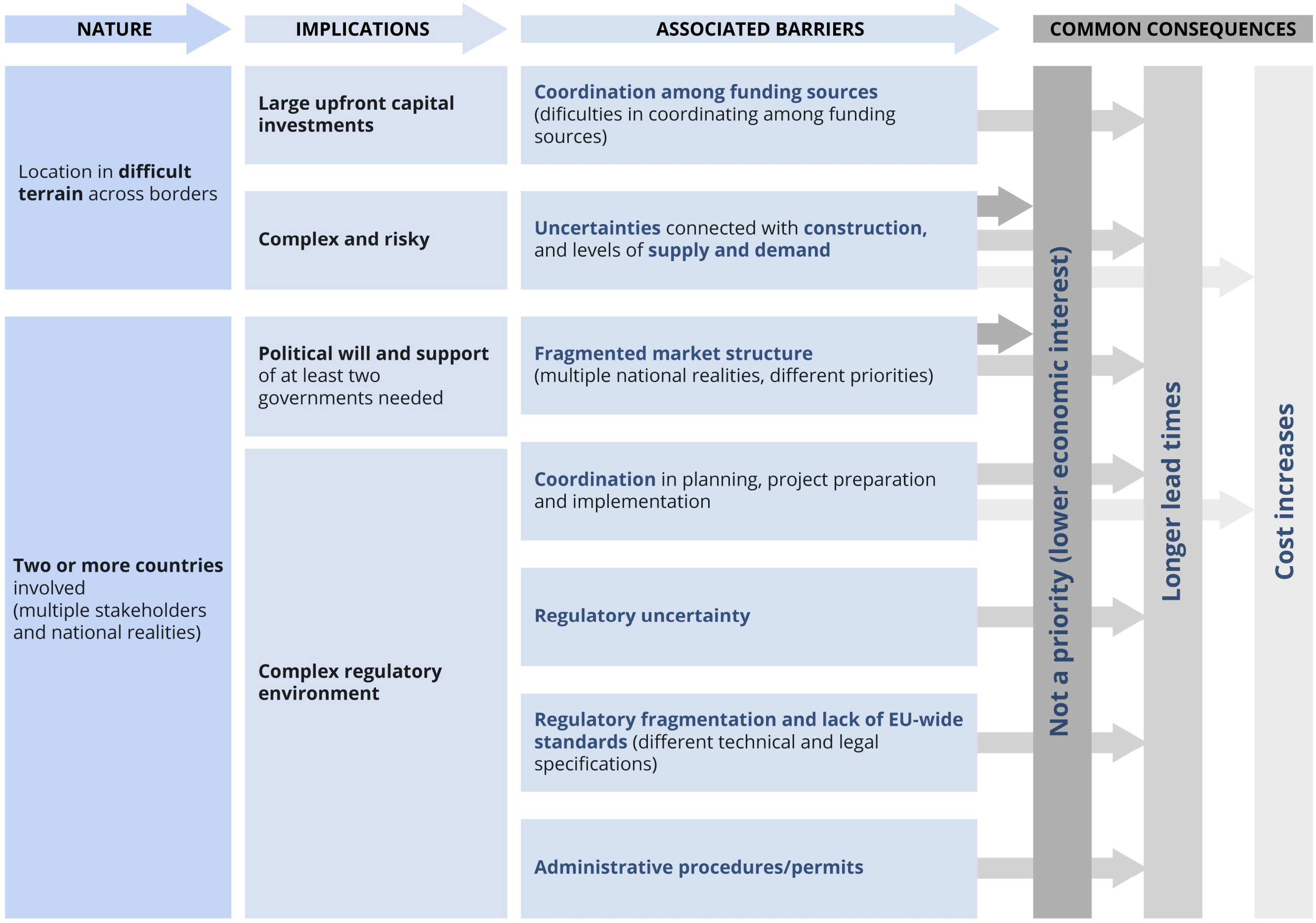


Figure 7. Main barriers to the realization of cross-border infrastructure projects, their causes and consequences (source: European Investment Bank, 2023)

According to the European Investment Bank (2023), the nature of the challenges of cross-border projects can be associated with the location and the number of involved stakeholders (at least two different countries with each own interest). As shown in Figure 7, the main barriers to these projects are:

- Coordination among funding sources.
- Uncertainties connected with construction and levels of supply and demand.
- Fragmented market structure.
- Coordination in planning, project preparation, and implementation.
- Regulatory uncertainty.
- Regulatory fragmentation and lack of EU-wide standards.
- Administrative procedures/permits.

Because of these barriers, the countries involved do not give priority to cross-border infrastructure projects as they have a lower economic interest, leading to longer lead times and eventually cost overruns (compared to infrastructure projects that take place within a single country).

2.2 Cross-border Railway Infrastructure

The transportation sector, especially railways, plays a crucial role in cross-border projects by facilitating the movement of people and goods across the European network. The Trans-European Transport Network (TEN-T) is a European transport network that fosters the efficient transportation of people and goods, ensures access to jobs and services, and enables trade and economic growth (European Commission, n.d.). It aims to create seamless transport systems across borders, without physical gaps, bottlenecks, or missing links, and to strengthen the economic, social, and territorial cohesion of the European Union (European Commission, n.d.).

TEN-T comprises railways, inland waterways, short sea shipping routes and roads linking urban nodes, maritime and inland ports, airports, and terminals. In this instance, the primary emphasis will be on rail infrastructure. The TEN-T consists of two layers: the core and the comprehensive network (European Commission, n.d.). The Rail Freight Corridors form part of the TEN-T and facilitate the movement of goods across the EU. Eleven Rail Freight Corridors (RFCs) are shown in the table below (see map in Appendix A – Map of the Rail Freight Corridors).

Table 1. Rail Freight Corridors in the EU

Corridor	Countries involved	Length (km)
Alpine – West Balkan	Austria – Slovenia – Croatia – Serbia – Bulgaria	2 145
Amber	Poland – Slovakia – Hungary – Slovenia	3 358
Atlantic	Portugal – Spain – France – Germany – Ireland (Via Port)	9 066
Baltic - Adriatic	Poland – Czechia – Slovakia – Austria – Italy – Slovenia	4 472
Mediterranean	Spain – France – Italy – Slovenia – Croatia – Hungary	11 410
North Sea – Baltic	The Netherlands – Belgium – Germany – Poland – Lithuania – Latvia – Estonia – Finland – Sweden	9 031
North Sea – Mediterranean	Belgium – Ireland – France – Luxembourg – The Netherlands	5 452
Orient / East – Med	Austria – Bulgaria – Cyprus – Czech Republic – Germany – Greece – Hungary – Romania – Slovak Republic.	6 480
Rhine – Alpine	Italy – France – Switzerland – Germany – The Netherlands – Belgium	3 460
Rhine – Danube	France – Germany – Austria – Czech Republic – Slovakia – Hungary – Croatia – Romania – Bulgaria	5 800
Scandinavian - Mediterranean	Austria – Germany – Denmark – Finland – Italy – Malta – Norway – Sweden	11 940

One of the most important characteristics of the railway system within the EU is that the components of this system are different in every Member State (see Table 2). This is also one of the main challenges that the EU faces in terms of interoperability. This heterogeneity of system causes disruptions in the train services, including maintenance, hindering smooth operations. For example, the train locomotive may need to be changed as it enters a different country as the power supply may not be the same. In terms of maintenance, the machinery used may be exclusive to a single country because of different standards.

Table 2. Types of system components.

Railway system components	Types
Signalling and train protection	No train protection, ETCS - European Train Control System, PZB - Punktförmige Zugbeeinflussung, ATB - Automatische Treinbeïnvloeding, ZSI 127 - Trainguard ZSI 127, ATC - Automatic train control, LZB – Linienzugbeeinflussung, KVB - Contrôle de Vitesse par Balises, TVM - Transmission Voie-Machine, SCMT - Sistema Controllo Marcia Treno, ASFA - Anuncio de Señales y Frenado Automático.
Electrification	Not electrified, 1.5 kV, 3 kV, 15 kV and 25 kV.
Track gauge	1 435 mm (most common in the EU), 1 668 mm (Spain and Portugal)

The railway system is regulated by national and international laws and regulations. The main international laws concerning the railway system and transport in the EU are the following:

- Regulation (EU) No. 913/2010: concerning a European rail network for competitive freight.
- Directive 2012/34/EU: establishing a single European railway area.
- Regulation (EU) No 1315/2013: union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU.
- Directive (EU) 2016/797: on the interoperability of the rail system within the European Union.

The EU introduced the Technical Specifications for Interoperability (TSIs) under the previously mentioned Directive (EU) 2016/797. The main objective is to meet the essential requirements and ensure the interoperability of the railway system. These TSIs provide a set the technical and operational standards that every component of the railway system should comply with.

Also, Regulation (EU) No 1315/2013 was set up by TEN-T for the Core Network to ensure interoperability and its proper functioning. In order to comply with the TEN-T Regulation, the RFCs have identified the requirements of different railway systems or components (based on Article 39 of the Regulation (EU) No 1315/2013). The list of requirements for the different railway systems is shown in the Table 3.

Table 3. Requirements of the TEN-T Regulation for different systems.

System/Component	Requirement - Description
Electrification	Full electrification of line tracks.
Track gauge	The nominal track gauge for new railway lines is 1 435 mm (there are exemptions*).
European Rail Traffic Management System (ERTMS)	Full deployment of the system.
For freight lines of the core network:	
Line speed	100 km/h.
Axle load	At least 22.5 tonnes.
Train length	Possibility of running trains with a length of 740 m.

* See Article 39 of the Regulation (EU) No 1315/2013.

Capacity allocation of the railway network in the EU is managed by the infrastructure managers (IMs) at a national level and by RFCs at the international level. If a rail undertaking (RU) wants to run a train in a single country, then the RU must have permission in advance from the respective IM. While for international journeys, the RU has the option to request capacity allocation from either the relevant RFC or from each IM of the countries through which the train will travel through.

2.2.1 Challenges in Cross-border Rail Infrastructure

It is important to mention that even though the rail infrastructure is considered a national asset, it remains part of the bigger EU transportation network. Therefore, infrastructure assets that are physically located in only one country but may have a considerable impact on one or more other countries (Lundgren et al., 2023).

As previously mentioned, the cross-border projects have multiple challenges and rail infrastructure projects are not an exception. According to the analysis of the European Commission: Directorate-General for Mobility and Transport (2022), the most important challenges for the TEN-T are insufficient and uncoordinated maintenance, natural disasters caused by climate change, and a lack of collaboration between the Member States and the European Commission to align their strategic transportation plans.

Additionally, Lundgren et al. (2023) outlined the barriers associated with rail cross-border transportation projects in different areas, which are:

- Governance challenges: For example, many stakeholders at different levels of government.
- Economic challenges: For instance, only calculating benefits on one side of a national border or increased costs due to higher insecurity.
- Legal and administrative challenges: For example, conflicting laws and regulations between the countries involved. Furthermore, the focus is primarily on national transport infrastructure that is not adjacent to a border. This prioritisation of internal issues in the first instance is also discussed by Ryan & Wretstrand

(2020). As mentioned in the previous section, this is also a common issue for all types of infrastructure projects.

- Political challenges: For instance, a lack of political interest or the risk of altering the balance of power between countries or within a country.
- Other challenges: These may relate to differences in technology, calculation models, or language.

The combination of technical, administrative, and infrastructural shows the lack of interoperability between the EU rail transport network. This can generate operational problems, resulting in slower transport operations and increased operating costs for the rail undertakings (European Union Agency for Railways, 2022).

Another barrier within cross-border rail transport, specific to public transport, is ticketing and public transport information (Ryan & Wretstrand, 2020). In other words, there is no standardisation of the fare between the corresponding authorities regulating the service: the user can find different fares depending on the platform used to buy the tickets.

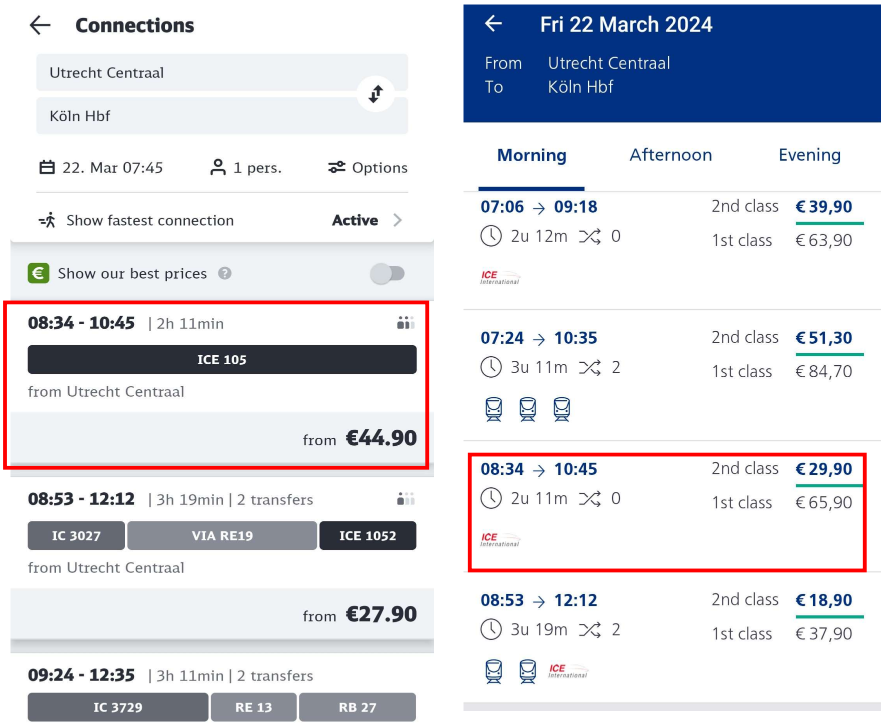


Figure 8. Example of lack of fare standardization (Utrecht Central Station - Cologne Central Station)

Figure 8 shows an example of this lack of fare standardisation, in which the same trip (direct train from Utrecht Central Station to Cologne Central Station at 08:34) has a different fare depending on the platform used to buy the tickets. According to Ryan & Wretstrand (2020), one reason for this difference in ticket pricing could be attributed to the lack of data sharing between the relevant authorities.

Regarding public transport information, there also are issues like different platforms displaying conflicting information or that the information provided is in different formats (Ryan & Wretstrand, 2020). This lack of standardisation of both services affects the quality of the service provided to users.

Gamón and Naranjo Gómez (2019) provide an example of challenges in cross-border railway transport at the borders of Poland, Germany, and the Czech Republic. The main obstacles include differences in electrification, communication, and safety systems, as well as a language barrier. The significance of the latter becomes evident, considering that effective communication between the train operator and the traffic controller is crucial in handling unexpected circumstances.

The simplification and harmonisation of border crossing regulations and establishing an official cross-border user forum have been mentioned as part of the solutions to the previously mentioned challenges. The European Commission is attempting to improve cross-border transportation with the Technical Specifications of Interoperability (TSI). The TSI aims to make the rail sector more efficient by eliminating 25 different sets of national rules (Directorate-General for Mobility and Transport, 2023). Reducing complexity and parallel rules helps to improve affordability and lower the basic cost of rail operations.

Furthermore, the European Commission plans to improve train availability, modernise the passenger railway infrastructure, and use the rail network efficiently to overcome the obstacles to cross-border rail services (Directorate-General for Mobility and Transport, 2021).

2.3 Maintenance Operations in Cross-border Sections

Infrastructure managers are in charge of the expansion, maintenance and operation of the railway system. The performance of the railway system is measured in terms of reliability, availability, maintainability and safety (RAMS). So, the main objective of the rail infrastructure manager is a to have a railway system that is reliable, safe, and has high-quality service and lower maintenance and operating costs.

According to the Nederlands Normalisatie-instituut (1999), maintenance is defined as the combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function. Maintenance can be divided into preventive and corrective maintenance. According to the Nederlands Normalisatie-instituut (1999),

- Preventive maintenance refers to the maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.
- Corrective maintenance is the maintenance carried out after fault recognition and intended to put a product into a state in which it can perform a required function.

Ideally, preventive maintenance should be enough to keep the railway system in good condition. However, due to the stochastic nature of failures in the railway components, corrective maintenance is always required. Rail maintenance operations are essential for the railway system as they help to extent the life cycle of the railway assets, maintain the safety standards and allow infrastructure development in order to have reliable and safe train operations. However, maintenance operations in the railway network generate TCRs, becoming part of the capacity allocation models as they restrict the capacity of the network temporally. In order words, railway lines that are in maintenance are restricted from use for a period of time in order to maintain it. The closure period will depend on the type of maintenance procedure.

Each infrastructure manager from the EU deals with TCRs differently, especially regarding the applied timeframe and periods. According to RailNetEurope (2022), this is mainly due to different construction and maintenance planning processes, which again depend on the budget and financial planning. In addition, differing national legal regulations had an influence on TCR management regarding the application of terms and communication with applicants.

As seen in Table 4, temporary capacity restrictions can be classified according to their duration and impact on rail traffic into major, high, medium, and minor impact TCRs. Therefore, the publication criteria for TCRs are defined according to their effects on capacity and rail traffic (RailNetEurope, 2022).

Table 4. Types of TCR according to their duration and impact (source: RailNetEurope, 2022)

	Consecutive days	**Impact on traffic(*)**
Major impact TCR	More than 30 consecutive days	More than 50% of the estimated traffic volume on a railway line per day
High impact TCR	More than seven consecutive days	More than 30% of the estimated traffic volume on a railway line per day
Medium impact TCR	Seven consecutive days or less	More than 50% of the estimated traffic volume on a railway line per day
Minor impact TCR	Unspecified	More than 10% of the estimated traffic volume on a railway line per day

* Estimated traffic cancelled, re-routed or replaced by other modes of transport

The impact on traffic is the impact that the maintenance operation has on the line capacity compared to a representative day. While the consecutive days are the sequence of calendar days on which TCRs apply on each day, on the same section without any interruption (RailNetEurope, 2022). It is based on the representative day chosen to calculate the impact on traffic and the volume of traffic impacted.

Regarding environmental impact, infrastructure renewal, maintenance activities and construction can cause 20% of carbon emissions throughout the railway system (Kaewunruen et al., 2022). These emissions vary depending on climate change, environmental conditions and the type of rail infrastructure (Kaewunruen et al., 2022).

The main stakeholders involved in the rail maintenance operations are:

- **Railway infrastructure managers:** any body or firm responsible in particular for establishing, managing, and maintaining railway infrastructure, including traffic management and control-command and signalling; the functions of the infrastructure manager on a network or part of a network may be allocated to different bodies or firms (European Parliament; Council of the European Union, 2012).
  Their main responsibilities are to manage and maintain the railway infrastructure and to ensure compliance with safety regulations and standards. The main values are responsibility, safety, reliability, and trust. They are responsible for a safe and reliable railway network as well as the maintenance works related to it (done by the contractors). Safety refers to prioritizing the safety of passengers, staff, and the public. They ensure safety by implementing and adhering to safety standards and protocols to prevent accidents and ensure the secure operation of the railway system. Trust is the confidence that the user and non-users have that the infrastructure manager will maintain a reliable and safe network and services. Finally, reliability means ensuring the consistent and dependable operation of railway infrastructure. This is achieved by striving to minimise disruptions, delays, and breakdowns.
- **Rail Freight Corridors:** A corridor organised and set up in accordance with the Rail Freight Regulation (Regulation (EU) No. 913/2010). A freight corridor means all designated railway lines, including railway ferry lines, on the territory of or between Member States, and, where appropriate, European third countries, linking two or more terminals, along a principal route and, where appropriate, diversionary routes and sections connecting them, including the railway infrastructure and its equipment and relevant rail services in accordance with Article 5 of Directive 2001/14/EC (European Parliament; Council of the European Union, 2010).
  RFCs are another figure of authority that deals with capacity allocation of the rail freight network in the EU in coordination with the relevant infrastructure managers. There are 11 RFCs (see Table 1 in the previous chapter).
- **Railway undertakings:** any public or private undertaking licensed according to the Directive 2012/34/EU, the principal business of which is to provide services for the transport of goods and/or passengers by rail with a requirement that the undertaking ensure traction; this also includes undertakings which provide traction only (European Parliament; Council of the European Union, 2012).
  Their main responsibility is to provide punctual and reliable train service to its users. Their main values are safety, reliability, and sustainability. Safety refers to prioritising the well-being of the passengers, staff, and the public. Reliability can be defined as the commitment to the consistent and reliable operation of train services. Finally, sustainability refers to promoting environmentally sustainable practices, such as the implementation of energy-efficient technologies.
- **Maintenance contractor:** the company responsible for building and/or maintaining the railway infrastructure according to the standards set by the railway infrastructure managers.
  Their main responsibility is to build and/or maintain the railway infrastructure according to the standards of the infrastructure managers. Their main values are responsibility, safety, and cost-effectiveness. They are responsible for building and maintaining the infrastructure according to the established standards. Safety refers to prioritising the safety of workers, passengers, and the public. Finally, cost-effectiveness means ensuring that the project is within the established budget without compromising safety and quality.

For the infrastructure managers, the maintenance is managed in different departments depending on the type of maintenance: capacity management takes care of the preventive maintenance while (rail) traffic operations oversee the corrective operations. In terms of cross-border coordination, each infrastructure follows different guidelines or protocols depending on the type of maintenance.

Regarding digital tools, RailNetEurope has developed two online applications for the coordination of maintenance operations within the railway network in the EU. The TCR Tool facilitates international coordination of TCRs by ensuring harmonization among all relevant stakeholders. The platform encompasses

TCR planning from three years ahead (in alignment with the referenced timetable) up to four months before a timetable change (RailNetEurope, n.d.). While, Train Information System (TIS) Incident Management Tool is an online platform created to enhance communication during railway operation disruptions. It assists dispatchers in identifying impacted trains and facilitates online communication with IMs (RailNetEurope, n.d.).

Table 5 shows the summary of the cross-border railway maintenance depending on the type of maintenance.

Table 5. Summary of the cross-border railway maintenance

Maintenance	Preventive	Corrective
Type	Planned	Not planned
Department in Charge	Capacity Management	Traffic Operations
Guidelines for coordination	Guidelines for Coordination/ Publication of Planned Temporary Capacity Restrictions for the European Railway Network	1- National incident management procedures 2- Handbook for International Contingency Management
Applications	TTR TCR Tool (RailNetEurope)	TIS Incident Management Tool (RailNetEurope) – Freight
Main Stakeholders	**Infrastructure Managers** **Rail Freight Corridors** Rail Undertakings (Maintenance) Contractors	

2.3.1 Coordination Process

The coordination process of the maintenance operations within the railway network is crucial as it allows the minimization of the impact on the transportation network, especially one as busy as the railway system. The coordination process is difficult as there is a high number of stakeholders involved, the stochasticity of the failures of the components, and the capacity usage of the railway network has to be requested in advance.

International coordination process is encouraged by different EU regulations: Directive 2012/34/EU (Annex VII), Regulation EU No 913/2010, and Proposal of document 52023PC0443 (on the use of railway infrastructure capacity in the single European railway area).

International coordination involves bilateral or multilateral agreements or partnerships among the relevant infrastructure managers of different countries. All IMs coordinate their TCRs to synchronize as much as possible their TCRs on both sides of a border point and to ensure that deviation routes are available (Infrabel et al., 2023). This is particularly important when lines or deviation routes affect multiple countries, and involvement with the Rail Freight Corridor (RFC) is necessary if the line is part of a corridor. In this process, IMs are responsible for planning the maintenance operations of the railway system, coordinating with RFCs, and negotiating with Railway Undertakings (RUs) due to their direct impact on their operations.

The coordination of the maintenance operations will depend on the type of maintenance:

Preventive Maintenance in Cross-border Sections

The objective of a coordination phase is to ensure that all infrastructure managers are involved in carrying out their respective TCRs, optimising their mutual interferences, and minimising the impact on the system and its users (RailNetEurope, 2022).

The coordination of TCRs shall ensure that planned capacity restrictions will consider the needs of both the infrastructure managers and the market by rationalising and minimising the gravity of the impact and duration of the capacity restrictions (RailNetEurope, 2022).

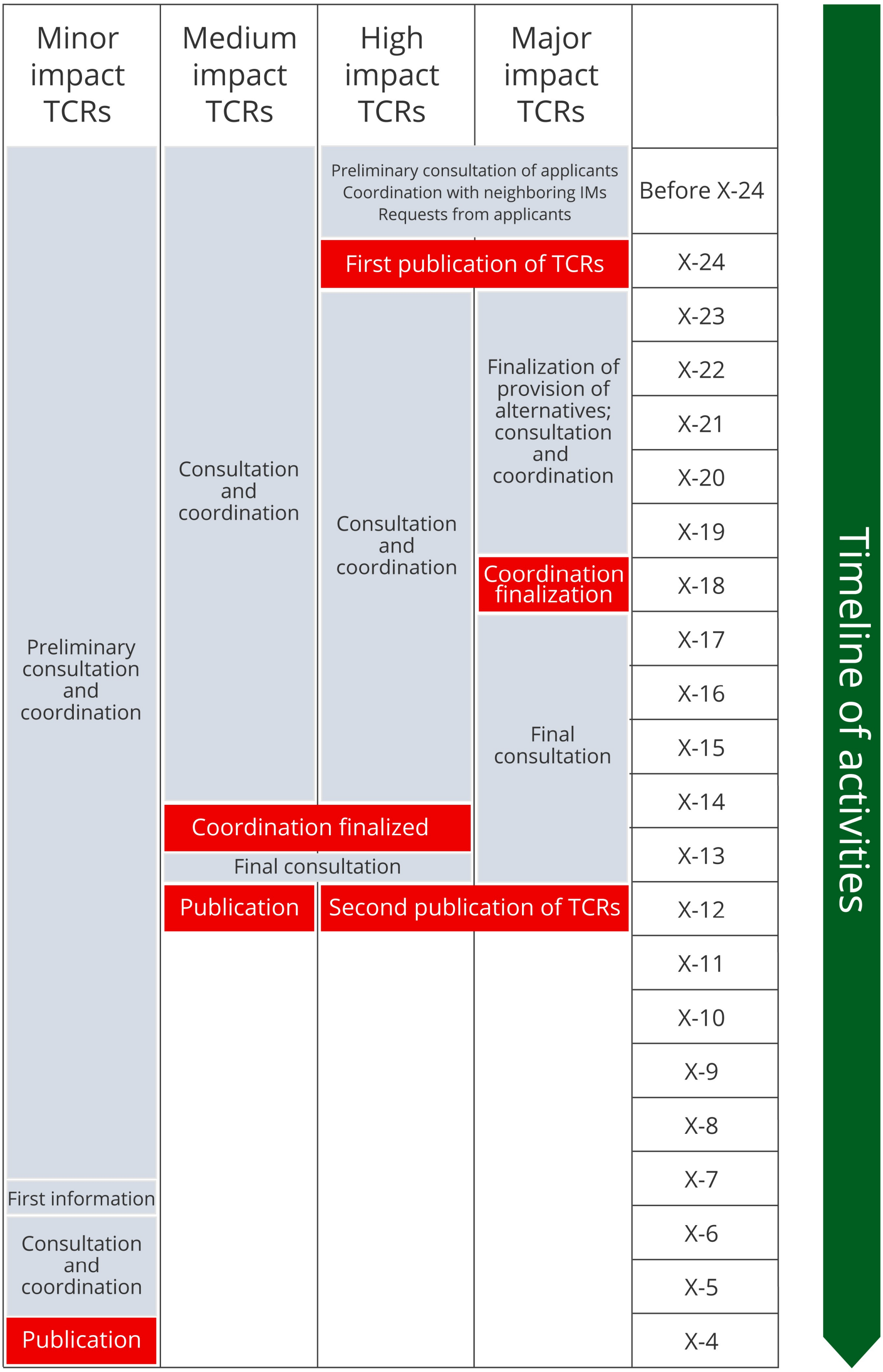


Figure 9. Timeline to coordinate TCRs according to RailNetEurope (2022)

The communication and coordination process will depend on the type of TCR: the higher the impact, the earlier that it has to be communicated (up to 24 months before the operation is applied). The Figure 9 shows the timeline to coordinate the TCRs according to RailNetEurope (2022). "X" represents the deadline for the month of the annual timetable change, and "n" is the number of months in advance of this deadline.

The main stages of the coordination activities for the minor and medium impact TCRs are the preliminary consultation and coordination, the consultation and coordination and finalization of the provision of alternatives, the coordination finalized, the final consultation, and the publication. While the high and major impact TCRs have a preliminary consultation, the first publication of TCRs, the consultation and coordination, the coordination finalized, the final consultation, and the second publication of TCRs.

The coordination of the TCRs starts as early as 2 years before their application and finishes up to four months before. All TCRs that are modified or defined after the last publication deadlines, such as an unforeseen breakdown of infrastructure outside the maintenance cycles or before the termination of the infrastructure component lifecycle, are considered as late TCRs (RailNetEurope, 2022). TCRs caused by force majeure (i.e. natural disasters or accidents) are not considered late TCRs (RailNetEurope, 2022).

While coordinating, the infrastructure manager needs to consult with the main relevant stakeholders: neighbouring infrastructure managers, applicants, and the main operators of relevant service facilities. If allocated paths are affected, the infrastructure managers must start a path alteration process. It is important to mention that if a freight corridor is affected then the Rail Freight Corridor should be informed as they are responsible for the TCR coordination and consultation process (within the affected corridor).

According to RailNetEurope (2022), when TCRs are received after the dedicated coordination/publication deadline but before path allocation, the infrastructure managers start a specific consultation phase on a case-by-case basis. These consultation phases are announced through agreed communication channels and are accessible to both affected and interested applicants.

According to the Capacity Strategy 2027 (2023), if disagreements occur among the involved stakeholders, none of the IMs have established a pre-defined escalation process related to TCRs with one or more neighbouring IMs. In most cases, if there's a disagreement among the stakeholders, escalation occurs within the regular national processes of the IMs.

Information Requirements on the TCR Publications

As stated by RailNetEurope (2022), each infrastructure manager shall publish on its web page the information about its TCRs according to the coordination timeline (see Figure 9). For major impact TCRs, the following information should be published in the first and second publications:

- Planned days.
- Time of day, and, as soon as it can be set, the hour of the beginning and the end of the capacity restriction.
- Section of line affected by the restriction.
- Where applicable, the capacity of diversionary lines.
- Criteria for which trains of each type of service should be re-routed with a preliminary allocation of the remaining capacity to the different types of train services to the extent known.

While for high, medium, and minor impact TCRs, the following information should be published:

- Planned days.
- Time of day, and, as soon as it can be set, the hour of the beginning and the end of the capacity restriction.
- Section of line affected by the restriction.
- Where applicable, the capacity of diversionary lines.

Infrastructure managers shall provide details on the offered train paths for passenger trains to affected applicants no later than four months and for freight trains no later than one month prior to the start of the capacity restriction unless infrastructure managers and affected applicants agree on shorter lead time (RailNetEurope, 2022).

In case of a major impact TCR, upon request of applicants (before X-24), the infrastructure manager shall provide them a comparison of the conditions to be encountered under at least two alternatives (e.g. original and one alternative TCR concept) of capacity restrictions (RailNetEurope, 2022). This comparison should include the duration of the capacity restriction, the expected indicative infrastructure charges based on currently valid rates, the capacity available for rerouting on diversionary lines, the available alternative routes, and the indicative travel times.

Corrective Maintenance in Cross-border Sections

Corrective maintenance is mostly applied to unexpected failures of the components of the railway system. The type of failures can generate disruptions at the national and international level. An international disruption is an unplanned disruption defined by its duration (based on the recovery forecast) and its impact on international train operations (RailNetEurope, 2021) and it is shown in Figure 10. A high impact can be assumed, as a rule of thumb, if 50% of the trains on the affected section need an operational treatment (RailNetEurope, 2021).

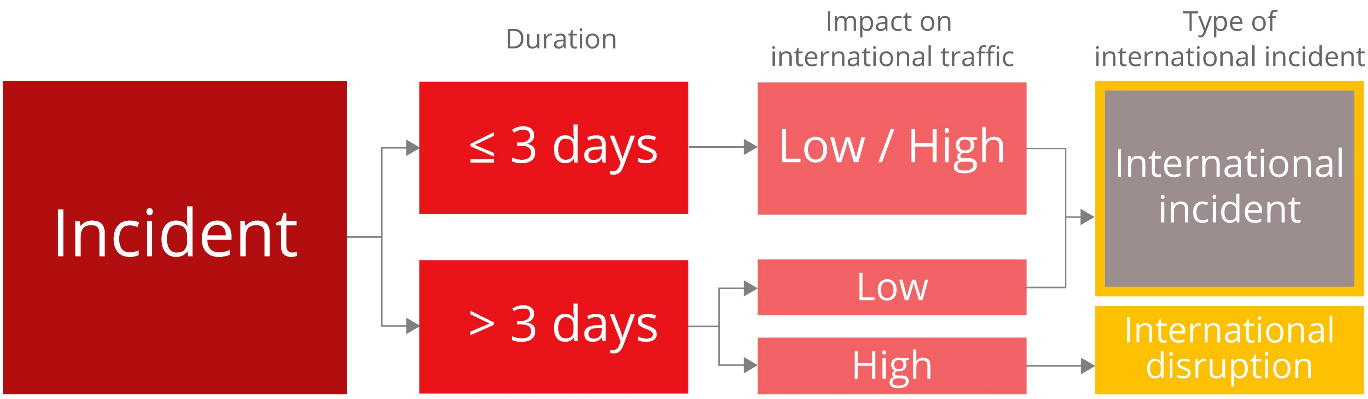


Figure 10. Definition of an international disruption (source: RailNetEurope, n.d.)

According to the Handbook for International Contingency Management (2021), international incidents will be operationally by IMs and RUs without the involvement of RFC. The incident will be handled on existing (bilateral) agreements, and the re-planning on the operational level will be done following national procedures.

It is important to mention that every line within a RFC should have a re-routing scenario in case of an international disruption. The re-routing scenarios have to be published within the Customer Information Platform (CIP). The main purpose of these scenarios is to minimise the impact on traffic during a disruption. According to the Handbook for International Contingency Management (2021), each re-routing scenario should include information about re-routing options including infrastructure parameters on the routes, the capacity and usability of re-routing option (if feasible), the locations where loading/unloading of the train can be done (if possible), and parking locations and capacities (if possible).

In terms of language, English will be used for international coordination. If all parties agree, another language may be used for telephone conferences. However, written information exchanged must be in English at a minimum (RailNetEurope, 2021).

In case of an international disruption, the national incident management procedures should be applied. The ICM is a complement to allow better international cooperation of IMs. The complete process map for the ICM is shown in the Appendix B – ICM Process Map. The incident management will be briefly discussed in the following sub-section; however, for more detailed information, the procedure can be found in the Handbook for International Contingency Management (ICM).

International Disruption

This sub-section is based on the Handbook for ICM and it highlights the main coordination process during an international disruption.

The initiating Infrastructure Manager notifies all neighbouring and other impacted IMs, particularly the traffic control centres of neighbouring IMs, directly and immediately. This notification is typically facilitated through TIS. Additionally, the relevant RFCs should also be informed about the interruption at this early stage. The national traffic control centre of the initiating IM will provide information about the interruption to the TIS Incident Management tool. This will allow the information to be shared with all affected IMs, applicants, and RFCs. It will also serve to declare the international disruption and to select the coordinating RFC.

After the international disruption is declared, a first set of information about the disruption is handed over from the initiating IM to the coordinating RFC as soon as possible but not later than 12 hours. Additionally, a first telephone conference on mitigation measures with the incident managers of all relevant IMs / ABs and affected RFCs ("incident management TelCo") shall be organised by the coordinating RFC within 12 hours after being informed by the initiating IM and between 7:00 am and 7:00 pm (RailNetEurope, 2021).

During this telephone conference, information about the incident is exchanged, and the next steps are organized. This includes a joint decision about relevant re-routings and required mitigation measures, whether a capacity coordination TelCo should be organized and by whom, the timeframe and responsibilities for the preparation of the IM offer (volume of maximum capacity/paths), and the deadline to provide the internationally coordinated capacity/paths adjusted for the specific situation.

After this, the IMs and allocating bodies will deal with capacity and path coordination during the disruption. This process can be divided into an assessment of capacity and path offer (IM offer) and an assessment of demand (of applicants). Throughout these processes, there is a continuous share and update of information within the involved parties. The details of both processes can be found in the Handbook for International Contingency Management (ICM).

When the situation goes back to normal, the international disruption case is closed by the respective infrastructure manager (also within TIS). Then, an evaluation report about the ICM case is done to ensure the regular collection of experiences and identification of the best practices from the simulations and/or real international disruptions, after every simulation /real case (RailNetEurope, 2021). The coordinating RFC supervises the proper information flow to all parties involved and directly manages the information to other RFCs, RFC partners, and relevant stakeholders.

Communication Process

According to the Handbook for ICM by RailNetEurope (2021), there are main three different communication processes (see Appendix C – Communication Process Map), and they will be described briefly below:

1. National traffic management communication process – to share train related information.

Any train related information is handled via national traffic control centres (NTCC) following the national rules and processes without RFC involvement.

2. ICM media communication process – to share information on general media releases.

The communication manager of the initiating IM joins the telco of incident managers to gather the basic information to prepare the press release and to provide this information about interruption (duration, impact, possible re-routings, TCRs, etc.) to the communication managers of affected IMs.

Media information published by RFCs: The initiating IM's Communication manager prepares the complete general information about the incident in English (scope, duration, map, consequences, possible mitigation/re-routing measures) and provides it to the RFC coordinator. Based on this information, the RFC coordinator publishes information on the RFC website and, if appropriate, using other social media channels in English and forwards the set of information provided by the initiating IM to all involved IMs and RFCs. The coordinating RFC consistently gathers and updates incident information, publishing the latest details on its English-language website and notifying all relevant IMs and RFC.

Media information published by IMs: The distribution and publication of the media information by affected IMs follows the national rules and procedures, based on the general information about the incident received from the initiating IM or RFC coordinator.

3. Information to stakeholders – to share information with the railway sector.

As soon as the RFC coordinator has received the general information about the incident, an email to the partners and relevant stakeholders shall be sent. This communication is done by the RFC coordinator at least at the beginning of the ICM process and its end. Information to IM national stakeholders is done based on the national IM rules and processes.

2.4 Digital Twins

The digitalization of railway infrastructure responds to the need of a railway owner to manage its operations and assess the condition and value of its railway infrastructure (Ciccone et al., 2022). To fulfil this need, the use of Building Information Modelling (BIM) and Digital Twins (DT) has become common within the infrastructure industry.

Nowadays, there are many tools used in the infrastructure industry that help to manage it, for example, digital twins. To support their decision-making process, asset managers require relevant and timely information about their assets. The application of digital twin technology has the potential to enhance maintenance and renewal decisions by providing more data on the asset performance and its condition, as noted by Vieira et al. (2022). On a larger scale, this could improve investment and resource planning by predicting the optimal timing for interventions in advance and with increased precision.

A digital twin can be defined as a digital representation of a physical entity that integrates different static and dynamic data, such as that acquired from building information modelling (BIM) and condition monitoring systems (Doubell et al., 2022). According to Vieira et al. (2022), a digital model represents a physical object without automated data exchange. Changes in the physical object do not affect the digital model, and vice versa. A digital shadow involves one-way automated data flow, where alterations in the physical object impact the digital model, but not the reverse. In contrast, a digital twin features a fully automated two-way data flow, enabling the digital model to control the physical object's operation. Changes in the state of either object influence the state of the other.

According to Jeong et al. (2022), the general purposes of the utilization of digital twin technology are process optimization, efficient product design, cause analysis, multi-disciplinary decision-making, and to prevent real-world problems in advance. Furthermore, the implementation of digital twins is divided into 5 stages which are defined in Table 6.

Table 6. Stages of evolution and its definition (source: Jeong et al., 2022).

Stage	Description
Stage 1 – Mirroring	Duplicating a physical object into a digital twin.
Stage 2 – Monitoring	Monitoring and controlling the physical object based on the analysis of the digital twin.
Stage 3 – Modelling and simulation	Optimizing the physical object through the simulation results of the digital twin.
Stage 4 – Federation	Configuring federated digital twins, optimizing complex physical objects, and inter-operating federated digital twins and complex physical objects. It is suitable for duplicating and optimizing the large-scale complex real world.
Stage 5 – Autonomous	Autonomously recognizing and solving problems in federated digital twins and optimizing physical objects according to the federated digital twin solution.

As stated by Doubell et al. (2022), digital twins frequently integrate a simulation aspect, allowing the digital representation of specific railway infrastructure segments to anticipate their own degradation patterns by leveraging historical and real-time data. This opens opportunities for predictive maintenance and other compelling data analytics applications that can validate or enhance current maintenance approaches.

Figure 11 shows the workflow of the digital twin application: it starts with physical assets which are monitored with sensors. The second step will be the generation of the digital asset (usually, a 3D model) with the data gathered by the sensors. The fourth step will be the prediction models using physics-informed models or machine learning algorithms. Once the predictions are done, the infrastructure managers have all the information needed to take action (via an actuator). Once, the maintenance action is done, the digital model updates itself with the new data. It is important to mention that some optimizations can be done offline, for example, by evaluating different maintenance strategies.

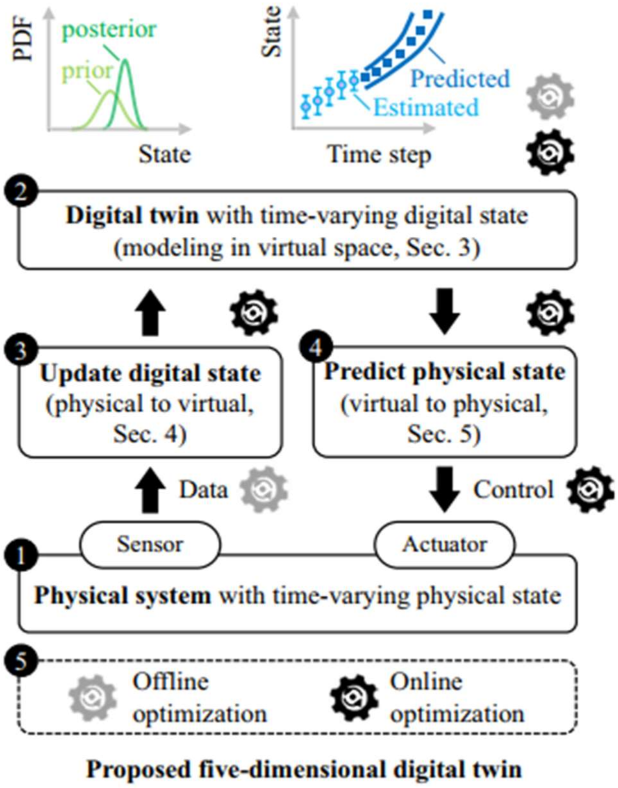


Figure 11. Digital twins model (source: Thelen et al., 2022)

In the railway sector, Galván-Nuñez et al. (2024) defines different implementation layers for a digital twin, illustrated in Figure 12. This figure also shows the expected elements within these layers. For instance, the physical and data acquisition layers are part of the mirroring stage as the components of the system, the required sensors for monitoring, and the data requirements and acquisition are defined. Ultimately, the federated digital twins and security and privacy layers are part of the federation stage, in which interconnected representation of track, train, and operations in addition to cybersecurity and privacy processes have to be set up.

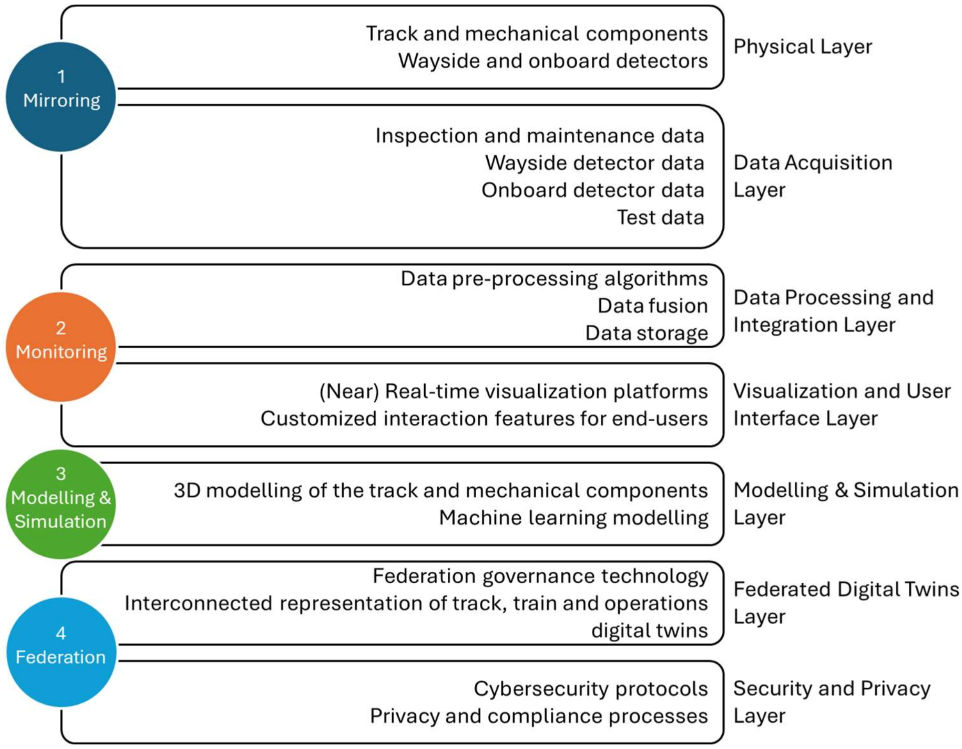


Figure 12. Implementation layers for digital twins in railways (source: Galván-Nuñez, 2024).

Digital twins are a tool that infrastructure managers can use to define and evaluate the maintenance strategy to be applied based on data on the current state of the infrastructure and prediction models. They can also enable collaborative planning among different stakeholders by sharing a common digital platform.

As discussed by Vieira et al. (2023), the main challenges of using digital twins are cybersecurity and access management, interoperability, data management, and change management. Cybersecurity becomes relevant as infrastructure companies often deal with sensitive information. One key challenge regarding data and models within the digital twins is that they should be standardized and delivered in common formats, protocols, and standards. Finally, it is important to mention that the rail infrastructure sector has a slow implementation of new technologies which can also hinder the use of digital twins.

Both of the previously proposed frameworks for digital twin implementation are not suitable for cross-border operations. The framework proposed by Thelen (2022) lacks the requirements for interaction with other DTs, making it inadequate for addressing data sharing, which is an important cross-border challenge. On the other hand, the model proposed by Galván-Nuñez et al. (2024) accounts for federation and data sharing but fails to consider the varying maintenance standards and different monitoring techniques used by different countries. Furthermore, neither framework provides a detailed methodology for practical application.

2.5 Assessment of Cross-Border Railway Maintenance

In this section, the analysis of the current situation of the cross-border railway lines is presented. A questionnaire is done to different infrastructure managers and other relevant stakeholders within the EU to define the importance, challenges, and opportunities within cross-border maintenance operations. This questionnaire is presented in the Appendix I – Questionnaire about Cross-border Maintenance Operations.

The questionnaire is divided into 5 main sections: the importance of cross-border lines, preventive maintenance, corrective maintenance, current challenges of the cross-border lines, and possible solutions. The questionnaire remained open from 14th May until 19th June, during which eight responses were collected from various institutions across the five different countries of the EU. Before analysing the questionnaire results, initial hypotheses regarding cross-border maintenance operations are formulated for each subsection based on insights from the literature review.

2.5.1 Importance of Cross-border Railway Lines

Within this subsection, the generalities and the importance of cross-border railway lines are presented. The main hypothesis for this subsection is that the importance of international railway lines is high and going to increase. This hypothesis is based on environmental policies, such as the EU Green Deal, which aims to promote the use of railways as a sustainable mode of transport.

The importance of cross-border railway lines across different countries is shown in Figure 13. Two experts did not provide which country the answers are related to. All of them consider that these lines are very and extremely important.

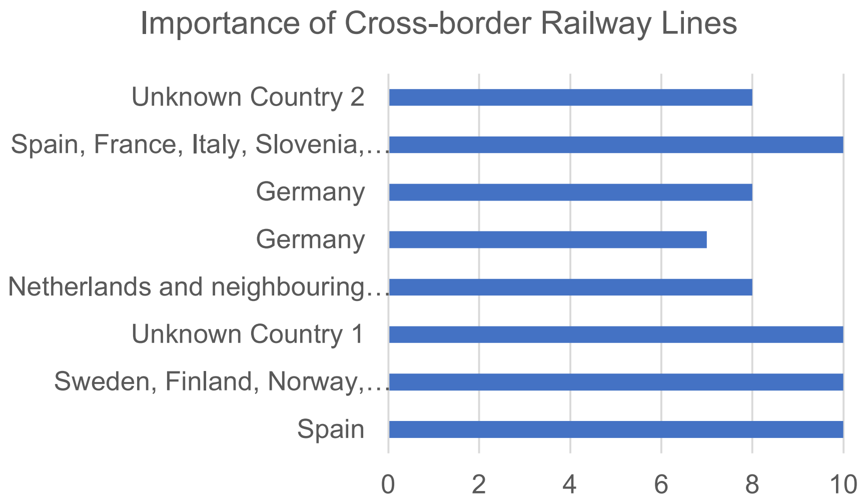


Figure 13. Expert opinion on the importance of railway lines

The importance of these international lines is expected to increase according to most of the experts due to the expansion of the market (in freight and passenger services), the need for improving connectivity within the EU, and sustainability goals set by EU regulation. Only one of the experts states that the main focus will be national lines, which is consistent with one of the challenges previously mentioned: different political priorities between the two countries (priority to national rail system).

According to expert opinion, the assessment of the performance and availability of cross-border lines has a generally positive outlook. Five out of the eight participants rate the performance and availability of these lines as good indicating that cross-border lines are generally reliable but occasionally encounter issues. Two participants rate them as fair, recognizing that cross-border lines face challenges but remain operational. Finally, one of the participants had no opinion on the subject.

The performance and availability of these rail lines are directly related to TCRs, which are one of the main causes of delays and train service cancellations. Having a good performance of these cross-border lines suggests that the current maintenance coordination process is effective but could benefit from optimization especially to accommodate the increase in the future train service demand.

According to the experts, cross-border railway lines have similar or slightly better performance levels than regular ones. It is also noted that performance issues in cross-border lines are not unique and can also be found in national lines. Examples of poor performance in cross-border lines include the High-Speed Line between Belgium and the Netherlands, attributed to construction errors, and the northern approach area of the Brenner Base Tunnel. One of the participants also highlighted the differences in track systems between countries as a significant challenge to improving performance, such as the varying track gauges between Spain and France. This last challenge also aligns with the previously identified issues associated with cross-border sections: different technical characteristics of the railway systems of the involved countries.

2.5.2 Cross-border Corrective and Preventive Railway Maintenance

Within this subsection, the evaluation of the coordination of maintenance operations in cross-border railway lines is presented. The main hypothesizes for this subsection are that stakeholders would be open to sharing more data about the rail condition to improve the coordination of TCRs and that data sharing is better for corrective maintenance than preventive maintenance. The first hypothesis is relevant as data sharing is essential for the coordination of TCRs and the implementation of digital applications. The second hypothesis tries to prove that corrective maintenance (incidents) is better coordinated than preventive maintenance.

For both maintenance processes, railway infrastructure managers were stated as the key stakeholders followed by the maintenance contractors. Rail freight corridors were not considered significant stakeholders, and railway undertakings were only recognized in preventive maintenance. The importance of these latter two stakeholders decreases as they are not directly involved in planning although they are highly affected by maintenance.

According to the experts, the main challenges that preventive maintenance faces in cross-border sections are: scarcity of resources (including personnel), ineffective maintenance programs, lack of suitable prediction algorithms, short maintenance windows, and agreements for line closures. Additionally, one of the participants highlighted that maintenance in cross-border sections has the same implications as maintenance on other lines within the country.

The main challenges that corrective maintenance faces in cross-border sections are similar to the ones faced by preventive maintenance according to the expert opinion. One of the participants also mentioned maintenance logistics and fault detection as additional challenges.

The coordination of maintenance operations was evaluated by four different criteria: communication between IMs, data sharing between IMs, quality of the current standard protocols for corrective and preventive maintenance, and overall coordination of the maintenance operation. The Figure 14 and Figure 15 show the results of the survey.

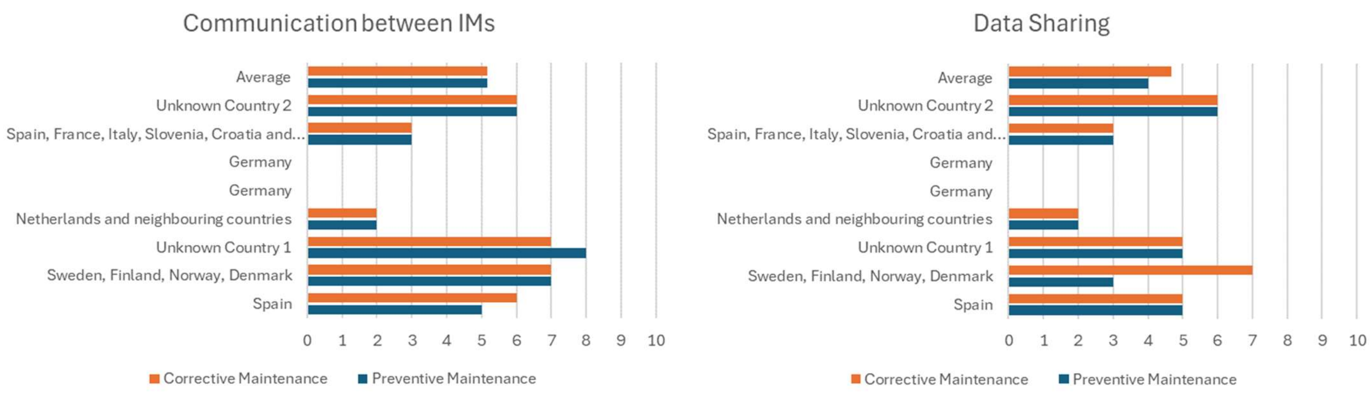


Figure 14. Evaluation of communication and data sharing between IMs

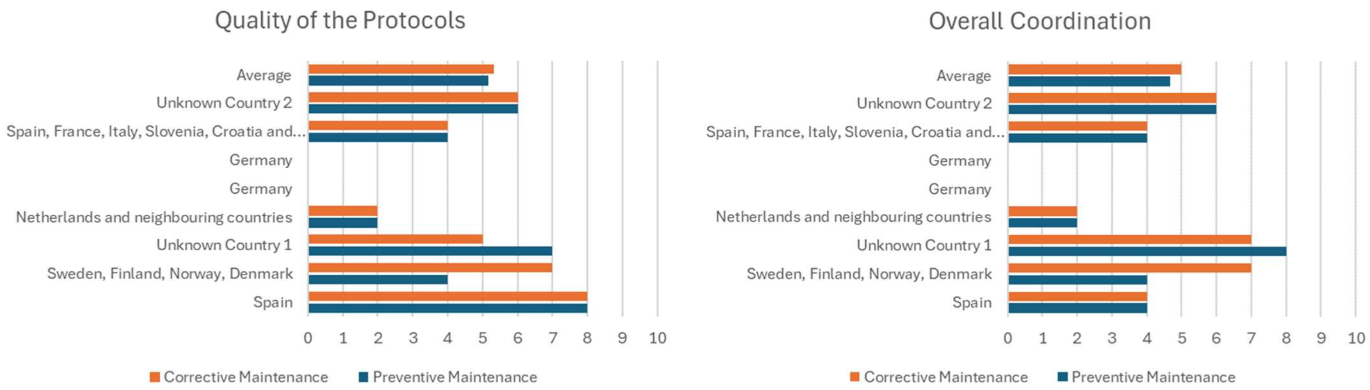


Figure 15. Evaluation of the quality of the protocols and the overall coordination

In Figure 14 and Figure 15, the general trend is similar across all evaluated criteria. In most cases, corrective maintenance has a higher average rating than preventive maintenance, except for communication, where the averages are the same for both types of maintenance. This verifies the second hypothesis made at the beginning of the section: preventive maintenance has better coordination than corrective. The higher ratings for corrective maintenance imply that reactive measures are better coordinated and communicated compared to preventive measures. For example, in the case of FRC, all the routes follow the incident management procedures and also have predefined re-routing scenarios in case an incident happens to minimize the impact on the users.

Finally, the disposition to increase data sharing to improve the coordination of preventive maintenance is low as only two out of the seven answers were positive about increasing the data sharing between IMs. This contradicts the first hypothesis made at the beginning of the section. Certain information about rail infrastructure (i.e. axle box acceleration (ABA) measurements) is considered sensitive, leading to reluctance among infrastructure managers to share more data, especially without clear and tangible (individual) benefits in sight. Another reason for the limited data sharing is that infrastructure managers may not possess the necessary data about their systems, or it may be incomplete.

2.5.3 Challenges in the Maintenance Operations in Cross-border Railway Lines

Within this subsection, the rating of challenges of maintenance operations in cross-border railway lines is presented. The main hypothesis for this subsection is that the lack of interoperability between countries is the most relevant challenge. This hypothesis is based on previous research indicating that differing national systems and standards severely affect the efficiency and effectiveness of cross-border railway operations. The rating for every challenge can be found in Appendix D – Rating of Challenges of Cross-border Maintenance Operations.

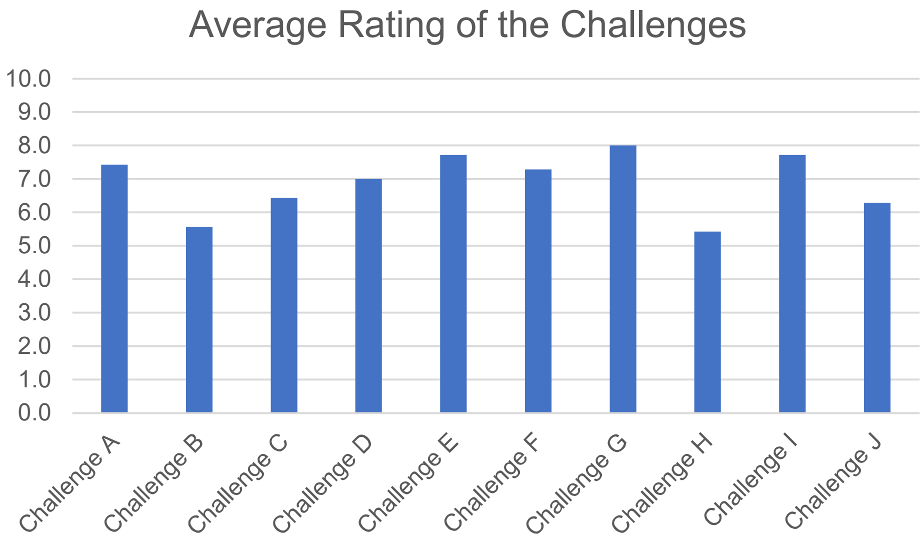


Figure 16. Average rating of the challenges of cross-border maintenance operations (see Table 7)

Table 7. Table of challenges

Challenge	Description
A	Involvement of many stakeholders from more than one country (lack of coordination).
B	Asymmetries in the distribution of costs and benefits (between the involved countries).
C	Conflicting laws and regulations between the involved countries (lack of EU-wide standards).
D	Lack of a coordinated network scheduling (timetable).
E	Different political priorities between the two countries (priority to national rail system).
F	Lack of unified socio-economic models for cross-border infrastructure planning.
G	Lack of data or information from the neighbouring country (i.e. stable timetable with the defined TCRs).
H	Use of different languages.
I	Different technical characteristics of the railway systems of the involved countries.
J	Lack of unified maintenance standards.

Figure 16 shows the average rating of the challenges: all of them have a relevant significance, with ratings between 5 and 8. The most significant challenge is the lack of information or data from the neighbouring country. On the other hand, the least significant challenge is the use of different languages. The hypothesis of this section does not comply with the data found, however, different technical characteristics of the railway system ranks as one of the most important challenges sharing second place with challenge E.

The lack of information sharing affects not only maintenance operations but also cross-border train services such as fare standardization (see example in Figure 8) and the alignment of service information. In contrast, the issue of using different languages has been addressed by implementing a neutral language or by training and hiring personnel who can communicate in the required languages. Looking forward, AI translation tools present promising future solutions to overcome language barriers.

Even though the lack of data sharing between countries is the main challenge, the willingness to increase data sharing is minimal. This reluctance can stem from either missing information or the fact that the neighbouring IM may not possess the requested data. It is important to remark that the objective of increasing the information sharing between countries is to optimize maintenance operations and improve decision-making as there is more information about the system.

Other significant challenges include differing political priorities between the two countries and the distinct technical characteristics of their railway systems. As previously stated, one of the experts mentioned that the main focus of maintenance would remain on national lines, which aligns with the previously mentioned challenge of differing political priorities, where priority is given to the national rail system over cross-border international lines.

In conclusion, the analysis reveals that the lack of data sharing between neighbouring countries is the most critical challenge in cross-border railway maintenance, contrary to the initial hypothesis focusing on interoperability. Significant issues also include differing political priorities and technical characteristics of railway systems. Addressing these challenges requires a digital and cooperative framework for holistic solutions and infrastructure digitalization. This framework aims to enhance interoperability, standardize maintenance practices, and optimize the performance of the EU railway network. The next chapter will develop the DCF.

Chapter 3. A Digital-Cooperative Framework to Improve the Coordination of Maintenance Operations

To address the multiple challenges of cross-border railway maintenance holistically, this chapter proposes and analyses a DCF for improving maintenance support decisions. This framework will composed of three parts as seen on Figure 17: the railway entity, the forum and the digital twin application. The proposed framework involves the EU Railway Entity having a forum (to improve maintenance operations and standards) as a support organization, while also utilizing digital twins as a tool to improve the decision-making and coordination of cross-border projects.

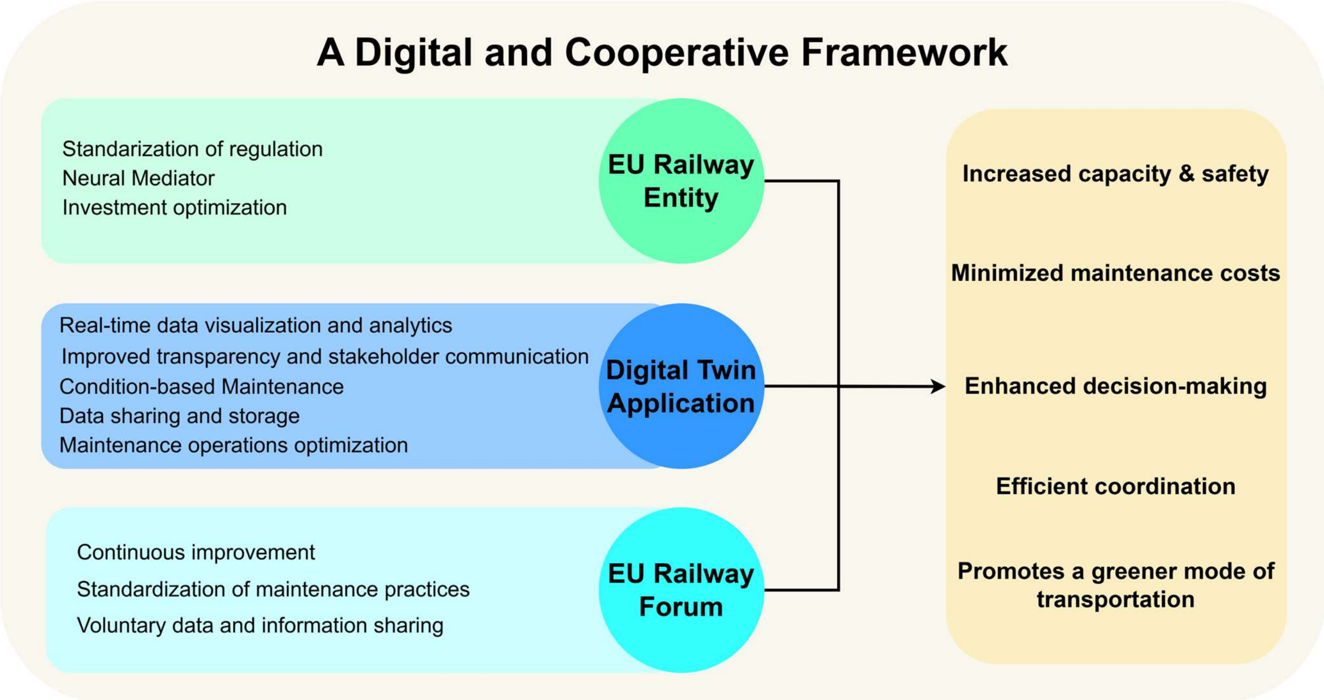


Figure 17. Diagram of a digital and cooperative framework

It is important to mention that the three components or solutions are different from each other and can be implemented on their own. However, they are not mutually exclusive and can be applied in parallel to complement each other. They tackle the challenges of cross-border railway sections in different ways. Table 8 shows a summary of the challenges solved by each solution individually.

Table 8. Summary of the challenges solved by each component individually

Challenge	**Solution 1 EU Entity**	**Solution 2 EU Forum**	**Solution 3 DT**
Involvement of many stakeholders from more than one country (lack of coordination).	X	X	X
Asymmetries in the distribution of costs and benefits (between the involved countries).	X		X
Conflicting laws and regulations between the involved countries (lack of EU-wide standards).	X	Partial	Partial
Lack of a coordinated network scheduling (timetable).	X		X
Different political priorities between the two countries (priority to national rail system).	X		
Lack of unified socio-economic models for cross-border infrastructure planning.	X		X
Lack of data or information from the neighbouring country	X	X	X
Use of different languages.	X	X	
Different technical characteristics of the railway systems of the involved countries.			
Lack of unified maintenance standards.	X	Partial	Partial
X = solved by solution || Partial = partly solved by solution || “Black space” = not solved by solution			

A key difference between solutions 1 and 2 lies in their approach to implementation. The forum can only make recommendations, and the adoption of these suggestions will depend on the willingness of the IMs. In contrast, the European Railway Entity would aim to enforce standards and regulations, making them mandatory for all involved parties.

The third solution, the application of a digital twin, promotes the use of digital applications to reduce the impact of maintenance operations by relying on real-time data and maintenance optimization models, using artificial intelligence. The digital twin technology enables a dynamic and accurate representation of the railway infrastructure, facilitating condition-based maintenance and efficient resource allocation.

In the following sections, the three components of the DCF and how they tackle each challenge are going to be detailed. Following these sections, a timeline for the implementation of the DCF is presented.

3.1 Component 1: European Railway Entity

The creation of a European entity that acts as a railway network coordinator within the European Union. This entity will be formed by the IMs and other allocating bodies within the EU to ensure the interest of each country involved (see the possible hierarchy structure in Figure 18). In addition, support organizations like the Community of European Railway Companies (CER), RailNetEurope, the European Network of Rail Regulatory Bodies (ENRRB), and others will help this new entity as consultants or auditing agents.

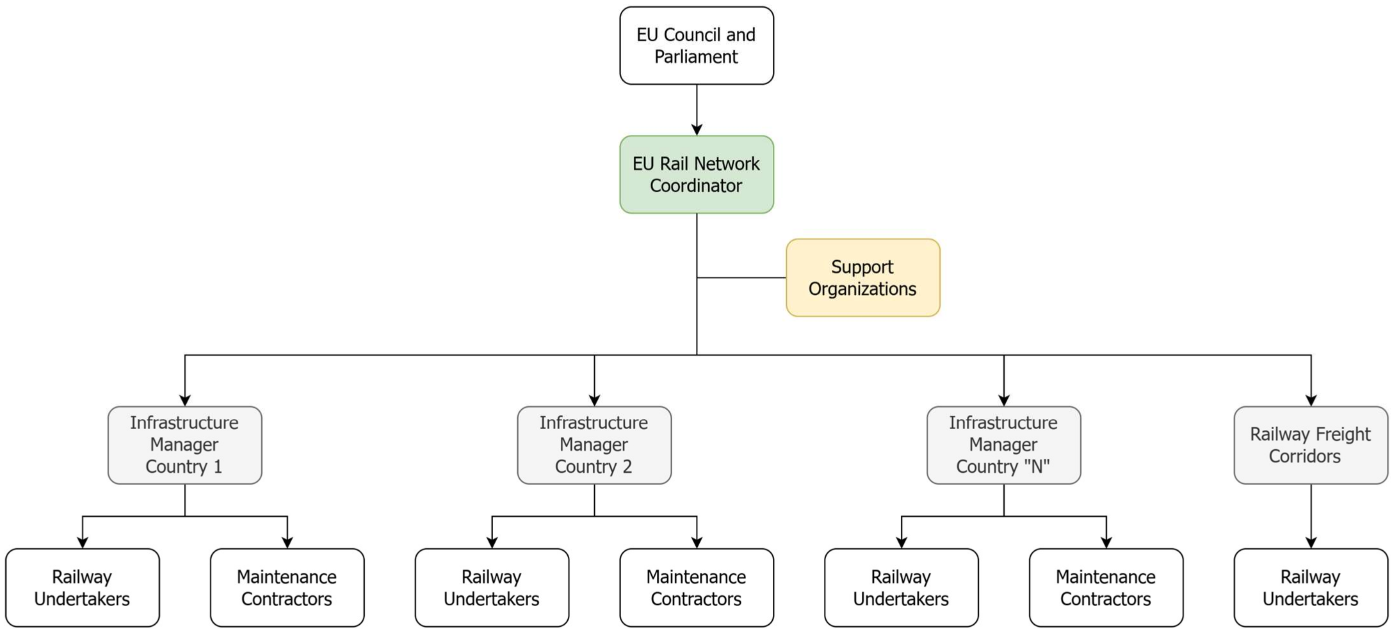


Figure 18. European Rail Network Coordinator (possible) hierarchy

The main objective of the organization is to coordinate the railway network efficiently within the EU, increasing cross-border transport without compromising national transportation. As seen in the Figure 18, the EU Railway entity will have hierarchical authority to mandate over the IMs and allocating bodies. In other words, it will have the authority to impose priorities over the IMs based on European interests, solving the challenge of having different political priorities in the cross-border sections. This entity would also have the mandate to harmonize standards, regulations, and practices to facilitate smooth cross-border railway operations. Moreover, it will also be in charge of managing and resolving cross-border conflicts or disagreements between its members acting as a neutral mediator.

The European Railway Entity will help address the lack of coordination among stakeholders as it would serve as a central coordinating body reducing the number of conflicts in cross-border sections. For example, it will receive discrete data updates about maintenance operations, following the coordination process of RailNetEurope. This centralization will help to improve capacity planning and network scheduling. Additionally, digital tools and applications will facilitate coordination and communication, enabling smooth data transfer between neighbouring countries.

Furthermore, this entity will solve the challenge of conflicting laws and regulations as it will harmonize laws and regulations related to railway operations. By promoting the adoption of common standards and regulations, it could eliminate barriers to cross-border operations. Another related challenge it would solve is the lack of unified maintenance standards. Support organizations, such as forums, will help identify conflicting maintenance practices and regulations. The European Railway entity will then develop and implement common maintenance standards and guidelines, providing clarity and consistency across national borders.

Finally, this organization will also solve the asymmetries in cost and benefit distribution. The entity could work towards creating a fair and equitable framework for sharing costs and benefits associated with cross-border railway projects. This could involve developing agreements and mechanisms to allocate resources fairly among participating countries based on factors such as usage, investment, and economic impact.

3.1.1 Benefits and Limitations

The creation of a European Railway Entity offers several advantages. Enhanced coordination would be a major benefit, as a centralized entity can facilitate better coordination among member states, infrastructure managers, and railway operators. This coordination can be achieved through information sharing, such as discrete data updates of the maintenance operations. This improved coordination is expected to lead to greater efficiency and reliability in cross-border rail services. Additionally, the organization would act as a neutral mediator in cross-border disagreements between its members, ensuring that conflicts are addressed efficiently, minimizing disruptions, and promoting smoother cooperation among member states.

Another advantage is standardization. By establishing common standards and regulations for railway infrastructure and operations, processes can be standardized to ensure interoperability, thereby reducing barriers to cross-border operations. Standardizing maintenance practices and protocols is particularly essential for ensuring the safety, reliability, and interoperability of cross-border railway infrastructure.

Furthermore, optimized investment would be another benefit. Centralized planning and decision-making can optimize investment in railway infrastructure, ensuring that resources are allocated efficiently and strategically to address key cross-border connectivity challenges. Finally, smooth cross-border rail connectivity can stimulate economic growth by facilitating trade, tourism, and regional development within the EU.

However, there are also limitations to this solution. Complex governance could be an issue, as establishing a new European entity may involve complex governance structures and decision-making processes, potentially leading to bureaucratic barriers and delays in implementation. As a European public institution, the standardization of regulations and the implementation of new procedures will be slow due to bureaucratic processes. This is particularly true when reforming laws, which requires changes at both national and international levels.

Moreover, sovereignty concerns are another drawback, as some member states may be reluctant to give authority over their railway networks to a centralized EU entity, raising concerns about their autonomy and national interests. Resource allocation could also pose a challenge, as there may be difficulties in allocating resources fairly and equitably among member states, particularly regarding funding for infrastructure projects and operational costs.

Finally, resistance to change from existing stakeholders, including national railway companies and infrastructure managers, may hinder the implementation of centralized coordination measures. These stakeholders may resist changes that could impact their autonomy and operations, potentially delaying the implementation of these measures.

Despite the challenges associated with the creation of the EU Railway Entity, the advantages promise a solid step towards a unified economic railway area and achieving effective coordination of the railway network, increasing its capacity. Table 9 shows the summary of the advantages and disadvantages of the European Railway Entity.

Table 9. Summary of benefits and limitations of the EU Railway Entity

Advantages	**Disadvantages**
Enhanced coordination	Complex governance
Standardization	Sovereignty concerns
Optimized investment	Resource allocation
Stimulated economic growth	Resistance to change

3.1.2 Present Initiative

In 2017, the Platform of Rail Infrastructure Managers in Europe (PRIME) PRIME decided to uptake the role of the European Network of Infrastructure Managers (ENIM) as foreseen in Article 7f of Directive 2012/34/EU establishing a single European railway area, as amended by Directive (EU) 2016/2370 (European Commission, 2024). After this, PRIME took the tasks of developing the EU rail infrastructure, supporting the implementation of the Single European Rail Area, exchanging best practices, monitoring, and benchmarking performance, and tackling cross-border bottlenecks, among others.

In July 2023, a proposal on the use of railway infrastructure capacity in the single European Railway Area was made via document number 52023PC0443. This proposal aims to establish ENIM as a European decision-making body for IMs, with binding decisions for all IMs. Currently, this proposal is awaiting the first reading position of the Council (European Parlament, 2024).

The main functions of the ENIM according to the Article 7f of the Directive 2012/34/EU (European Parliament; Council of the European Union, 2012) are the following:

- Develop Union rail infrastructure.
- Support the timely and efficient implementation of the single European railway area.
- Exchange best practices.
- Monitor and benchmark performance.
- Tackle cross-border bottlenecks.
- Discuss the application of: Cooperation in relation to charging systems on more than one network (Art. 37) and Cooperation in the allocation of infrastructure capacity on more than one network (Art. 40).

According to Article 56 of the proposal (European Commission, 2023), the ENIM shall be also responsible for the development and adoption of three European frameworks for capacity management, coordination of cross-border traffic and disruption and crisis management, and performance review. Additionally, it will be in charge of the coordination of the infrastructure managers.

The ENIM will appoint a Network Coordinator to support its tasks and report to a Performance Review Body on performance-related matters while seeking or receiving advice from the European Network of Rail Regulatory Bodies (ENRRB). According to Article 59 of the proposal (European Commission, 2023), the main tasks of the network coordinator are:

- Acting as Secretariat: prepare meetings, documents, decisions, and opinions of ENIM.
- Contributing to Frameworks: aid in the preparation of the European frameworks for capacity management, cross-border traffic management, disruption management, crisis management, and performance review.
- Operational Coordination: facilitate operational coordination between infrastructure managers.
- Identifying Obstacles: recognize rules, procedures, and tools at the national or infrastructure manager level that create obstacles for multi-network rail services.
- Contact Point for Enquiries: serves as a central contact point for enquiries related to capacity planning and allocation, potential capacity requests, information related to rail incidents, and temporary capacity restrictions.
- Stakeholder Engagement: act as the first point of contact for stakeholders outside the rail sector interested in using rail services, providing contacts to relevant actors at infrastructure managers and other operational stakeholders.
- Applicant Liaison: serve as a contact point on behalf of ENIM for applicants and other operational stakeholders on various issues, particularly those not explicitly covered by the Regulation, and support ad hoc activities, especially during crisis situations.

Regarding the management of scarce capacity, the IMs must manage limited capacity and resolve conflicts using objective, transparent, and non-discriminatory procedures. According to Article 8 of the proposal (European Commission, 2023), these procedures should assess alternative options for the use of infrastructure capacity based on the following socioeconomic and environmental criteria, provided the necessary data is available:

- Operating Costs: Assess the costs for rail transport service operators and the impact on prices for their customers.
- Time-Related Costs: Evaluate the time costs for customers of rail transport services.
- Connectivity and Accessibility: Consider the connectivity and accessibility benefits for people and regions served by the rail transport services.
- Environmental Impact: Measure the emissions of greenhouse gases, local air pollutants, noise, and other external costs associated with rail transport services and their likely alternatives.
- Safety and Public Health: Analyse the safety and public health implications of rail transport services and their likely alternatives.

Regarding resolving capacity conflicts using socio-economic and environmental criteria, it is essential to ensure that these criteria are adaptable to various market conditions. IMs should apply these criteria flexibly for multi-network or cross-border offers, ensuring effective responses to different regional and market realities.

The role of network coordinator has two potential candidates: RailNetEurope taking up as a network coordinator and the creation of a new European rail international capacity allocation body (ERICA) (RailNetEurope, 2023). The appointment of the network coordinator will be decided after the approval of the draft Regulation.

The difference between them is that ENIM operates at a strategic level, while the Network Coordinator handles the operational and administrative aspects, ensuring that the directives and frameworks developed by ENIM are effectively implemented and adhered to by infrastructure managers. In other words, ENIM focuses on high-level coordination, framework development, stakeholder consultation and providing recommendations while the network coordinator operates in a supporting role to ENIM. It handles secretariat tasks, facilities operational coordination, and serves as a point of contact for various stakeholders.

The current setup presents several limitations for effective cross-border railway coordination. First, the structure and functions of the EU Railway Entity as proposed are divided between the two organizations, ENIM and the Network Coordinator. ENIM can develop frameworks and provide recommendations but lacks the authority to enforce compliance among infrastructure managers. The decision-making power rests with the national infrastructure managers and regulatory bodies. Additionally, while ENIM contributes to crisis management frameworks, its role is more about facilitating coordination rather than direct intervention. This can limit its effectiveness in real-time crisis situations.

Second, the role of the Network Coordinator is primarily administrative and supportive, acting as a secretariat and contact point. This limits its ability to influence or mandate operational decisions directly. Furthermore, the Network Coordinator can identify obstacles created by national rules or procedures but lacks the authority to remove or amend these obstacles directly. They must rely on national infrastructure managers to take action.

Overall, neither the ENIM nor the Network Coordinator has the power to mandate over infrastructure managers as proposed in the solution. Additionally, they do not possess the mandate to arbitrate conflicts or resolve disagreements between countries. In the end, their roles are primarily focused on coordination, support, and providing recommendations.

3.1.3 Indicators

The following indicators assess the impact of the EU Railway Network Coordinator on improving cross-border railway operations within the EU.

- Cross-Border Traffic Disruptions: this indicator measures the number and duration of disruptions in cross-border railway traffic. It reflects the ability of the entity to minimize operational disruptions through better coordination.
- Reduction in Maintenance Downtime: it measures the decrease in the total downtime of cross-border railway sections due to maintenance. It shows the effectiveness of the EU Railway Network Coordinator in coordinating and optimizing maintenance schedules.
- Performance indicator: this indicator evaluates the efficiency and effectiveness of maintenance activities, assessing improvements in the performance. For example, the entity will establish a range of acceptable performance levels for track quality. Maintenance operations will be done based on these predefined performance thresholds, and the quality of the executed maintenance activities will be evaluated against these standards. This ensures that the track quality meets the required performance levels, maintaining safety and reliability across the network.

3.2 Component 2: European Railway Forum

The second component of the framework to improve the maintenance operations in cross-border sections is to establish a forum for infrastructure managers that will act as a support organization for the EU Railway Entity. Its main goal is to improve the current cross-border guidelines and agreements. It follows the notion of continuous improvement of the current protocols and coordination of maintenance operations.

The forum can be based on or part of existing organizations like PRIME and/or RailNetEurope. The meeting can be done at least two times per year in which the IMs and relevant stakeholders (i.e. maintenance contractors) share their experiences and lessons learned from real cases and simulations (in the case of ICM). This becomes more relevant, especially in corrective maintenance (i.e. unplanned disruptions).

The creation of the forum could help address the lack of data or information from neighbouring countries as it can facilitate a platform for voluntary information sharing. This platform would not only facilitate effective communication between IMs but also enhance the overall maintenance operations. For instance, as each country becomes familiar with the maintenance practices of its neighbours, it becomes easier to coordinate activities and schedules, leading to more synchronized and efficient cross-border railway maintenance.

The forum will initiate discussions on the implementation of DT technology, emphasizing the standardization of formats and the development of security and privacy protocols. It will also track the progress of digitalization and DT implementation among IMs, sharing challenges and offering guidance to other members. This ongoing support will ensure the standardization and the dissemination of best practices.

The forum could partially help with the challenge of conflicting laws and regulations as it can only identify the points of conflict and give suggestions on how to solve them. Additionally, the forum could mitigate conflicts arising from differing laws and regulations between involved countries by promoting the development of standardized guidelines and agreements.

Finally, the language differences would be mitigated as the forum will establish a common language for the guidelines and standards. However, the language of communication between neighbouring countries would be defined by the involved parties.

3.2.1 Benefits and Limitations

The main benefits of the creation of a European Railway Forum include enhancing information sharing about maintenance practices between railway entities, resulting in better-informed decision-making and planning. This information sharing would help with the continuous improvement of coordination and maintenance processes. In the end, it will result in improved coordination among railway stakeholders from different countries as the country becomes familiar with the maintenance practices of its neighbours.

The forum would also identify incompatibilities and promote the development of standardized guidelines and agreements, reducing conflicts that arise from differences in regulations and practices. Also, the forum could potentially reduce administrative burdens and increase operational efficiency by suggesting standardized processes and procedures.

Nevertheless, the forum also presents several limitations. The main one is that the forum is based on voluntary information and data sharing due to inconsistent participation. This could lead to partial datasets or information.

Member countries may have divergent priorities or interests, making it challenging to reach an agreement on certain issues, such as maintenance thresholds. Even with agreed-upon guidelines or agreements, implementing them uniformly across all member countries may pose logistical and practical challenges due to different national circumstances. Additionally, since the suggestions of the forum for improvement and shared knowledge are recommendations rather than laws, infrastructure managers are not obligated to apply them.

Overall, while the European Railway Forum has the potential for improving cross-border railway operations through information sharing, standardization, and enhanced coordination, its success will largely depend on overcoming information-sharing challenges and ensuring that member countries align their priorities and commitments. Table 10 shows the summary of the advantages and disadvantages of the European Railway Forum.

Table 10. Summary of benefits and limitations of EU Railway Forum

Advantages	**Disadvantages**
Information sharing	Based on voluntary information sharing
Standardization of maintenance practices	Different national priorities
Improved coordination	Implementation challenges

3.2.2 Present Initiatives

There are several existing initiatives that align with the proposed solution. Some of these initiatives are briefly introduced below:

- **Platform of Rail Infrastructure Managers in Europe (PRIME):** established in 2013, PRIME is a high-level forum where European decision-makers and CEOs of IMs meet to discuss a variety of topics with a strategic impact on the development of the European rail systems (EIM, 2019). Its main objective is to facilitate the exchange of views, knowledge, and best practices between Infrastructure Managers (IMs) and the European Commission, and it focuses on key matters concerning the implementation of the Single European Rail Area (EIM, 2019).
- **Forum Train Europe (FTE):** FTE is a European association of railway undertakings and service companies that promotes cross-border rail freight and passenger traffic in Europe (Forum Train Europe, n.d.). One of the main objectives of this institution is to promote standardization of processes and tools and help to increase the competitiveness of rail in Europe.
- **RailNetEurope (RNE):** established in 2004, RailNetEurope is an association of European Rail Infrastructure Managers. It acts as an umbrella organization, coordinating its members' international processes in key areas such as Capacity Management, Traffic Management, Corridor Management, IT, and Sales & Legal Matters (RailNetEurope, n.d.). Its mission is to assist its members in addressing the challenges of the railway sector in Europe and to promote international rail traffic.
- **European Union Agency for Railways (ERA)**: established in 2004 by Regulation (EC) 881/2004 (which has been repealed by Regulation (EU) 2016/796). ERA is an independent EU agency that has the main objective of devising the technical and legal framework for creating a Single European Railway Area (SERA) (European Union Agency for Railways, 2023).
- **European Network of Rail Regulatory Bodies (ENRRB)**: established in 2013, the ENRRB is a group that facilitates the active cooperation of rail regulatory bodies and information exchange between these bodies (Directorate-General for Mobility and Transport, n.d.). One of the main tasks is to develop common principles and practices for decision-making.

While RNE, ERA, and ENRRB are not forums, they are an entity, an agency, and a group respectively. These organizations can effectively support the concept of a forum to enhance cross-border rail operations, as they already engage numerous important stakeholders within the rail sector. In the case of RailNetEurope, this entity has already some experience in the standardization of processes in TCRs and incident management.

One of the limitations of the present initiatives is the incomplete involvement of key stakeholders. For example, not all EU infrastructure managers are part of these organizations. Additionally, the participation of Railway Undertakings (RUs) as service users and maintenance contractors would add significant value to the forum. Another limitation is the slow propagation of information, even among involved stakeholders. For instance, some departments within an Infrastructure Manager (IM) may be unaware of the tools or guidelines provided by these support organizations.

3.2.3 Indicators

Three possible indicators to measure the impact of this forum are suggested below:

- Stakeholder Participation Rate: this indicator tracks the percentage of relevant stakeholders (e.g., infrastructure managers, and railway operators) participating in the forum. It reflects the level of engagement and cooperation among different entities.
- Number of Harmonized Guidelines and Standards Developed: it measures the number of new or updated guidelines and standards that are harmonized across different countries. Furthermore, it indicates the effectiveness of the forum in creating consistent maintenance practices.
- Number of Best Practices Shared and Implemented: the objective of this indicator is to promote continuous improvement and knowledge transfer among stakeholders to enhance efficiency and safety in cross-border railway maintenance. It tracks the identification, sharing, and implementation of effective methods in cross-border railway maintenance operations.

3.3 Component 3: Digital Twin Application

The third and most innovative component to improve the maintenance operations in cross-border sections is to create a new framework based on digital applications (using transparent models and data sharing) to support maintenance decisions in cross-border lines. This tool will help the Entity and the IMs with the cross-border maintenance operations optimization and coordination. It is important to mention that the use of these digital (twin) applications helps to solve multiple challenges at the same time in an integral way.

This technology integrates real-time data from sensors and operational systems to provide accurate insights into asset performance and maintenance needs. By using transparent models and sharing data across borders, this approach promotes collaboration and informed decision-making among stakeholders. The digital twin framework would enable predictive maintenance, optimizing schedules, and reducing disruptions. Standardized interfaces ensure compatibility between different railway systems, improving overall efficiency and coordination in cross-border maintenance.

The creation of a digital twin will partially help with the challenges of conflicting regulations and the lack of unified maintenance standards as it can help identify conflicts between regulations, maintenance standards and procedures across borders. Once identified, stakeholders can collaborate to find compatible solutions and standardize maintenance practices and regulations. Furthermore, digital frameworks can facilitate smooth data sharing and communication between infrastructure managers of different countries, overcoming barriers related to data accessibility and information exchange.

Digital applications can facilitate the integration of socio-economic factors into maintenance planning and decision-making, tackling the lack of unified socio-economic models. In addition, they can enable more transparent cost-sharing mechanisms and better allocation of resources based on data-driven insights, in so doing addressing asymmetries in cost distribution among involved countries. Environmental factors can also be included within the models of the digital twin to account for the environmental impact of the maintenance operations.

Finally, digital applications can help bridge the gap between diverse technical systems by providing interoperable solutions (i.e. standardized data exchange formats and adaptive control systems), enabling smoother coordination of maintenance activities across railway networks with different technical characteristics.

3.3.1 Benefits and Limitations

The creation of a digital twin application offers several key benefits. Firstly, the digital twin application will facilitate data sharing and storage between IMs via cloud servers and applications. Having a shared and more complete dataset of the railway system will significantly improve the coordination and optimization of maintenance operations in cross-border sections. Improved transparency is also a crucial advantage. Transparent models and data-sharing mechanisms promote visibility and accountability across stakeholders, fostering trust and collaboration in cross-border maintenance operations.

Enhanced decision-making is another benefit, as digital twin applications can provide real-time data visualization and analytics, enabling infrastructure managers to make informed maintenance decisions promptly. This leads to improved efficiency and reduced downtime. Furthermore, digital applications can be cost-effective by optimizing maintenance schedules and resource allocation, potentially reducing costs associated with unplanned downtime and reactive maintenance.

Digital twins can also enhance stakeholder communication by allowing real-time monitoring and prediction of component failures, enabling stakeholders to coordinate maintenance operations in advance and minimise their impact. Enhanced interoperability is another benefit, as digital frameworks can facilitate interoperability between different railway systems by standardizing data formats and communication protocols, thereby optimizing cross-border operations.

Nevertheless, there are also disadvantages to consider. The initial investment required to implement digital applications and infrastructure can be significant, encompassing technology costs, personnel training, and system integration expenses. The cost of setting up a DT will depend on several factors including the complexity of the system to be digitalized, the type and volume of data to be collected, and the specific instrumentation required based on a physical inspection of the element to be monitored. This inspection helps determine the necessary sensors and other hardware, ensuring that the DT can accurately reflect and monitor the real-world system. Additionally, data security and privacy concerns are also critical, as sharing sensitive data across borders raises issues of data security and compliance with privacy regulations. This demands robust cybersecurity measures and data governance frameworks.

Technical challenges are another significant disadvantage. Integrating digital applications into existing infrastructure and workflows may pose issues such as compatibility, data synchronization, and system interoperability. Participating IMs will need to define the standards for the digital twin models, including data formats and maintenance criteria. For example, the optimization and scheduling models for maintenance need to be defined and validated by all affected parties.

As digital twins heavily rely on data and data sharing, one significant limitation arises from the potential constraints or incompleteness of available data. This limitation introduces uncertainties at various levels of the functionality of the DT. Incomplete data can affect the accuracy of predictive models and decision-making processes within the digital twin framework. Moreover, discrepancies in data quality or availability between different stakeholders or across international borders can further complicate the integration and effectiveness of the digital twin. Lastly, resistance to change is a potential barrier, as stakeholders accustomed to traditional maintenance practices may resist adopting new digital frameworks, requiring significant stakeholder engagement efforts.

Despite these challenges, the potential advantages of digital twins in enhancing cross-border railway maintenance operations and overall system efficiency make them a promising solution for future infrastructure management. Table 11 shows the summary of the advantages and disadvantages of the digital twin application.

Table 11. Summary of benefits and limitations of digital twin application

Advantages	**Disadvantages**
Improved data sharing	Initial investment
Improved transparency	Data security and privacy concerns
Cost-effectiveness	Technical challenges
Enhanced interoperability	Resistance to change

3.3.2 Present Initiatives

The digitalization of the infrastructure is seen as a need for the IMs as it helps reach the environmental goals of the EU by optimising the performance of the railway system. The digitalization of the infrastructure is also being promoted in the proposal on the use of railway infrastructure capacity in the single European Railway Area (document number 52023PC0443), particularly in Article 62. This article states that infrastructure managers implement capacity management and traffic management processes using digital tools and services.

According to Article 62 (European Commission, 2023), the deployed digital tools and services provided shall:

- Improve the performance and quality, including full interoperability, of the services infrastructure managers offer to applicants.
- Enhance the transparency of rail capacity management and traffic management across all phases.
- Reduce the administrative burden for applicants by requesting each piece of information only once and providing information or data in a single place, especially concerning cross-border services.

These digital tools and services are set to be applied from December 2026 (European Commission, 2023). However, this deadline poses a challenge as each IM must first assess its current level of digitalization. They also need to determine the feasibility of integrating existing systems into the new digital framework. It is important to remark that the implementation of new technologies in the railway industry is slow compared to others as it has to comply with many regulations and safety requirements. Furthermore, robust data management and security protocols must be established before implementation to ensure the protection of sensitive information and compliance with privacy regulations.

In the case of digital twin technologies, no infrastructure managers within the EU are yet to fully utilise this technology. Instead, some functions such as 3D visualization, simulation (of component degradation), and optimization of maintenance operations have been used independently. According to Spanevello (2021), research and innovation in the railway sector have been done through EU initiatives such as Shift2Rail and Horizon Europe, aimed at developing a framework for railway digital twins. Shift2Rail focused on predicting and controlling the performance of the rail assets (Spanevello, 2021).

According to Sahilbhutada (2023), some real-world examples of the use of digital twins in other industries are:

- Energy sector - Virtual power plant: Siemens has created DT of a unified energy network consisting of solar panels, wind turbines, and other energy storage devices. The main objective is real-time monitoring, optimization, and energy management of the generated energy.
- Construction Industry – Digital twin platform: Cityzenith generated a DT platform called SmartWorld Pro. This platform builds a dynamic DT representation of cities using different data sources. The main functions of this DT are scenario simulations, resource optimization, urban analysis, and promoting stakeholder participation.
- Aerospace industry – Digital twin for aircraft maintenance: Rolls-Royce uses digital twins to track the functioning of its engines and streamline maintenance procedures (Sahilbhutada, 2023). Scheduling maintenance is done efficiently due to real-time monitoring and failure prediction models.

As previously mentioned, the initial investment in digital twins and data management, especially in terms of cybersecurity, are some of the main limitations of the implementation of this technology within the railway sector.

Finally, existing digital twin frameworks are not suitable for cross-border railway operations. In practice, there are numerous DT framework options, and each infrastructure manager or maintenance company adheres to its own standards, leading to a lack of uniformity and coordination. This fragmentation presents significant challenges for cross-border maintenance operations, which require uniform data sharing and standardized protocols.

As previously mentioned in the Digital Twin sub-section, there is no existing DT specifically designed for railway cross-border operations. Frameworks like the one proposed by Thelen (2022) lack interaction capabilities for data sharing, while the Galván-Nuñez et al. (2024) framework includes federation but ignores varying railway maintenance standards and monitoring techniques across countries. Additionally, both lack a detailed implementation methodology essential for real-world application.

A cross-border DT for railways must incorporate interaction capabilities with other DTs to facilitate data sharing. It should also standardize railway maintenance protocols and accommodate different monitoring techniques used by various countries. Additionally, a comprehensive and detailed methodology for implementation must be provided to ensure practical applicability. By addressing these requirements, a robust and effective DT framework for cross-border railway operations can be established, enhancing coordination and efficiency across international borders.

3.3.3 Indicators

Four possible indicators to measure the impact of this solution are suggested below:

- Data sharing and integration rate: this indicator assesses the percentage of data shared and integrated between the management systems of the different countries. It measures the effectiveness of the digital framework in facilitating information exchange.
- Utilization rate of digital applications: this indicator tracks the percentage of stakeholders using new digital tools. The objective is to reflect the adoption and practical implementation of digital frameworks.
- Maintenance efficiency improvement: the most important indicator as it measures the improvements in maintenance efficiency, such as reduced time and cost. It shows the impact of digital tools on optimizing maintenance activities and scheduling.
- Environmental indicator: digital twins application can help model and measure the environmental impact of a line closure due to maintenance operations. This indicator could quantify the additional carbon dioxide emissions resulting from extended travel distances due to re-routing or modal shifts for passengers. For example, it can assess the extra distance travelled by re-routed trains and calculate the associated increase in carbon emissions. Additionally, this indicator can incorporated into maintenance optimisation models, ensuring that the environmental costs are considered when planning and coordinating maintenance activities.

3.3.4 Digital Twin Implementation Framework

Before setting up a digital twin model, it is essential to define the level that the digital twin model must have to comply with the cross-border challenges in railway lines. Table 12 shows the main functionalities of the different stages of a digital twin model.

Table 12. Main functionalities of the different stages of a digital twin

DT – Level	Digital Documentation	Visualization	Supervision	Modelling & Simulation	Collaboration	Automation
Level 1 - Mirroring	X	X	Partial			
Level 2 - Monitoring	X	X	X			
Level 3 – Modelling and Simulation	X	X	X	X	Partial	
Level 4 – Federation	X	X	X	X	X	Partial
Level 5 – Autonomous	X	X	X	X	X	X
X = functionality is fully supported at that level.						

Visualization involves creating virtual models, which can be either 2D or 3D depending on stakeholder needs. Supervision refers to real-time monitoring of the physical asset. Modelling and simulation means the use of degradation and maintenance optimization models to predict the behaviour and optimize operations within the railway system. Meanwhile, collaboration implies data and information sharing between main stakeholders (through digital tools). Lastly, automation means autonomously recognizing and solving problems using AI tools with minimum human intervention.

Stage 3 has partial collaboration because the model of one country can incorporate data from other countries. However, this input process relies on the (standardized) data shared by the other country and it is entered manually, which introduces the possibility of human error. There is no digital and automated way to share information. In contrast, Stage 4 features an automated and dedicated process for data sharing among countries, enhancing reliability and reducing the risk of errors.

Regarding automation, stage 4 has partial automation as some of the maintenance optimization and scheduling models can be automated by the use of ML and AI tools. However, it always requires human verification before taking some major maintenance actions. On the other hand, stage 5 autonomously recognises and solves problems and optimises physical objects according to the federated digital twin solution without or with minimal human interaction.

To address cross-border challenges effectively, the implementation of stage 4 of a digital twin model is recommended (see Figure 19). This tool provides a multistakeholder platform for data sharing, thereby resolving the significant challenge of the lack of data from neighbouring countries. The framework to set up a digital twin for railway system or components is shown in the Figure 20 and Figure 21.

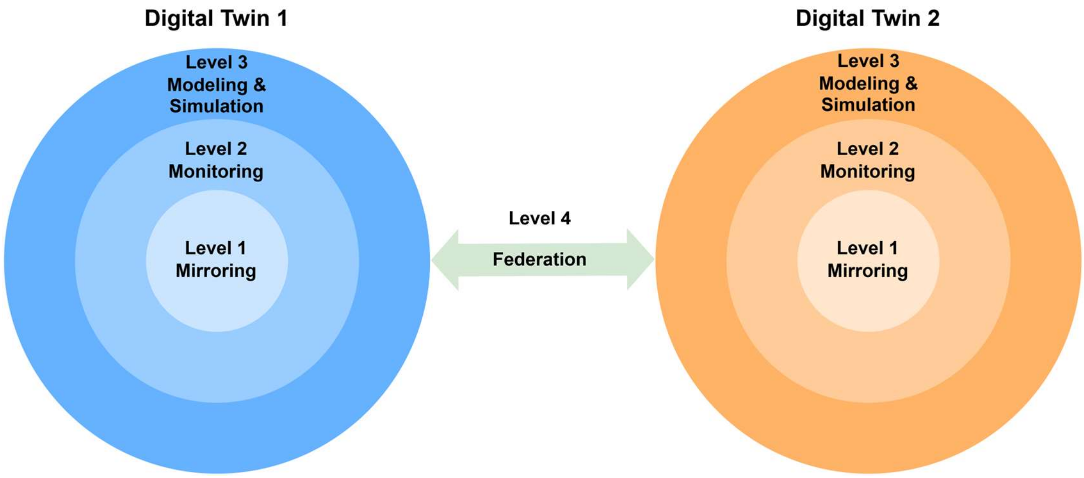


Figure 19. Diagram of the digital twin evolution stages (modified from source: Jeong et al., 2022)

In addition to defining the level of implementation for cross-border sections, the data requirement for each level should be defined to ensure that each level is supported with the appropriate data inputs. The data needed for implementing a DT will vary based on the complexity of the system and the level of implementation. As the level of implementation increases, so does the amount of data required to set up and maintain the DT.

Table 13 shows the basic data requirements and its privacy level for the different levels of implementation. Each level builds upon the previous, increasing the complexity and amount of data required to create a fully functional and automated digital twin system.

Table 13. Data requirements and sensitiveness level for different implementation levels of DT

Data Requirements	**Sensitive Data**	**Digital twin**				
		Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Location data		X	X	X	X	X
Geometry data	Partial	X	X	X	X	X
Mechanical properties		X	X	X	X	X
Operational data		X	X	X	X	X
Environmental data			X	X	X	X
Real-time sensor data	X		X	X	X	X
Maintenance logs	X			X	X	X
Maintenance scheduling	Partial			X	X	X
Data from neighbouring country	Partial				X	X
Detailed operational data	X					X
X = data is required or sensitive || Partial = data is partly sensitive						

A partial level of data privacy means that not all data details are required at every stage of implementation, but as the implementation level progresses, the necessity for detailed data increases. For example, basic geometric data of the infrastructure might suffice for visualization purposes at Level 1. However, as the level of implementation increases, more complex geometric details are necessary to accurately simulate and monitor the infrastructure. Likewise, for maintenance scheduling, partial data may be adequate for initial operational planning, but detailed scheduling information becomes critical at advanced levels to optimize maintenance activities and minimize downtime.

Sensitive data involves information that needs protection due to privacy, security, or competitive reasons. Real-time sensor data, for example, is considered sensitive because it might include live tracking of train positions, speed, and track conditions, which could pose significant security risks if accessed by unauthorized parties. Similarly, maintenance logs contain detailed historical records of maintenance activities, which could reveal system vulnerabilities if exposed. Additionally, these logs may disclose proprietary maintenance methods and processes used by contractors, potentially compromising their competitive advantage.

The framework on how to implement a DT is shown in a flowchart in Figure 20 and Figure 21. The first step is to define the purpose of the DT. The main objective of setting a DT is to implement condition-based maintenance operations and as an additional objective, the coordination between countries can be improved. The second step involves specifying the data and technologies necessary to establish the model. This will depend on the components being monitored and modelled.

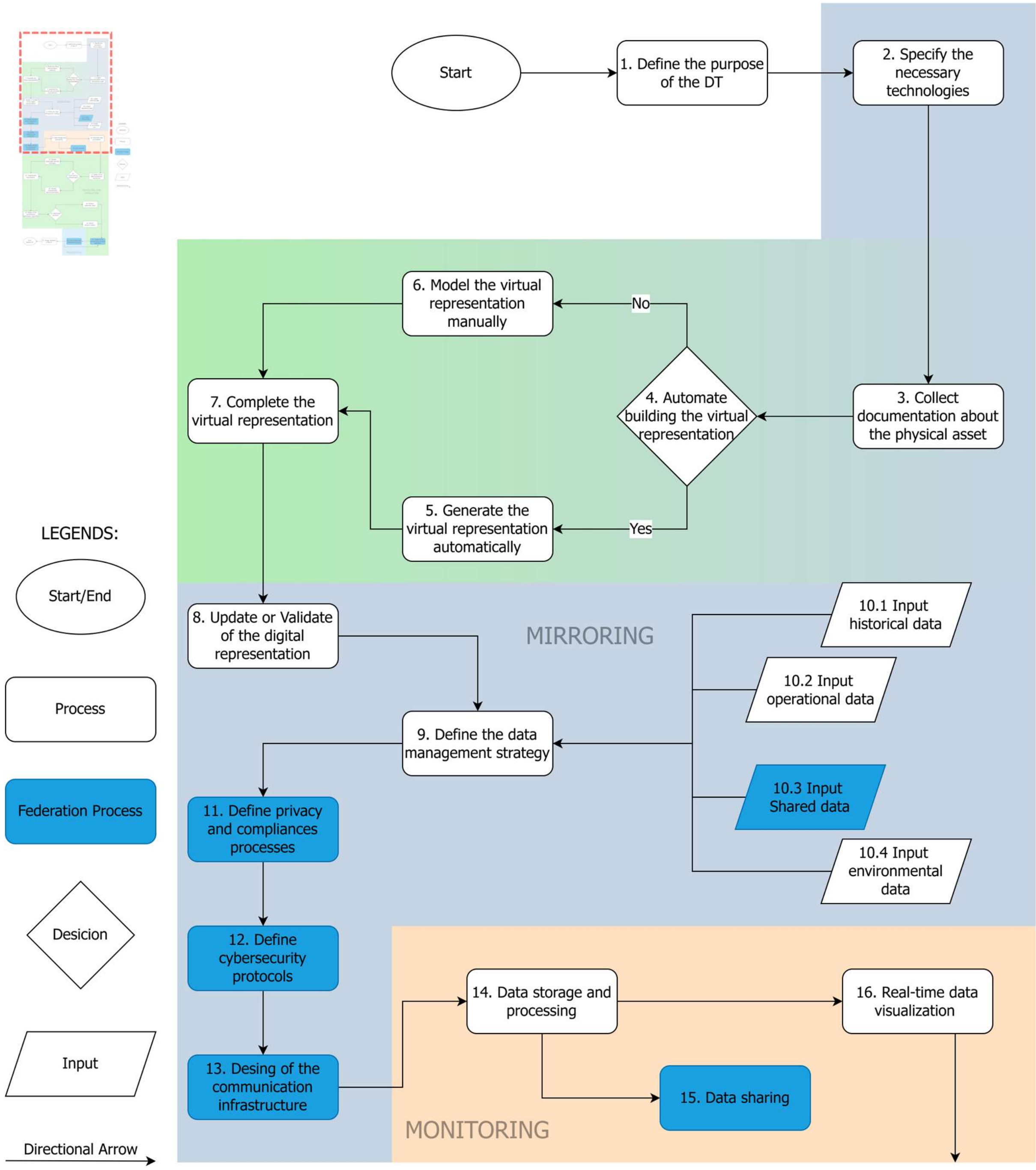


Figure 20. Part 1 of the flowchart for DT implementation (modified from sources: Dirnfield Turocy, 2022, and Marrone et al., 2023)

Within the mirroring stage, step 3 of the process is to collect documentation of the physical asset to build a virtual representation (that can be automated or not). Before the generation of the virtual representation, its level of detail should be defined as generating a virtual representation is resource-consuming. The generation of the model can be done from scratch, through existing models from the design and building phase, using Point Cloud Data, among other methods. Once the virtual representation is created, a validation process or update is required to ensure that the physical and virtual models match.

Next, the data management strategy should be defined. This strategy defines how data is managed and includes standardization of data types for future data sharing. The data type should be defined by the relevant stakeholders. The input of data flow consists of historical, operational, environmental, and shared data. Historical data can include maintenance logs and track geometry data, while operational may consist of the position of the rail and the characteristics of the rail section. Environmental data includes weather conditions and shared data consists of relevant maintenance information from neighbouring countries.

In the final steps of the mirroring stage, the privacy and compliance processes that every stakeholder must follow are specified to ensure adherence to data protection regulations and industry standards. This ensures that data handling practices comply with relevant regulations and protect the privacy of all parties involved.

After step 11, the cybersecurity protocols and the design of the communication infrastructure are defined. As infrastructure data is considered sensitive information, cybersecurity protocols are essential to protect this data and ensure the integrity and confidentiality of the information exchanged between stakeholders. This includes implementing robust encryption methods, access controls, and regular security audits to prevent unauthorized access and data breaches.

For the communication design, it is essential to specify enabling technologies such as sensors, cloud services, and communication links between physical and virtual assets in detail. Ensuring constant and secure communication is critical to the effective functioning of the digital twin.

For the monitoring stage, the storage and processing of the data is done. After the data is processed, the relevant data is shared with the other stakeholders. Furthermore, infrastructure managers would also have access to real-time visualization of the data, allowing them to monitor the condition of the railway in real-time and make informed maintenance decisions. This real-time access could facilitate quicker responses to issues and enhance the overall coordination and efficiency of cross-border maintenance operations.

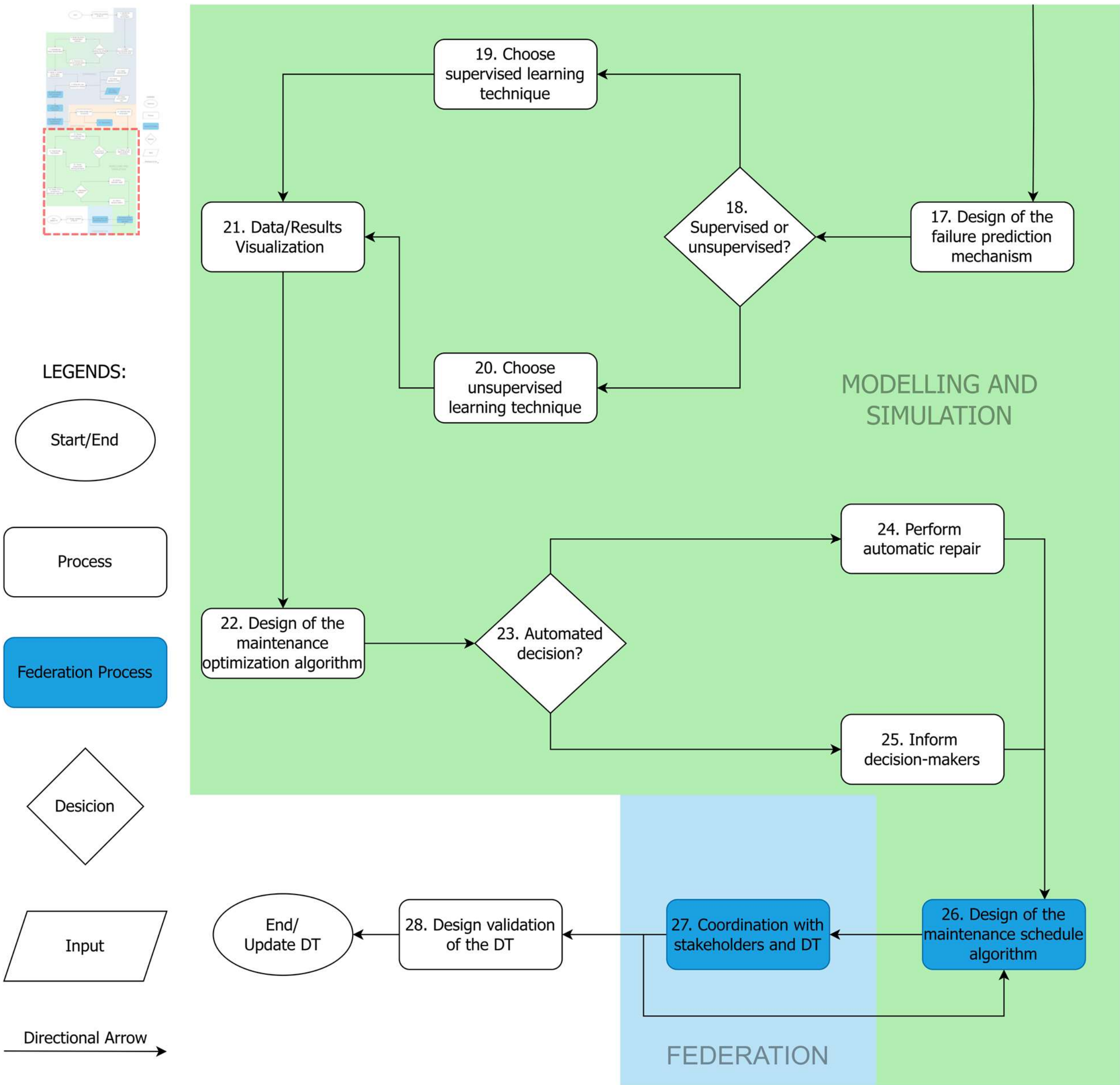


Figure 21. Part 2 of the flowchart for DT implementation (modified from sources: Dirnfield Turocy, 2022, and Marrone et al., 2023)

In the modelling and simulation stage, the failure prediction or degradation mechanism of the analysed component or system is developed using supervised or unsupervised machine learning techniques. For example, an unsupervised learning technique like k-means clustering can be utilized for anomaly detection. In contrast, a supervised technique such as a deep convolutional neural network (CNN) can be employed for automatic defect detection. Once the degradation model is defined and validated, the visualization of the results (data prediction) is created to help the infrastructure managers visualize the possible outcomes.

In the following step, as in the previous one, the maintenance optimization algorithm of the analysed component is designed and validated. This model will optimize the maintenance operations via a multi-objective function that takes into account multiple objectives such as maximizing availability, minimizing costs and environmental impact, and enhancing component performance. Additionally, performance standards on when to perform maintenance operations should be defined by the relevant IMs, taking into account their safety regulations.

It is important to remember that the DT models are a tool to support decision-making. Whether to automate the repair process or not depends on the importance of the component and the confidence in the developed models. If the decision is not automated, the model provides the decision-makers with possible solutions.

Once the maintenance decision is made, then the maintenance schedule algorithm is designed. It will consider the maintenance operation of other components within the same line and the maintenance schedules in the relevant countries and then will define when the optimal timing for maintenance operations. This process is also related to the federation stage as it needs data from the DT of the neighbouring country.

The final stage is the federation, in which the digital twin communicates with other digital twins of the neighbouring countries and with the different stakeholders through digital applications allowing better coordination of the maintenance operations.

The coordination process will follow the flow chart in Figure 22. Once the type of maintenance is decided by the infrastructure manager, the coordination of maintenance activities varies depending on their impact. For minor TCR, maintenance occurs within routine schedules that minimally affect operations, thus requiring no additional coordination. In this case, the railway undertakings have been already notified of when and where the routine maintenance will occur.

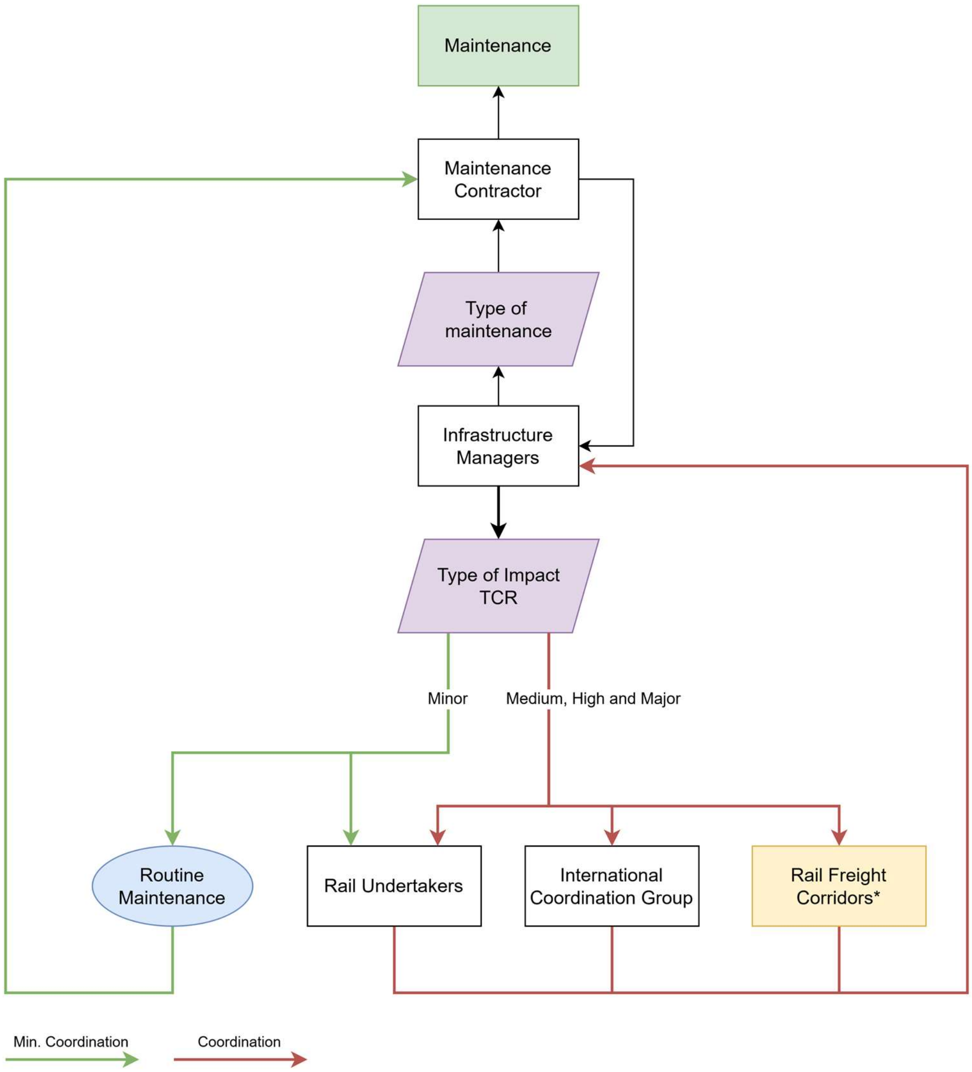


Figure 22. General coordination flow chart

When a TCR has a medium, high, or major impact, the railway undertakings, relevant international coordination groups, and applicable rail freight corridors should be notified and coordinated. These stakeholders should proceed according to the consultation process proposed by RailNetEurope (see Figure 9).

If the relevant infrastructure managers agree with the scheduling proposed by the DT, the maintenance operation proceeds as scheduled. However, if there is disagreement, both IMs enter into a negotiation process to find a mutually acceptable solution. The data sharing and communication processes will follow the previously established privacy and cybersecurity protocols (steps 11 and 12 in Figure 20). Additionally, this data sharing is reflected as input for data management (see step 10.3 in Figure 20).

The last step of the implementation is the validation of the digital twin model and its main functionalities. This involves running the model in parallel with real-world operations for a defined period to calibrate it and receive feedback from users. Validation confirms the reliability and effectiveness of the digital twin as a decision-support tool for maintenance operations.

It is important to remember that once the implementation process is done and the DT model is operational, it will continuously update itself with new data, creating a feedback loop between the physical representation and the virtual model.

3.4 Implementation of the Digital and Cooperative Framework

The implementation of this cooperative approach is a complex process because it involves establishing European-level organizations and systems. To simplify this process and increase the chances of successful implementation, a 6-stage timeline is proposed (see Figure 23). This timeline provides a structured approach to the implementation of a cooperative framework that incorporates the European Railway Forum, the European Railway Entity, and Digital Twin Technology. By following these phases, the EU can improve the coordination and efficiency of cross-border railway maintenance operations, ultimately contributing to the sustainability and reliability of the railway network.

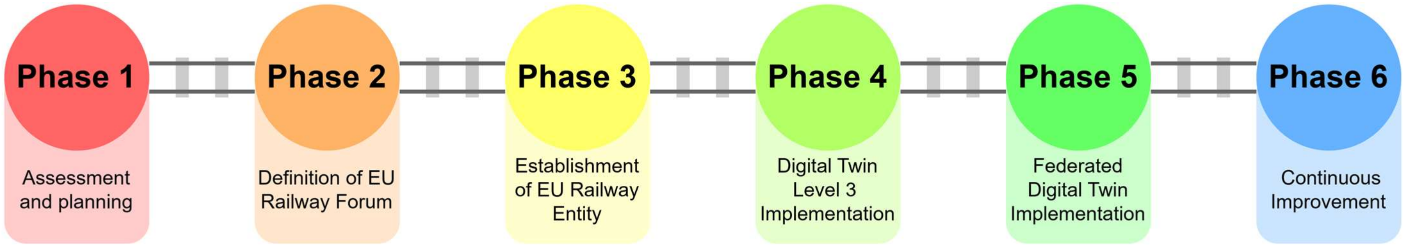


Figure 23. Implementation timeline of the DCF

In the next sections, each phase is going to be described. At the end of each phase, a quick win sub-section will be introduced to remark the benefits of each phase.

3.4.1 Phase 1: Assessment and Planning

This phase can be divided into two main steps: stakeholder engagement and the initial assessment of the European situation regarding the three components of the approach.

Stakeholder Engagement
In this step, the European Commission (through ENIM) will engage with key stakeholders including IMs, railway undertakings, maintenance contractors, and relevant EU bodies such as the PRIME and RailNetEurope. This engagement aims to gather input and build consensus on the cooperative approach, specifically regarding the objectives and scope of the EU entity, the forum, and the digital twin application.

Initial Assessment:
An initial assessment of the current situation will be conducted to effectively plan the implementation of the cooperative approach. This assessment will provide an overview of the existing landscape regarding the different components of the approach and guide the planning process. The assessment will be divided as follows:

- For the EU Railway Forum: the first step involves mapping out the different existing forums and their specific focuses. This will help identify gaps and opportunities for enhancing collaboration and information sharing among stakeholders. Information from existing initiatives (such as RailNetEurope and PRIME) is used to establish a baseline knowledge of current coordination and communication practices for maintenance operations in cross-border sections.
- For the Digital twin application: each IM will evaluate their current level of digitalization and readiness for digital twin implementation. This evaluation will consider the specific needs of each country and determine the feasibility of integrating existing systems into the new digital framework.
- For EU Railway Entity: each IM will assess and identify areas of improvement of the current proposal on the use of railway infrastructure capacity in the single European Railway Area (document number 52023PC0443), which is currently under revision by the European Commission (EC). This will help to understand the proposed changes and prepare for the integration of the EU Railway Entity.

Phase 1 - Quick wins: Identification of maintenance practices and coordination processes between different stakeholders. Identification of digitalization progress and needs for each IM.

3.4.2 Phase 2: Definition of the EU Railway Forum

The main objective of the second phase is to establish the European Railway Forum, with representatives from all member states. The forum can be integrated into existing organizations like PRIME and/or RailNetEurope as these organizations already have a solid foundation in supporting the improvement of the EU railway network and its services. Their established structures, resources, and networks provide an ideal platform for enhancing coordination, sharing best practices, and driving continuous improvement in maintenance and operations across member states.

As previously stated, the forum will be responsible for sharing information between its members and the continuous improvement of maintenance and coordination practices. To ensure ongoing progress and adaptation to new developments, the forum will meet at least twice a year.

The first meetings will be conducted to share current practices and identify conflicting practices and processes as well as key areas for improvement within the Member States and the cross-border sections. Additionally, IMs and relevant stakeholders (e.g., maintenance contractors) share their coordination experiences and lessons learned from real cases and simulations, particularly in incident management in cross-border scenarios.

Regarding the EU Railway Entity, the European Commission will improve the proposal based on the feedback and suggestions given by relevant organizations such as IMs and the European Rail Infrastructure Managers (EIM). This collaborative approach ensures that the proposal addresses the practical needs and concerns of those directly involved in railway operations and management.

Regarding digital twin implementation, each member state will develop their national implementation plan, establishing its specific priorities. This will involve a detailed assessment of cross-border sections, defining the types of data and monitoring systems required. The plan will also outline steps for data collection and digitalization, as well as the establishment of robust security and privacy protocols to ensure data integrity and protection.

Phase 2 - Quick wins: Standardization of maintenance practices by the identification of conflicting practices and regulations. Information sharing between main stakeholders such as maintenance practices and coordination processes.

3.4.3 Phase 3: Establishment of the EU Railway Entity

The main objectives of the third phase are the establishment of the EU Railway Entity and the implementation of level 2 of DT (within cross-border sections). After the approval of document number 52023PC0443, a network coordinator will be appointed by the ENIM within 12 months according to Article 58 of the same document. In parallel, ENIM will be responsible for developing and adopting the following frameworks:

- European Framework for Capacity Management: This framework will establish guidelines and standards for managing railway capacity across the EU, ensuring efficient and equitable use of resources. Additionally, the consultation mechanisms for European and cross-border matters will be incorporated into the European Framework for Capacity Management, ensuring that all relevant stakeholders are involved in the decision-making process and that their concerns and inputs are considered. Transparent socio-economic and environmental models will be developed to help with the procedures of railway capacity scarcity.
- European Framework for the Coordination of Cross-Border Traffic Management, Disruption Management, and Crisis Management: This framework will provide protocols for managing cross-border traffic and handling disruptions and crises, promoting efficient operations across member states.
- European Framework for Performance Review: This framework will set criteria and methods for evaluating the performance of railway operations, ensuring continuous improvement and accountability.

The development and implementation of these frameworks should be done within 12 of the approval of the proposal. ENIM will have the help of the EU network coordinator and the Forum to develop these frameworks.

The Forum will still focus on helping to identify conflicts between regulations and maintenance practices and will define points of improvement regarding maintenance coordination and practices. Additionally, it will assist ENIM in developing and improving frameworks, and disseminate information about these new frameworks to IMs. Moreover, the Forum will develop and conduct training programs for personnel on the new coordination frameworks, ensuring that all stakeholders are well-informed and equipped to implement the latest standards and practices.

Furthermore, the forum can also initiate discussions on the implementation of DT technology, focusing on the standardization of formats and the development of security and privacy protocols. This early engagement will help address potential challenges and ensure a smoother integration of DT into the overall framework.

Regarding digital twins, each infrastructure manager will start with the implementation of levels 1 (visualization) and 2 (monitoring) of their national models, especially focusing on cross-border sections. Meanwhile, they will also work in degradation and maintenance optimization models. Additionally, each IM will create and conduct training programs for personnel on the new maintenance coordination practices and the use of new digital applications.

Phase 3 - Quick wins: Improvement of the performance of the EU rail network due to the introduction of the EU frameworks. Establishing a monitoring system for cross-border sections, enhancing safety and decision-making. Standardization of format for DT technologies.

3.4.4 Phase 4: Digital Twin Level 3 Implementation

The main goal of the fourth phase is the implementation of the third level of Digital Twin. First, the DT will be improved by the feedback and initial results of the previous phase. Achieving DT level 3 involves transitioning to condition-based maintenance, using standardized and approved degradation and maintenance optimization models. These models should receive approval from national authorities to ensure uniformity and reliability.

To facilitate this transition, pilot sections will be identified to refine the models and gather feedback from users. Additionally, these pilot projects will test the federation of digital twins, focusing on data sharing and security protocols. This step is crucial for ensuring smooth integration and effective data management across different national systems. Each IMs will keep conducting training programs for personnel on the new maintenance coordination practices and the use of new digital applications.

Regarding the EU Railway Entity, it will help with the coordination of cross-border sections. Additionally, it will keep improving its frameworks and reach a consensus on which socioeconomic and environmental model(s) to use in order to solve the capacity conflicts in cross-border sections. Furthermore, it will use EU funding programs to support the digitalization initiatives of the Member States and other cross-border projects.

As previously stated, the digital tools and services should be operational from December 2026 according to the current proposal on the use of railway infrastructure capacity in the single European Railway Area (document number 52023PC0443). However, this deadline may be unrealistic due to the varying national circumstances and necessities of each IM, as well as potential budget constraints. New deadlines per country should be established, taking into account their national circumstances.

The Forum will keep assisting the EU Railway Entity with the improvement of its frameworks. Regarding the digitalization of the infrastructure, the Forum can monitor the progress of the IMs, sharing their challenges and providing advice to other members. This ongoing support will help ensure that best practices are disseminated and that all IMs are equipped to overcome common obstacles.

Phase 4 - Quick wins: Condition-based maintenance through the application of a Level 3 DT, minimising maintenance costs. Efficient coordination of cross-border with the help of the EU entity.

3.4.5 Phase 5: Federated Digital Twin Implementation

The main objective of the fifth phase is the full implementation of the cooperative approach as IMs reach level 4 of DTs. This level, known as federation, enables efficient data sharing and coordination of maintenance operations between neighbouring countries.

Following the pilot period, digital twin applications will be enhanced based on feedback and results gathered through the forum. Achieving full implementation of Level 4 DTs will enable communication and data sharing between DTs from neighbouring countries. This will facilitate better coordination and optimization of maintenance operations across borders, ensuring more efficient and reliable railway services.

Regarding the EU Railway Entity, it will develop an evaluation mechanism to ensure the effectiveness of the cooperative approach. Additionally, it will continue using EU funding and research programs, such as Shift2Rail and Horizon Europe programs to improve the EU railway network and its services.

Finally, the EU Railway Forum will continue to focus on the improvement of the coordination and maintenance practices and spreading relevant information.

Phase 5 - Quick wins: Improved cross-border coordination and maintenance operation optimization using DT, increasing the capacity of the railway network. Increasing capacity and reliability of the network promotes the use of train, reducing emissions of CO_2 due to the modal shift.

3.4.6 Phase 6: Continuous Improvement

The main objective of the final phase is the continuous improvement of the cooperative approach:

- EU Railway Entity: will focus on improving the coordination and performance of the EU railway network and its services. It will conduct periodic reviews of the cooperative approach to ensure it meets the evolving needs of the railway system. Based on these reviews and emerging trends, the entity will make necessary adjustments to strategies, frameworks, and technologies. Moreover, the entity will foster innovation by encouraging participation in EU research programs and the adoption of new technologies, thereby maintaining the future readiness of the railway infrastructure.
- EU Railway Forum: as in the previous stage, it will continue to focus on the improvement of the coordination and maintenance practices and spreading relevant information. This ongoing effort aims to ensure that best practices are shared, improvements are implemented consistently, and all stakeholders remain informed about the latest developments and guidelines.
- Digital twins: each IM will focus on enhancing their DTs by continuously updating their models and progressing towards Level 5, which encompasses full automation of DT processes.

Phase 6 - Quick wins: Improvement of coordination frameworks and maintenance practices for the railway network. Automatization of maintenance and coordination processes via DT.

Chapter 4. Analysis and Impact of the Digital and Cooperative Framework

This chapter will analyse the components of the framework using expert opinions gathered through the questionnaire about cross-border maintenance operations. Additionally, a cost-benefit analysis will be conducted to justify its implementation. Finally, the impact of the DCF is assessed through game theory.

4.1 Analysis of the Components of the DCF

This subsection presents the analysis of the components of the framework. Each component was evaluated as an individual solution to rate them according to different criteria, as detailed in the last part of the questionnaire (see Appendix I – Questionnaire about Cross-border Maintenance Operations). This section of the questionnaire had two parts: the first part asked experts to suggest solutions for improving cross-border maintenance operations, and the second part introduced three potential solutions, which experts then evaluated according to various criteria.

According to expert opinion, participants suggested several potential solutions for improving the coordination of maintenance operations: implementing the same work frameworks in both countries, fostering cross-organizational learning about maintenance programs and concepts, and using new digital frameworks to support maintenance decisions. These solutions are different from each other: the first one seeks to standardize practices across countries, the second one emphasizes the sharing of knowledge about maintenance, and the third one focuses on the use of an innovative digital tool to optimize maintenance decisions.

The three possible solutions that were introduced in the questionnaire to improve the coordination of maintenance operations were:

- **Solution 1**: Create a European entity to manage and resolve cross-border conflicts.
- **Solution 2**: Establish a forum for infrastructure managers to enhance cross-border guidelines and/or agreements.
- **Solution 3:** Create new frameworks based on digital applications, transparent models, and data sharing to support maintenance decisions in cross-border lines.

The first two solutions provided by the experts fit well on both solutions 1 and 2. The establishment of a European entity or a forum aims to standardize maintenance practices and facilitate the sharing and improvement of current maintenance practices within the EU.

The rating of the criteria and their importance is done in the questionnaire in the section on possible solutions (see Appendix I – Questionnaire about Cross-border Maintenance Operations). Five out of the eight experts replied to this section. The criteria used to rate the solutions and their description are shown in the following table:

Table 14. Criteria for rating the solutions

Criteria	Description
Impact	If the solution is implemented, to what extent do you expect a (positive) impact on the coordination of maintenance operations.
Stakeholder acceptance	If the solution is implemented, what would be the level of acceptance and support from relevant stakeholders, including infrastructure managers, railway operators, and regulatory bodies.
Implementation complexity	If the solution is implemented, what would be the complexity and ease of implementation for each solution, considering factors such as technological requirements, regulatory compliance, and organizational readiness.
Cost	Assess the financial implications of implementing each solution. It considers the costs associated with setting up and maintaining the proposed mechanisms.
Innovation and future-proofing	Assess how innovative and future-ready each solution is, considering its ability to utilize new technologies, adapt to evolving industry trends, and promote ongoing improvement in cross-border maintenance practices.

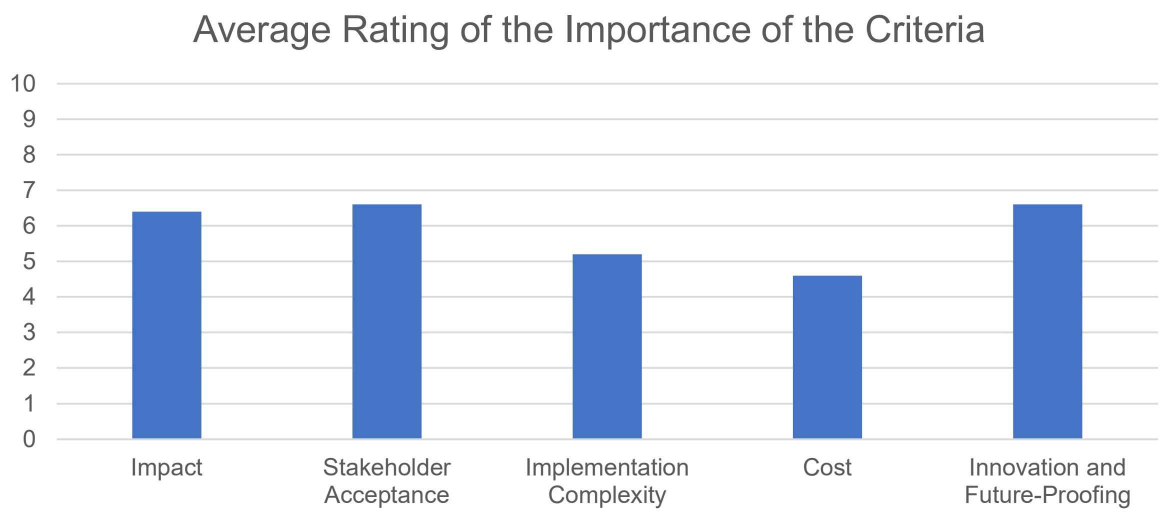


Figure 24. Average rating of the importance of each criteria

Figure 24 shows the average ratings of the importance of each criteria. Stakeholder acceptance and innovation and future-proofing are regarded as the most important criteria while the cost is considered the least important. Additionally, the impact that each solution has on the system is regarded almost as important as the highest-rated criteria.

Having a solution that has a high stakeholder acceptance is the most important criteria especially when involving multiple stakeholders from different countries with varied interests. High acceptance facilitates dialogue between stakeholders and facilitates the eventual implementation of the solution. Having a future-proof solution is also important because it means that the solution can adapt to different scenarios and the fast-changing technological environment. Impact is always considered important because the IMs want to maximize the capacity of the network to ensure availability and reliability, especially with the future increasing train services demand.

Figure 25 illustrates the average ratings for each criterion across different solutions. The impact and stakeholder acceptance follow similar trends: the forum approach is rated as having the highest impact and the most stakeholder support. On the other hand, the EU network coordinator is considered to have the least impact and support by the stakeholders. Regarding cost, the EU network coordinator is considered to have the highest cost while the forum has the lowest. Digital twin application and the EU railway forum are considered to be the most future-ready alternatives as they not only promote the improvement of current practices but also adapt to the evolving needs of the industry. Finally, while the three solutions have a similar implementation complexity, the forum is perceived as having the least complexity.

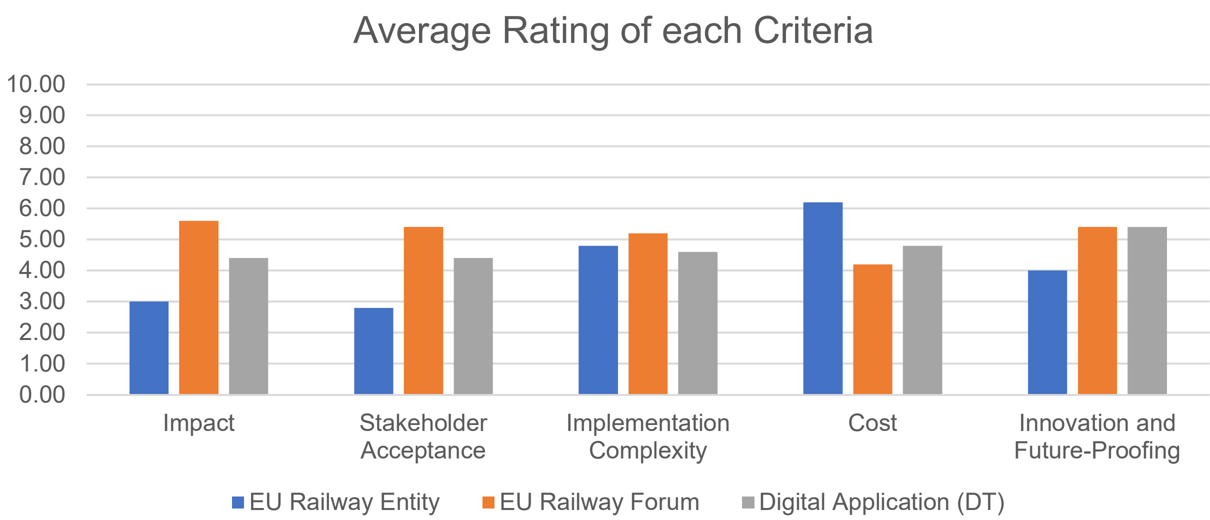


Figure 25. Average rating of each criteria according to the different solutions

The forum facilitates voluntary data sharing among its members and supports the continuous improvement of ongoing practices and agreements without mandating their implementation. This flexibility increases stakeholder approval, allowing implementations fitted to specific contexts. Additionally, the costs associated with establishing and maintaining the forum are lower than the other two solutions as the forum would require fewer resources.

The EU Railway entity is less attractive due to its higher hierarchical status, which could conflict with national interests. The impact of the entity will depend on the level of authority it holds over. These different national interests could also affect the impact, making it difficult to reach common agreements. Moreover, it is also not viewed as future-proof because, like any governmental organization, it lacks the flexibility and agility to adapt quickly. Amending laws and regulations within such a bureaucratic framework often takes considerable time, reducing its effectiveness in rapidly evolving scenarios.

The digital twin application is considered the most innovative and future-proof solution. This approach promotes the digitalization of infrastructure, enabling the monitoring and optimization of the railway system. Digital twins allow the transition from preventive or time-based maintenance to condition-based maintenance. Furthermore, digital twins can integrate multiple digital systems, creating a more holistic digital environment. The flexibility of a digital system makes this solution highly adaptable and future-proof, as it can simulate various maintenance scenarios and adjust models or parameters in response to real-world conditions.

However, the implementation of digital twins comes with significant costs, making it the second most expensive option (see Figure 25). These costs come from the initial investment in monitoring systems, personnel training, specialized software, and operational expenses such as equipment and system maintenance. Regarding implementation complexity, digital twins in cross-border contexts are considered less feasible because of low data availability of the neighbouring countries, data security concerns, and the need for standardization of models and maintenance standards.

Overall, the three proposed solutions each offer distinct advantages and address the challenges of cross-border railway maintenance in unique ways. Each solution aims to reduce the impact of maintenance operations and enhance the attractiveness of the railway system to users, thereby supporting sustainability goals. The forum is the most practical and cost-effective option, facilitating voluntary data sharing and continuous improvement without mandating implementation. On the contrary, the digital twin application, while presenting implementation challenges, offers the greatest potential for innovation and future readiness by promoting digitalization and real-time optimization of the railway system.

4.2 Cost-Benefit Analysis of the DCF

It is important to remark on the cost and benefits of the proposed approach to justify its implementation. The main cost and benefits of the cooperative approach can be summarized in the next table:

Table 15. Main costs and benefits of the DCF

Cost	Benefit
Initial setup costs	Improved coordination
Operational costs	Enhanced data sharing and decision-making
Training, research and development	Cost savings
-	Increased safety and reliability
-	Environmental and socioeconomic benefits

The initial setup cost includes establishing the coordinating bodies, particularly the EU Railway Entity. The forum will not require a significant initial investment, as the organization that assumes this function is already operational. For the digital twin implementation, costs can be broken down into the following categories:

- Inspection: Evaluating the area to be instrumented, which includes conducting surveys and assessments to understand the specific needs and conditions of the railway infrastructure.
- Instrumentation: Procuring and installing IoT devices, sensors, and other necessary hardware to monitor and collect data.
- Servers/Cloud Storage: Setting up server infrastructure or cloud system to store, process, and manage the vast amounts of data generated by the digital twin system.

- Software: Developing or acquiring software for data analysis, visualization, and predictive modelling. This includes licenses for specialized software such as ANSYS for finite element modelling and other tools required for digital twin applications.
- Modelling: Creating detailed digital models of the railway infrastructure, incorporating geometric data, mechanical properties, operational data, and real-time sensor inputs.

The operational costs consider various elements essential for the effective functioning of the cooperative approach. These include the personnel involved in both the forum and the EU Railway Entity, as well as the expenses related to maintaining a website and digital tools. Additionally, the cost of renting office space for the EU Railway Entity should be taken into account.

For the DT, ongoing expenses will include keeping the DT models up to date, managing cloud storage, and ensuring data security. Maintaining the monitoring system is also crucial, which involves periodic updates, calibration of sensors, and ensuring the overall reliability and accuracy of the instrumentation.

Another significant expense is personnel training on the use of new technologies like DT and its associated tools such as drones and VR/AR technologies. Proper training is essential to ensure that engineers and maintenance operators can effectively utilize these technologies and maximize their potential benefits.

The EU Railway Entity will fund research and development projects to create standardized models that incorporate socioeconomic and environmental factors. Furthermore, the entity will allocate funds to support programs such as Iam4Rail and Shift2Rail. These initiatives aim to explore innovative methods to enhance maintenance operations in cross-border sections, ensuring the railway network remains efficient, reliable, and sustainable.

On the other hand, improved coordination of cross-border sections is one of the benefits of the cooperative approach. Harmonizing maintenance practices between neighbouring countries will reduce delays and increase the capacity of the network by optimizing the use of available resources. Coordinated schedules will also enhance efficiency, ensuring that maintenance activities are conducted perfectly across borders.

Additionally, real-time information exchange through cloud applications will facilitate timely data sharing between countries, enabling infrastructure managers to make informed decisions. This improved data exchange will help to identify potential issues early and coordinate responses effectively, improving the performance of cross-border railway operations. Furthermore, the forum will serve as a platform for sharing knowledge about maintenance practices and coordination strategies in cross-border sections.

One of the main benefits is the cost savings due to the condition-based maintenance which will optimize the maintenance operations done the system. Additionally, the frequency and cost of inspections can be significantly reduced by using DT technology, which enables remote monitoring and the use of AR/VR tools, thus saving time and resources. Furthermore, coordinated maintenance activities help to lower overall operational costs by avoiding redundant efforts and optimizing maintenance schedules.

The cooperative approach also increases reliability and safety. Consistent standards ensure that all segments of the railway network meet high safety and reliability standards. DT facilitates early detection of potential failures, significantly improving safety, particularly in critical infrastructure such as bridges. In terms of reliability, coordinated strategies and frameworks help mitigate risks associated with cross-border maintenance activities, especially during incidents.

Finally, the cooperative approach reduces environmental impact by optimizing the use of resources and schedules, reducing CO_2 emissions and the overall environmental footprint. DT complemented by Building Information Modelling (BIM) can incorporate the circularity models during the construction or maintenance phases. Moreover, improved maintenance and coordination in cross-border sections enhance connectivity and accessibility for regions, fostering economic growth and social integration.

The benefits of a cooperative approach often outweigh the costs due to the significant improvements in operational efficiency, cost savings, and enhanced safety and reliability. The coordination in cross-border sections becomes cost-effective when:

1. High Traffic Volume: High-frequency usage justifies the need for efficient and reliable operations.
2. Complex Cross-Border Networks: Complex railway networks benefit significantly from standardized data sharing and coordination.
3. Aging Infrastructure: Older infrastructure requires more frequent maintenance, making predictive and condition-based maintenance crucial for IMs.
4. Socioeconomic Impact: Coordinated maintenance reduces service disruptions, which minimizes the economic impact on businesses and commuters relying on timely rail services. Efficient rail operations support both regional and cross-border economic stability and growth, enhancing connectivity and productivity across borders.
5. Environmental Impact: Reducing the frequency and duration of disruptions lowers the carbon footprint associated with rerouting and delays. Additionally, condition-based maintenance optimizes operations and resource usage, leading to more sustainable and environmentally friendly railway management.

The DCF for cross-border railway maintenance offers numerous benefits, including enhanced coordination, data sharing, and cost savings, which significantly outweigh the initial and ongoing costs. It ensures a more reliable, efficient, and sustainable railway network, aligning with the environmental and socioeconomic goals of the EU. The strategic implementation and continuous evaluation of this approach will be crucial for its success and long-term impact on the European railway system.

4.3 Impact of the DCF through Game Theory

A cooperative game theory model, specifically employing the Shapley value, is used in this section to measure the possible impact of the DCF. This model will allow for a comparative analysis between each country operating independently versus forming a coalition to manage the maintenance of the cross-border rail line. By calculating the Shapley value, the model will quantify the benefits of cooperation, demonstrating the value each country contributes to the coalition and the potential gains from collaborative efforts.

The main objective of the game is to minimize the cost of maintenance and reduce the number of times the railway line is closed. The players are the countries involved in the maintenance coordination, for this study: countries A and B.

Shapley value is going to be used to solve this model because it provides a fair distribution of the total gains (or costs) to the players. It is fair because it takes into account the contribution of each player to every possible coalition, ensuring that every player receives their fair share based on their marginal contributions.

Individual Maintenance Costs

- If Country A maintains the rail line alone, it incurs a cost of C_A and the line is closed T_A times.
- If Country B maintains the rail line alone, it incurs a cost of C_B and the line is closed T_B times.

Joint Maintenance Cost

- If Countries A and B cooperate, they could share the maintenance cost. The total cost can be reduced to C_{AB}, which is at least less than the sum of individual costs ($C_{AB} \leq C_A + C_B$), and the number of closures is reduced to T_{AB}, which is less than the maximum of individual closures ($T_{AB} < T_A + T_B$).

4.3.1 Considerations

The objective of the thesis is to demonstrate the impact of a coordinated approach to cross-border railway maintenance operations. To achieve this, the model will be simplified. The TCRs will be assumed to have a major scale impact on the system, involving 30 or more days of closure. These TCRs will consider total possession of the track.

The model will involve two players, reflecting the predominant management of cross-border railway maintenance by the two most relevant IMs. The planning horizon for the model will be set at three years, aligning with the coordination process for medium, high, and major TCRs, which begins at least two years in advance.

Incidents occurring within the planning horizon will not be considered, as they correspond to corrective maintenance. Similarly, small-scale maintenance operations are usually conducted during maintenance windows and do not affect railway network capacity. They will be excluded from the analysis. Once maintenance operation is applied, no further maintenance will be required for the rest of the planning horizon.

The maintenance cost for the coalition will be calculated as the sum of the individual maintenance costs for each country. This approach accounts for the fact that each country employs different maintenance contractors, who can only operate within their designated territories.

The possession cost will be simplified to account for the revenue loss from Track Access Charges (TAC) due to line closures. On average, this cost is €60,000 in the EU (PRIME, n.d.), although it can vary depending on the specific country. However, it is important to consider that the cost of closing a line includes more than just TAC. Additional costs are incurred from the inconvenience and increased time for passengers due to train rerouting or cancellations, as well as extra expenses faced by freight rail undertakings from rerouting shipments.

It is important to mention that the maintenance cost should also account for the environmental and socio-economic impacts. These factors are subjective and challenging to quantify, and their inclusion would provide a more comprehensive assessment. Future research should incorporate these considerations to ensure a holistic evaluation of maintenance operations.

Finally, these major closures could also be utilized to perform additional small-scale maintenance operations, taking advantage of the line closure. However, these marginal gains are not considered in the current analysis.

4.3.2 Scenarios of Maintenance Application

Every maintenance application requires at least a line closure. The scenarios on when the possible maintenance operations can occur are divided as follows:

Scenario A – One Possible Situation

The Figure 26 shows the decision tree associated with scenario A and it is described as follows:

- Year 1: both countries perform maintenance operations. For the coordinated approach, only one line closure is needed, while the line is closed at least twice in the uncoordinated approach.
- Years 2 and 3:
    - Best and worst case: No additional maintenance is needed.

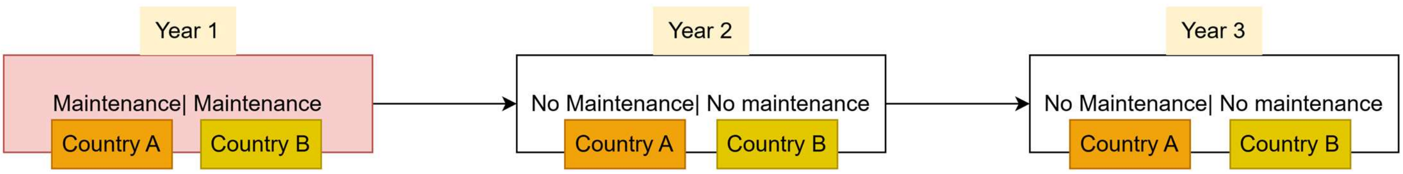


Figure 26. Situation tree for scenario A

Scenario B – Three Possible Situations

The Figure 27 shows the decision tree associated with scenario B and it is described as follows:

- Year 1: country A has to apply maintenance, while Country B does not, or vice versa.
- Years 2 and 3:
    - Best scenario: no extra maintenance is needed (applies for both coordinated and uncoordinated approaches).
    - Worst scenario: one more maintenance operation is required, causing the line to be unavailable.

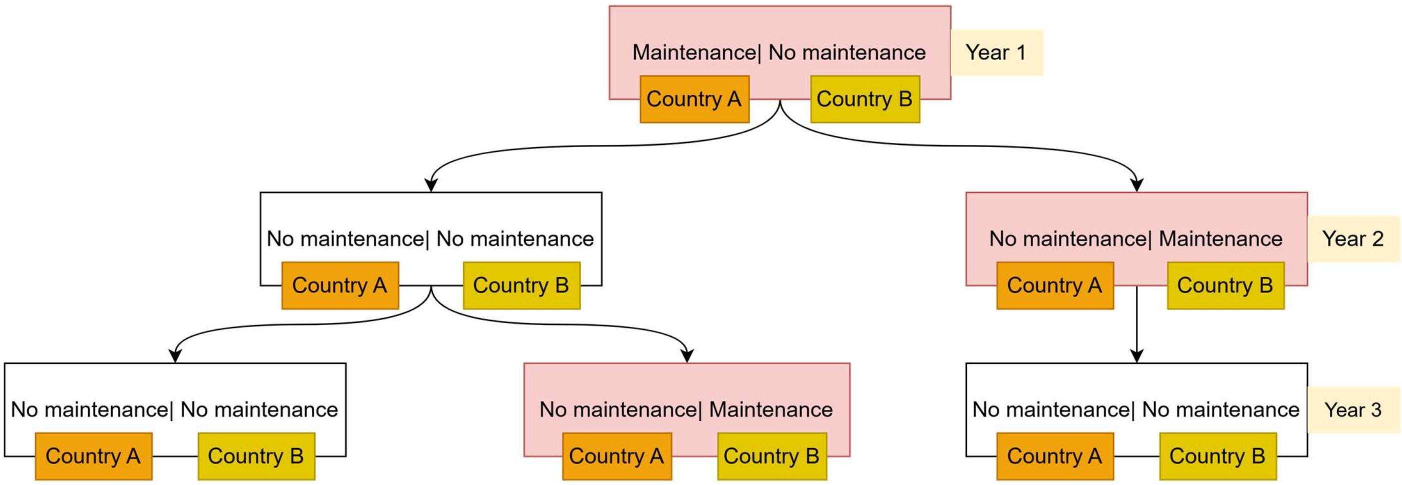


Figure 27. Situation tree for scenario B

Scenario C – Eight Possible Situations

The Figure 28 shows the decision tree associated with scenario C and it is described as follows:

- Year 1: both countries do not perform maintenance.
- Years 2 and 3:
    - Best scenario: No additional maintenance is needed.
    - Worst scenario: Maintenance is needed. Even though there are multiple sub-scenarios of maintenance (see Table 16), the difference between a coordinated and an uncoordinated approach is the number of line closures. When TCRs are coordinated, the number of line closures is minimized, typically resulting in just one closure. On the other hand, the line is closed at least twice in an uncoordinated approach.

Table 16. Sub-scenarios of maintenance for the worst scenario C

	Sub-scenario 1		**Sub-scenario 2**		**Sub-scenario 3 (Vice versa)**	
Country	Year 2	Year 3	Year 2	Year 3	Year 2	Year 3
A	x	o	o	x	x	o
B	x	o	o	x	o	x
# **Line Closures**	1 or at least 2		1 or at least 2		1 or at least 2	
x = Maintenance || o= No maintenance						

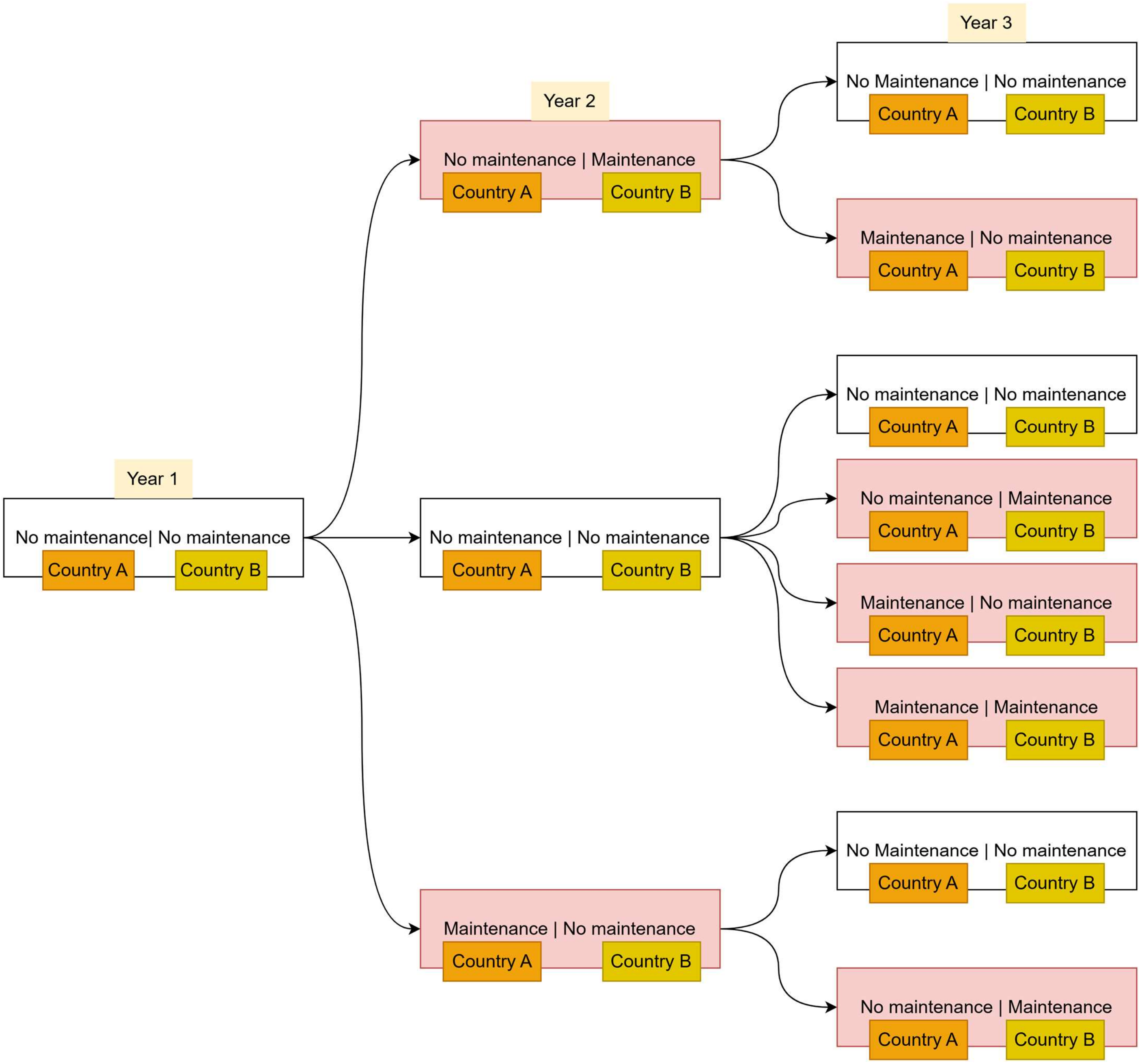


Figure 28. Situation tree for scenario C

Finally, to illustrate how maintenance decisions can be made using shared data through a common degradation model, refer to Appendix E – Shared Track Degradation Model. This appendix provides an example of the degradation model for Scenario B. Integrating these models and their standards into a digital twin can significantly improve maintenance processes in cross-border sections by facilitating real-time data sharing and analysis.

4.3.3 Impact of a Coalition

In the previous section, the number of line closures ranged from 0 to at least 2. If there are no line closures, coordination is not required. Therefore, to demonstrate the added value of coordination, only scenarios involving at least one line closure will be considered. The potential solutions will vary depending on whether there is a cooperative approach by forming a coalition or if each country acts individually, leading to more line closures.

If there is no coalition:

- Cost for Country A:

$$C_A = C_{Maintenance\_A} + (C_{Possession\_A} + C_{Possession\_B})$$

- Cost for Country B:

$$C_B = C_{Maintenance\_B} + (C_{Possession\_A} + C_{Possession\_B})$$

If there is a coalition, the cost would be:

$$C_{AB} = (C_{Maintenance_A} + C_{Maintenance_B}) + C_{Possession\_AB}$$

The possible coalitions that can be made are: **{∅}**, **{A}**, **{B}** and **{A,B}** or **{B,A}**. The value function $v(S)$ for a coalition, **S**, is the negative of the total cost, as the objective is to minimize costs. The value functions for each coalition are:

$$v(\emptyset) = 0$$

$$v(\{A\}) = -C_A = -C_{Maintenance\_A} - (C_{Possession\_A} + C_{Possession\_B})$$

$$v(\{B\}) = -C_B = -C_{Maintenance\_B} - (C_{Possession\_A} + C_{Possession\_B})$$

$$v(\{A,B\}) = v(\{B,A\}) = -C_{AB} = -\left(C_{Maintenance_A} + C_{Maintenance_B}\right) - C_{Possession\_AB}$$

Shapley Value Calculation

The Shapley value for each player is calculated as the average of their marginal contributions to all possible coalitions. The formula for the Shapley value is:

$$\phi(N, v) = \frac{1}{|N|!} + \sum_{S \subseteq N \setminus \{i\}} |S|!\,(|N| - |S| - 1)!\,[v(S \cup \{i\}) - v(S)]$$

Where N is the number of players and v is the value of the pay-off function.

Marginal Contribution of Country A

The contribution to the empty set is:

$$v(\{A\}) - v(\emptyset) = -C_A - 0 = -C_{Maintenance\_A} - (C_{Possession\_A} + C_{Possession\_B})$$

The contribution when joining Country B is:

$$v(\{A,B\}) - v(\{B\}) = -C_{AB} + C_B$$

$$v(\{A,B\}) - v(\{B\}) = -C_{Maintenance_A} - C_{Possession_{AB}} + (C_{Possession\_A} + C_{Possession\_B})$$

Finally, the average marginal contribution for Country A is:

$$\phi_A = \frac{1}{2}[-C_A + (-C_{AB} + C_B)]$$

$$\phi_A = -\boldsymbol{C_{Maintenance_A}} - \frac{\boldsymbol{C_{Possession_{AB}}}}{2}$$

Marginal Contribution of Country B

The contribution to the empty set is:

$$v(\{A\}) - v(\emptyset) = -C_A - 0 = -C_{Maintenance\_A} - (C_{Possession\_A} + C_{Possession\_B})$$

The contribution when joining Country A is:

$$v(\{A,B\}) - v(\{A\}) = -C_{AB} + C_A$$

$$v(\{A,B\}) - v(\{A\}) = -C_{Maintenance_B} - C_{Possession_{AB}} + (C_{Possession\_A} + C_{Possession\_B})$$

Finally, the average marginal contribution for Country B is:

$$\phi_B = \frac{1}{2}[-C_B + (-C_{AB} + C_A)]$$

$$\phi_B = -\boldsymbol{C_{Maintenance_B}} - \frac{\boldsymbol{C_{Possession_{AB}}}}{2}$$

Coalition vs No Coalition

According to the previous subsection, if both countries form a coalition:

- Country A should bear a cost of:

$$C_{Maintenance_A} + \frac{C_{Possession_{AB}}}{2}$$

- Country B should bear a cost of:

$$C_{Maintenanc\ _B} + \frac{C_{Possession_{AB}}}{2}$$

Then, the total cost of maintenance for the coalition is:

$$C_{Maintenance_B} + C_{Maintenan\quad A} + C_{Possession_{AB}}$$

While the total cost of maintenance if both countries perform the maintenance operations individually is:

$$C_{Maintenance\_B} + C_{Maintenance\_A} + (C_{Possession\_A} + C_{Possession\_B})$$

By reducing the number of closures to T_{AB}, the cost of possession of the coalition becomes less than the combined possession costs if each country conducted its maintenance operations independently ($C_{Possesion\_AB} < C_{Possesion\_A} + C_{Possesion\_B}$). By cooperating, both countries reduce the total cost and share it fairly based on their contributions to the coalition. A numerical example is given in Appendix F – Numerical Example of a Coalition Game.

Chapter 5. Case Studies

Within this chapter, two case studies are presented. The first case study focuses on implementing DT as a tool of the DCF for improving maintenance support decisions in a bridge for railways between two countries. The second case study examines the current state of rail cross-border sections and their maintenance operations in the Netherlands, providing an implementation plan and assessing the potential impact of the Digital Cooperative Framework (DCF). Additionally, this case study covers how the DCF would have affected the coordination of the Betuweroute during major impact TCR due to rail works between Emmerich and Oberhausen.

5.1 Case Study 1 –Bridge between Two Countries

In this sub-section, an example of the implementation of a DT is presented. Assuming the EU Railway Entity and the Forum are already established, the focus will primarily be on the implementation of Digital Twin (DT) technology as a tool for improving the maintenance support decisions.

5.1.1 Digital Twin Implementation

A digital twin is implemented to reduce the impact of the maintenance operations in a bridge between two countries (see Figure 29). A bridge is used as an example as it is often a critical element within the network. This digital twin model aims to monitor its structural health and optimize the maintenance operations of a bridge. The digital twin will also help with the implementation of condition-based maintenance and the coordination of the operations.

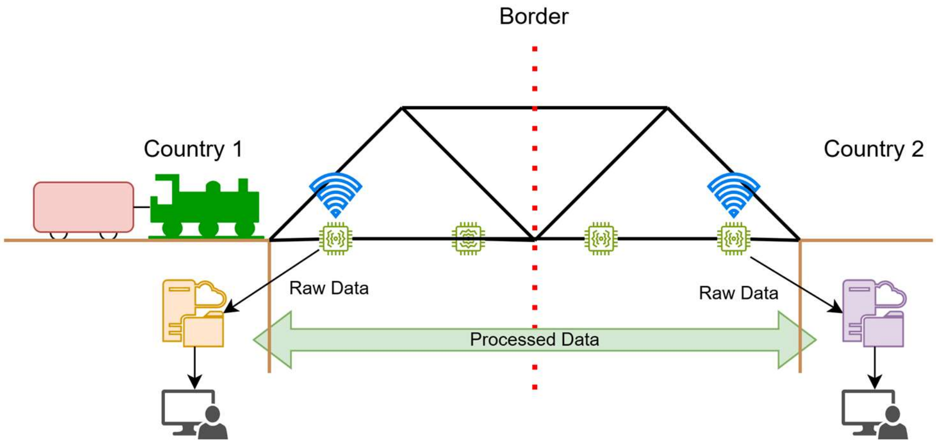


Figure 29. Simple diagram DT for a bridge that connects two countries

This implementation example is based on a case study by Armijo & Zamora-Sánchez (2024). This example will focus on the superstructure of the bridge. It will not take into account the electric and signaling systems into account. The framework for implementing the DT in this example follows the flowcharts in Figure 20 and Figure 21, consisting of the following steps:

- To accomplish the objective of the DT, vibration-based monitoring is suggested as it tracks the dynamic response of a bridge structure. The DT model can detect anomalies that deviate from the normal vibration pattern, thereby improving safety through early detection.
- Collect the preliminary data about the structure: geometric details, location, mechanical specifications (typology and materials), and operational data such as loading and velocity.
- Define necessary technology tools for the digital implementation:
    - Software: ANSYS (FE Modelling), Autodesk Revit or Three.js (3D modelling).
    - Sensors: accelerometers.
    - Measuring devices: UAV LIDAR or Static LIDAR. The difference between them is the accuracy and the density of points generated.
    - Connectivity and IoT devices: 4G getaway and Wi-Fi devices.
    - Other: cloud servers and applications (i.e. Microsoft Azure) and power sources (solar panels or/and batteries).
- Generate a virtual representation of the structure (see Figure 30). The generation can be manual or automatic. Manual modelling involves drawings and on-field measurements, while automatic modelling

utilizes LIDAR technology and software post-processing. In the end, validation between the physical and virtual models is done.

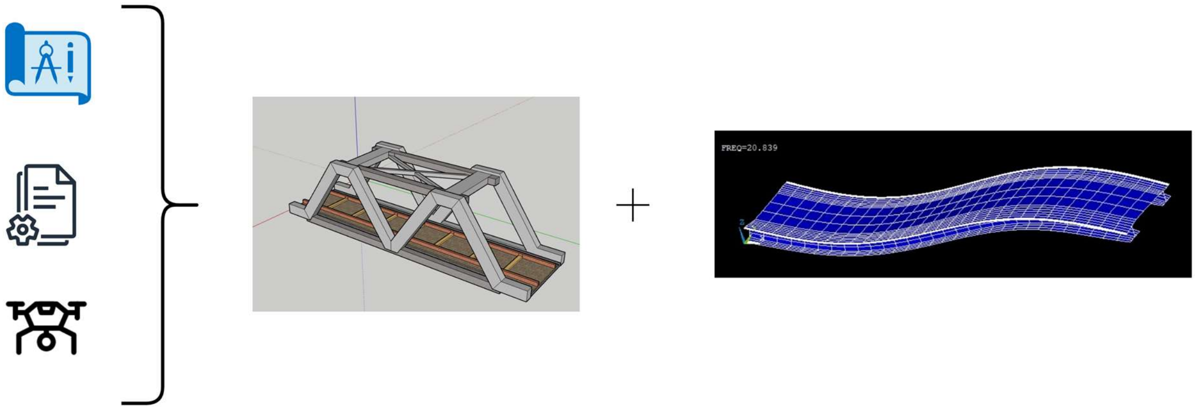


Figure 30. Generation of a virtual model (FEM image - modified from source: Armijo & Zamora-Sánchez, 2024)

Additionally, a parameterized 3D FE model of the bridge is developed using ANSYS software, incorporating the specific characteristics of the bridge. From this initial FEM bridge model, the first three principal vibration mode shapes and frequencies are calculated. These serve as a foundational baseline for subsequent measurements and model calibration. The failure modes for the bridge are defined, which can be either serviceability limit states (ELS) or ultimate limit states (ELU).

- Define the data collection and management plan:
    - Collect relevant historical data like previous acceleration measurements and maintenance logs (if possible).
    - Environmental data should be collected if any of the models need this type of data. This data can be collected through environmental sensors that measure parameters such as temperature, humidity, light, and rainfall.
    - Shared data from the neighbouring country is done through the communication of DTs. It contains maintenance schedules and acceleration measurements.
    - The locations or elements of the system to be monitored (critical sections, deck, piles, bearings, etc.) and the stresses to which they are exposed.
    - Data collection through accelerometers following a structural health monitoring plan.
- The privacy and cybersecurity protocols are defined, outlining access permissions and data security measures. For example, blockchain networks are employed as a security protocol to ensure data integrity, distributed storage, and secure information dissemination. This enhances the auditability and accountability of digital twin (DT) operations while safeguarding the confidentiality and authenticity of shared data (Yan et al., 2023).
- Data transmission: The data from the sensor will be transmitted via Wi-Fi using protocols like TCP/IP, MQTT, or XMPP. MQTT protocol for communication between the sensors and the middleware can be used due to its lightweight nature, low bandwidth usage, and suitability for IoT and SHM applications (Armijo & Zamora-Sánchez, 2024).
- Data storage and processing: the middleware processes daily the raw sensor data stream (via MQTT), performing real-time analysis to detect vibration events caused by passing trains. Additionally, the middleware isolates the free vibration segment of the signal and performs a fast Fourier transform (FFT) analysis on it to identify the prominent vibrational frequencies (see).
  Then, the data storage is done through the cloud storage of Microsoft Azure. The raw FFT data is processed and transformed for future use in machine learning (ML) algorithms. Within this stage, the data that can be shared with other stakeholders is also prepared taking into account standardization protocols (such as the use of RailML, and Industry Foundation Classes (IFC)).
  It is important to remark that the discussion on standardizing DT formats can be initiated through the EU Railway Forum and subsequently reaffirmed by the EU Railway Entity and IMs.
- Preliminary visualization: Once the data is stored and processed, the visualization of the FFT data can be done. This will help engineers in preliminary analysis and decision-making.
- Define failure prediction mechanism: The curated dataset is crucial for training and retraining machine learning models that classify vibration patterns using automated techniques such as machine learning. At the end of each day, the data from the accelerometers are transferred to the cloud storage to increase the training dataset, continuously enhancing the accuracy of the machine learning models suitable for

predictive maintenance. As stated by Armijo & Zamora-Sánchez (2024), the process involves several key steps:

- Filtering outliers in the vibration frequencies that deviate from expected ranges.
- Identifying the top three principal vibration peaks for each bridge crossing event.
- Employing k-means clustering to group similar vibration patterns.
- Labelling the clusters to establish a supervised training dataset.

Any anomalies or changes in the typical cluster distribution can indicate a potential structural issue requiring further inspection (Armijo & Zamora-Sánchez, 2024).

- Visualization through digital twin application (see Figure 31): the application will incorporate a BIM viewer to display the 3D model of the bridge. It will integrate real-time sensor data, along with notifications and alerts.

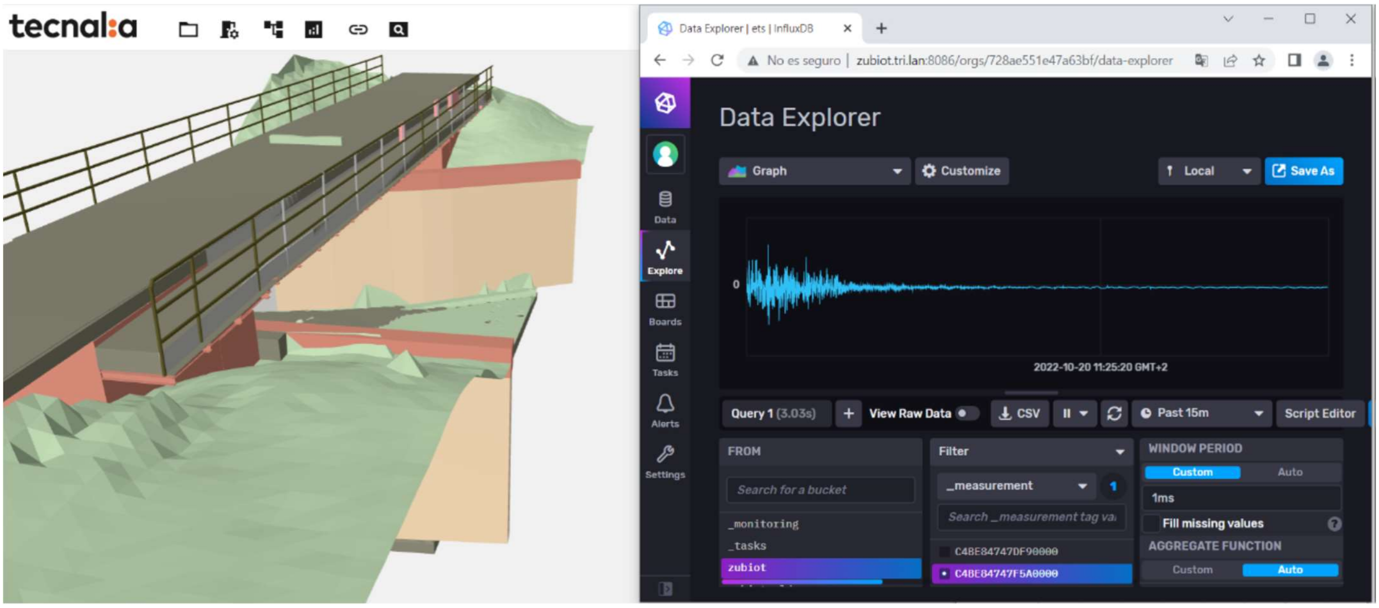


Figure 31. Example of a digital twin application (source: Armijo & Zamora-Sánchez, 2024)

- The type of anomaly can be identified through machine learning algorithms. Inspection should be done to verify the results. Additionally, AR and VR tools could facilitate the inspection process. Finally, the ML models will suggest possible options for maintenance.
- Maintenance optimization model: this model will optimize the maintenance operations using a multi-objective function which maximizes availability and minimizes costs and environmental impact. It incorporates performance standards to ensure safety compliance and determines the optimal timing for each maintenance operation.
- Once the action is decided, the maintenance operation will go into a scheduling optimization algorithm. This algorithm will determine the most suitable timing for applying the maintenance action, considering concurrent activities along the same railway line and coordinating with maintenance operations in neighbouring countries in the cross-border section. The outcome will be a preliminary schedule for the maintenance operation.
- Then the coordination process will follow the flow in Figure 22. If the relevant infrastructure managers approve the schedule proposed by the DT, the maintenance operation proceeds as planned. In cases of disagreement, both IMs engage in negotiations in which the EU Railway Entity would act as a mediator to reach a mutually acceptable solution. Ultimately, the final schedule is confirmed and communicated to all the relevant stakeholders.
- Finally, the validation of the DT model involves assessing its effectiveness in monitoring the structural health and optimizing bridge maintenance operations. This process includes running the DT model in parallel with real-world operations over a specified period to calibrate it and gather feedback from users.

It is important to remember that once the implementation process is done and the DT model is operational, it will continuously update itself with new data, creating a feedback loop between the physical representation and the virtual model.

Advantages and Disadvantages of the Implementation of the Digital Twin

The main advantages of the implementation of a cross-border digital twin for the bridge structure are enhanced coordination and collaboration, increased safety and reliability, standardized maintenance practices, and economic and environmental benefits. The DT facilitates improved coordination and collaboration between countries by enabling data sharing through cloud applications and creating unified schedules using optimization models based on the shared data.

The DT also increases safety and reliability through monitoring, ensuring the entire bridge structure is continuously assessed, thus enhancing overall safety. Additionally, the DT enables early detection of structural issues, preventing severe problems and further boosting reliability.

Standardized maintenance practices are achieved by identifying conflicts in maintenance protocols and standards between countries. Additionally, the DT ensures consistent quality of maintenance work across the entire bridge as inspections can also be conducted remotely using drones or AR technology.

The bridge DT offers economic benefits by reducing costs through condition-based maintenance, which optimizes schedules and lowers inspection costs. Environmentally, the DT promotes efficient resource use and reduces emissions by preventing unnecessary maintenance and optimizing necessary ones. This approach minimizes the carbon footprint, reduces fuel consumption, and cuts down on material waste. Additionally, a more available and reliable network promotes train use, one of the greenest modes of transportation.

However, implementing a DT for this cross-border infrastructure also has limitations, including high initial costs, data quality issues, data privacy and security risks, and technical integration challenges. Regarding implementation costs, the investment required is significant, covering technology costs, personnel training, and system integration expenses for the systems of both countries.

Data quality issues, such as missing or poor-quality data, can deteriorate the accuracy and reliability of the DT model. Incomplete or inaccurate data can lead to incorrect assessments and decisions. For example, if the accelerometers in one country are damaged or not properly calibrated, it can result in flawed data and compromised analysis. Regarding data privacy and security risks, sharing data through cloud applications poses potential security threats, such as hacking. Additionally, ensuring cybersecurity across multiple jurisdictions can be challenging.

Finally, technical integration challenges include the complexity of integrating data from diverse systems. For instance, the use of different data formats or coordinate systems can complicate the sharing process. Additionally, reaching an agreement on degradation and scheduling optimization models for the cross-border DT can be difficult.

5.2 Case Study 2 – The Netherlands

The coordination process for cross-border maintenance operations is going to be explored in detail within the Netherlands. This study will focus on the implementation of the DCF and its potential benefits and limitations within the Dutch railway system. Additionally, it will asses how the DCF would impact the planned maintenance of the Betuweroute, specifically for a major impact TCR occurring between Emmerich and Oberhausen.

5.2.1 Description of the Current Situation

The Netherlands has a complex and dense railway system that combines freight and passenger transportation. Despite its relatively small size, The Netherlands handles increasing amounts of cargo due to its major ports and excellent connections within the European Union via the TEN-T corridors. Within this network, three rail freight corridors go through The Netherlands: the Rhine-Alpine (RFC1), the North Sea-Mediterranean (RFC2), and the North Sea-Baltic (RFC8) (see Appendix G – Rail Freight Corridors in The Netherlands).

According to CBS (2024), cross-border goods transport in The Netherlands reached around 38 million tons in 2022, with 27 million tons departing from the country and 10 million tons arriving within its borders. Most goods departing and arriving in the country are destined for Germany and Belgium (CBS, 2022).

As for passenger transport, The Netherlands has at least 11 international connections with different countries within the EU in 2022 (see Figure 32). Belgium has the most daily connections, while Austria and Switzerland have the fewest. Additionally, in 2023, a new night train service called the European Sleeper began operating, connecting Brussels to Prague via Amsterdam and Rotterdam. It is important to remark that the EU is promoting the expansion of long-distance cross-border passenger transport projects to reach its environmental goals.

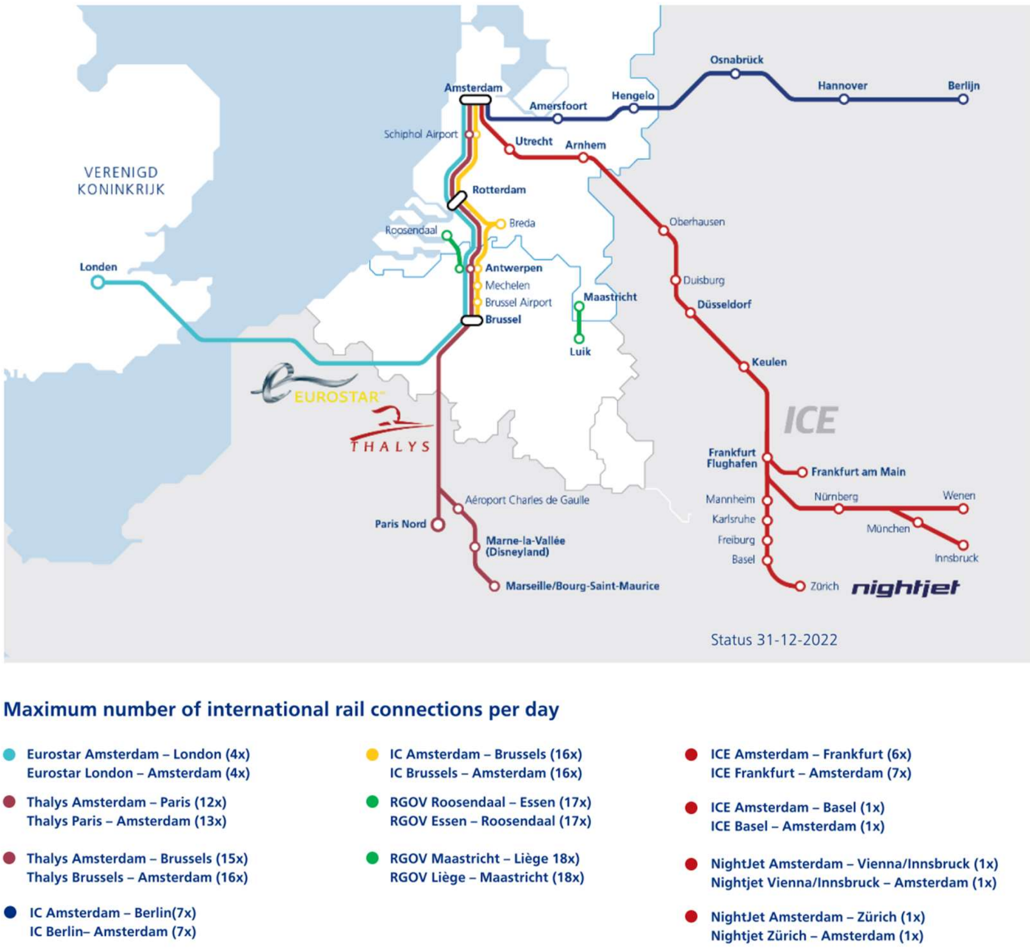


Figure 32. International train services connections in The Netherlands (source: NS, 2022)

The Netherlands has borders to the East with Germany and to the South with Belgium. Figure 33 shows the cross-border sections between them, while Table 17 lists the stations located near the border and indicates the type of traffic and whether the section is part of a rail freight corridor.

Figure 33. Cross-border railway lines in The Netherlands (modified from source: OpenRailwayMap, 2024)

Table 17. Railway cross-border sections of The Netherlands

Neighbouring country	Cross-border section	Traffic	RFC
Germany	Nieuweschans (NL) – Weener (DE)	Passenger-Mixed	-
Germany	Coevorden-Heege (NL) – Laarwald (DE)	Freight	-
Germany	Hengelo (NL) – Bad Bentheim (DE)	Mixed	RFC8
Germany	Glanerbrug (NL) – Gronau (DE)	Passenger-Mixed	-
Germany	Zevenaar (NL) – Emmerich (DE) (Betuweroute)	Mixed	RFC1, RFC8
Germany	Venlo (NL) – Kaldenkirchen (DE)	Mixed	RFC1
Germany	Eygelshoven Markt (NL) – Herzogenrath (DE)	Mixed	-
Germany	Bocholtz (NL) – Aachen-Vetschau (DE)	Not in use	-
Belgium	Eijsden (NL) – Visé (BE)	Mixed	-
Belgium	Maastricht (NL) – Lanaken (BE)	Freight	-
Belgium	Weert (NL) – Hamont (BE)	Freight	-
Belgium	Rotterdam Centraal/Breda (NL) – Antwerpen Centraal (BE) (HSL-Zuid)	Passenger	-
Belgium	Roosendaal (NL) – Essen (BE)	Mixed	RFC2, RFC8
Belgium	Sas van Gent (NL) – Zelzate (BE)	Freight	RFC1, RFC2

5.2.2 Maintenance Operations in Cross-border Sections

In the Netherlands, ProRail is the railway infrastructure manager. It is a private limited liability company, and the Dutch state is the sole shareholder. According to the Ministerie van Infrastructuur en Waterstaat (2018), its main functions include constructing, managing, and maintaining railway infrastructure, such as tunnels, level crossings, overhead lines, signs, and points. Additionally, it is responsible for managing and maintaining railway facilities, including stations, as well as allocating network capacity.

Maintenance operations are reflected in the capacity models for allocation as they represent capacity restrictions in the network. Depending on the type of maintenance, the maintenance operations are planned by different departments: Capacity Management is responsible for planned maintenance (i.e. preventive maintenance) and Traffic Operations is responsible for daily operations and unplanned maintenance (i.e. corrective maintenance).

In general, maintenance operations are divided into two groups small-scale maintenance and large-scale maintenance. The first group is managed by performance-based maintenance contracts (PGOs). This type of contract runs for five years and includes all track and switches, power supply, signalling, overhead wire, civil structures, and telecom (Nilsson & Nyström, 2014). While the second group is independent tender contracts, which last for the period of construction.

Small-scale maintenance operations in the Netherlands are organized by regions, with each region managed by a different contractor. There are a total of 21 maintenance regions (ProRail, n.d.), and seven of them border neighbouring countries (see Figure 34). The Drenthe and Twente regions have each two connections with Germany while the Gelre and De Peel regions have only one. The Zeeland region has two connections with Belgium while Brabant has only one. Finally, the region with the most cross-border connections is Limburg with five: 3 to Belgium and 2 to Germany.

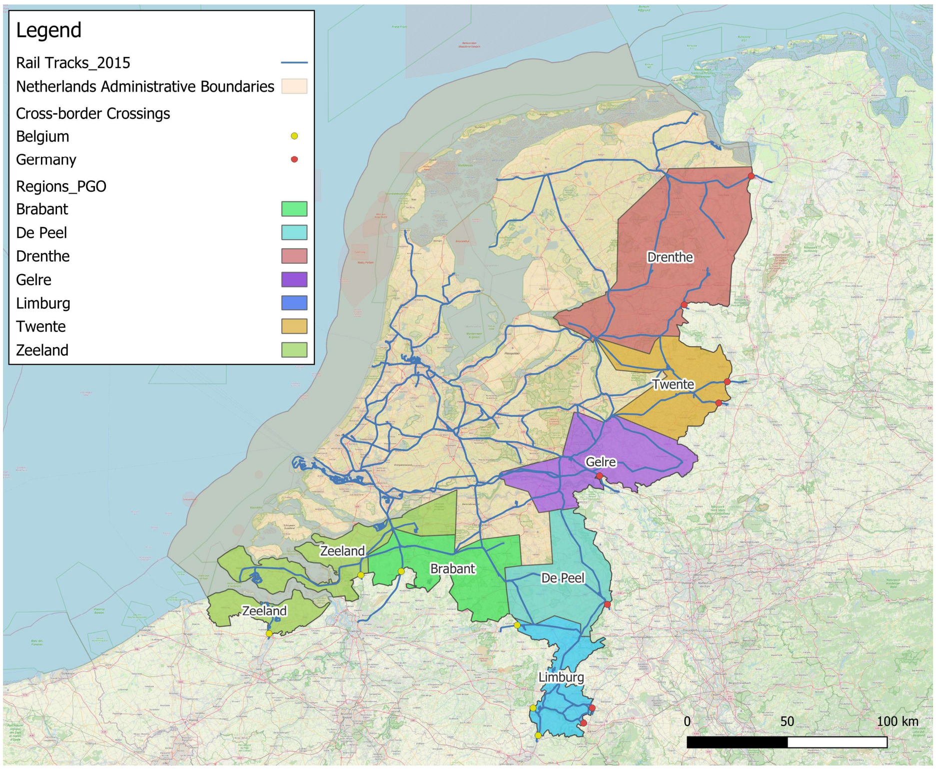


Figure 34. Contract regions in the cross-border sections (modified from source: Nilsson & Nyström, 2014)

ProRail uses reliability, availability, maintainability, safety, health, and environment (RAMSHE) to specify the functional terms that it wants the contractor to achieve. These specifications are then to be upheld by the contractor providing rail maintenance within a fixed price (Nilsson & Nyström, 2014). Monitoring the compliance of the railway system with the standards is performed by a separate third party (Nilsson & Nyström, 2014).

For small-scale maintenance operations, the contractor monitors the state of the railway system and chooses when to apply the maintenance operations within the available maintenance windows. It is important to remark that the IM does not intervene in the maintenance practices, it only gives that standards and checks that they are met. There are bonuses and penalties for not complying with the requirements regarding e.g. safety matters, speed reductions, exceeding time on track. While for large-scale maintenance operations, the IM defines the period when the operations should be done and the construction specifications and standards that should be followed.

Stakeholders

The main stakeholders involved in the cross-border railway maintenance operations are:

- Railway infrastructure managers: There are three IMs involved: ProRail (The Netherlands), Infrabel (Belgium), and DB Netz (Germany).
- Rail Freight Corridors: As previously mentioned, there are three RFCs that use the Dutch railway network: Rhine-Alpine, North Sea-Mediterranean, and North Sea-Baltic. The Rhine-Alpine and the North Sea-Baltic routes link The Netherlands to Belgium and Germany, while the North Sea-Mediterranean connects The Netherlands to Belgium.
- Railway Undertaking
- s: In The Netherlands, the RUs are divided into passenger carriers, freight forwarders, infrastructure carriers (contractors), and others. The main passenger carriers are NS, Arriva, and the international passenger services (see Figure 32). There are six infrastructure carriers: BAM Infra Rail B.V., Eurailscout Inspection & Analysis B.V., Rail Transport Service Germany GmbH, Strukton Rail Equipment B.V., Voestalpine Railpro B.V., and VolkerRail Materieel en Logistiek B.V. According to Statista (2023), the three main rail freight companies in 2017 were DB Cargo, Captrain and Rotterdam Rail Feeding.
- Maintenance Contractors: The contractors for the small-scale maintenance operations that are involved in the cross-border sections are VolkerRail, ASSET Rail and Strukton Rail. As for large scale, the tender is opened to the different construction companies.
- Other stakeholders: These refer to other actors that are not directly involved in the maintenance process, for example: Ministerie van Infrastructuur en Waterstaat (main shareholder of ProRail), environmental organizations, non-users (local residents) and users (train users or users of freight transportation services).

The Figure 35 shows a power-interest grid to assess the engagement level and power held by the different main stakeholders regarding the railway system and its maintenance operations. Stakeholders with higher authority have more control and influence in handling the other working under them, such stakeholders come under the category of high power, the vice versa in the low power. Similarly, stakeholders who share common objectives tend to be more involved in operations, categorizing them as high interest, while the opposite holds for low interest. The grid contains four sections, divided according to the power held by the stakeholder and their interest in the whole system.

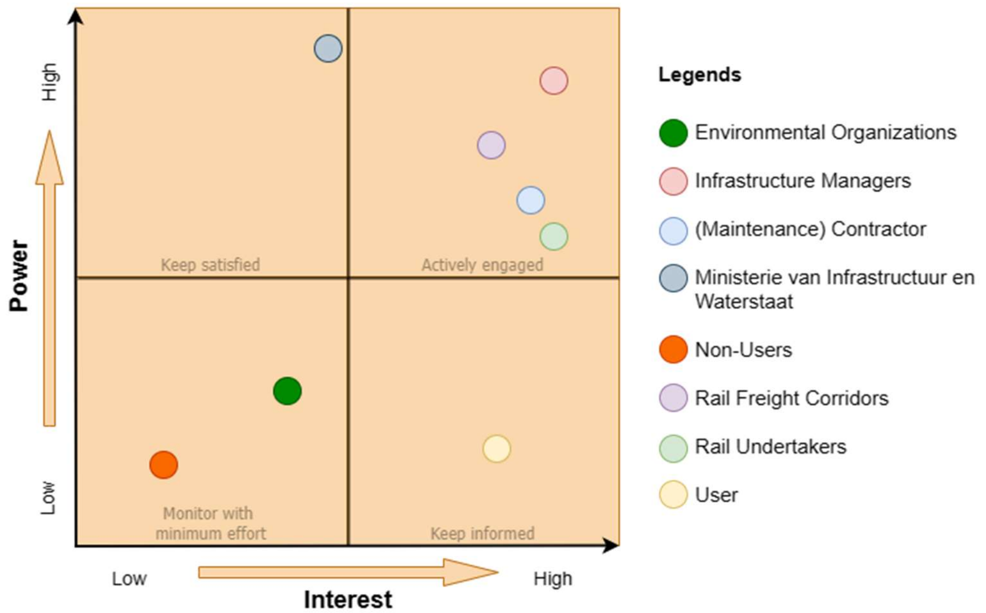


Figure 35. Stakeholder power-interest grid.

Coordination of Maintenance Operations in Cross-borders

ProRail plans its works on and near the tracks in Temporary Capacity Restrictions (TCRs), making a distinction between Periodical TCRs (also: Weekly TCRs or Maintenance Windows) and Regular TCRs (or just TCRs) (ProRail - Capacity Management, 2022). Periodical TCRs are usually weekly recurring TCRs and are planned supply-driven and later filled with concrete work. Regular TCRs are tailor-made based on known activities.

According to ProRail - Capacity Management (2022), maintenance windows are allocated in the yearly timetable on all track sections in the Netherlands and facilitate TCRs for short-cycle maintenance as well as other minor TCRs. Each maintenance window has the following main characteristics:

- they last at least 4 hours;
- the number of maintenance windows at a certain location depends on the historical and/or expected need for maintenance and projects;
- they are mainly planned at night hours and spread as much as possible over all nights of the week;
- they are repetitive every week (with some exceptions, view the Capacity Strategy 2026 Netherlands).

The planning of TCRs is consulted on a national level. At border crossings, ProRail coordinates the Capacity Model with the infrastructure manager of the neighbouring country concerned (ProRail - Capacity Management, 2023). Additionally, ProRail, along with Infrabel and DB Netz, shares internationally relevant TCRs with RUs, although these discussions are not part of the formal consultation process.

According to the Capacity Strategy 2027 (2023), TCR alternatives are usually discussed in regional meetings, except for complex projects with long-term scopes, which have their own dedicated consultation process. The request for an alternative TCR scenario is not limited to Major TCRs and can be proposed during consultation meetings.

The TCR consultation process of ProRail is shown in the Figure 36. This consultation process involves negotiation with the relevant RUs, IMs, and RFCs on when to execute and how to minimize the impact of the maintenance operations. The TCR major and high TCRs are planned from X-27 onwards, including a high-level consultation before X-24. A more detailed consultation begins at X-17, resulting in a publication at X-12. The consultation of minor TCRs has a main focus from X-10 onwards but can be part of the "X-12" consultation phase as well (Infrabel et al., 2023). All RUs are consulted before each publication. ProRail holds continuous meetings throughout the year with the RUs.

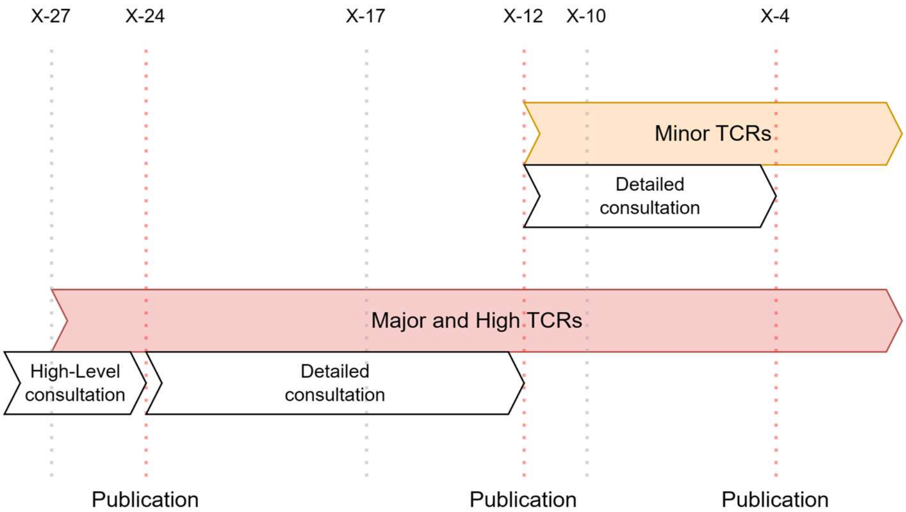


Figure 36. TCR consultation process of ProRail

In the maintenance windows, works can be planned without further consultation of RUs or coordination with neighbouring IMs, both before and after the X-4 publication (ProRail - Capacity Management, 2022). Additionally, they are planned throughout the network in such a way that (deviation) routes remain available on all days of traffic demand between the main origin and destination locations of freight trains and night trains, including border crossings with locations in Germany and Belgium (ProRail - Capacity Management, 2022).

The publication of the TCRs is done through the Capacity Strategy document, which can be found on ProRail and/or RailNetEurope websites. Additionally, the TCR Tool by RailNetEurope can be used to publish and coordinate the TCRs. For the final publication, the exact size (at track level) and duration of the TCR are determined and consulted with applicants (ProRail - Capacity Management, 2022). Additionally, the clustering of TCRs is finalized.

International coordination of train operations is done by a multilateral agreement between ProRail, Infrabel, and DB Netz ("BeNeDe Group"). Additionally, ProRail participates in international railway cooperation organizations such as PRIME and RailNetEurope. It is important to remember that the RFCs should be included in the coordination if the train line is part of the corridors.

The BeNeDe Group meets 8 times per year and currently focuses on the coordination of TCRs two timetables ahead. The planning of TCRs is synchronized and one or multiple deviation routes, based on historical experience, are safeguarded to provide sufficient rerouting capacity (Infrabel et al., 2023). Also, a standardized Gant chart for the TCRs is used by the three IMs. Additionally, the "2-day approach" is used by the BeNeDe Group. The "2-days approach" means that twice a year RUs are invited to the regular coordination meetings of IMs, which are extended with an extra day: IMs do their normal coordination on the first day and discuss the results with RUs on the second day (Infrabel et al., 2023).

The coordination process of the maintenance operations in ProRail follows the following flow chart:

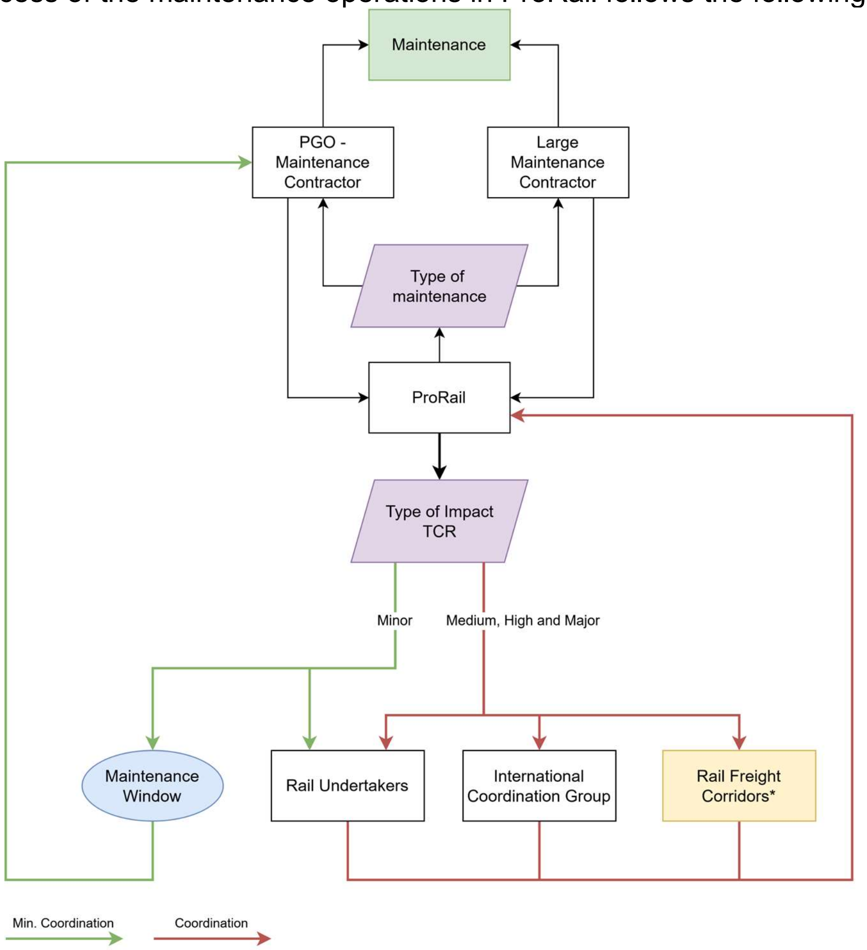


Figure 37. Coordination flow chart

To maintain the railway system, ProRail divides the maintenance operations depending on their scale. Small-scale maintenance is handled by the PGO maintenance contractor, while large-scale operations are done by larger maintenance contractors. The coordination of maintenance activities varies depending on their impact. For minor TCR, the maintenance operations will be executed within a maintenance window so no further coordination is needed. In this case, the railway undertakings have been already notified of when and where the maintenance windows will occur.

When a TCR has a medium, high, or major impact, the railway undertakings, the international coordination group (i.e. the BeNeDe Group), and the relevant (s) rail freight corridors should be notified and coordinated. These stakeholders should proceed according to the consultation process previously discussed (see Figure 36).

5.2.3 Challenges in Cross-border Sections

The main challenges that ProRail faces in improving maintenance operations in cross-border sections are numerous and complex. First, the involvement of many stakeholders complicates the coordination of maintenance operations because there are many different interests within the planning of the cross-border maintenance operations and meeting all of them is not feasible. For example, the importance of a specific line will change depending on the country.

In the Netherlands, the contractors have the autonomy to perform maintenance to the system while ProRail is responsible for setting and ensuring compliance with standards. This means that the coordination of maintenance operations with neighbouring countries should also that into account the contractor scheduling for the specific line.

Second, there is a significant lack of data sharing. Even though there are multiple coordination groups, the information and data sharing between the relevant countries is minimal. In order words, only basic details about upcoming maintenance operations, such as when the TCR is going to occur, what the capacity restrictions are, and the re-routing alternatives (if necessary), are shared. Detailed information about the railway state is highly restricted a thus not shared between neighbouring countries limiting the coordination and maintenance optimization potential.

One example of this challenge in cross-border operations is the capacity management model estimations differ between Germany and the Netherlands, but only the results are communicated, omitting the underlying assumptions made in each model. This also highlights an important issue, as discussed in Chapter 4, where there is a reluctance to share data between neighbouring countries.

Another challenge is the lack of information from the contractors. The information on the maintenance operations shared between the contractor and the IM is minimal. Without detailed information about maintenance schedules and procedures, IMs cannot effectively coordinate activities across borders. Moreover, incomplete information makes it difficult to optimize maintenance activities and generate maintenance optimization models.

Additionally, there is a lack of long-term planning of TCRs. Effective coordination requires stable and long-term planning of TCRs. Stability refers to creating an application plan and consistently adhering to it, especially in terms of timing. This becomes challenging because of the complexities of the tendering process and how the contract with the maintenance companies is managed. Coordinating TCRs shortly in advance is ineffective, as it does not provide enough time for all parties to negotiate favourable timing for performing the TCRs. By that stage, the TCRs are already fixed requirements in the rail system.

Aligning different national interests with broader cross-border railway priorities is a complex challenge across the EU, including in The Netherlands. Different political interests often make this alignment difficult. Additionally, without financial incentives and political will from all the involved countries, it is difficult to implement effective cross-border maintenance solutions. The European Union needs to provide clear mandates and flexible funding to cross-border railway projects to encourage cooperation among countries.

Finally, different maintenance standards pose a challenge. Maintenance standards in Belgium and Germany differ from those in The Netherlands. When different countries have varying maintenance standards, it can lead to inconsistencies in maintenance procedures, creating confusion and inefficiencies when coordinating maintenance activities across borders. Moreover, standards directly impact the quality and safety of maintenance work. Conflicting standards may result in varying levels of quality and safety. In terms of equipment, each contractor uses country-specific equipment for maintenance operations, hindering interoperability when needed across borders.

5.2.4 Implementation of the DCF

The implementation of the cooperative approach is discussed in this subsection. The next table defines the key actions that ProRail has to take in every implementation phase of the approach.

Table 18. Key actions of ProRail according to the implementation phase

Implementation Phase	ProRail - Key Actions
1	**Entity Role** Assess and identify areas of improvement or concerns about the Proposal document number 52023PC0443. **DT Implementation** Evaluate the current level of digitalization and readiness for DT implementation. Determine the feasibility of integrating existing systems into the new digital framework.
2	**Forum Role** Exchange and share information about maintenance and coordination practices, especially with Germany and Belgium (as part of the BENEDE group). Share coordination experiences and lessons learned from real cases and simulations of cross-border maintenance operations. **DT Implementation** Create detailed roadmaps for the national implementation of DT technology, aligning with the ProRail Digitalization Vision 2040, and ensure that these roadmaps are shared within the organization.
3	**Entity Role** Collaborate in creating frameworks: the European Framework for Capacity Management, the European Framework for the Coordination of Cross-Border Traffic Management, Disruption Management, and Crisis Management and the European Framework for Performance Review. Cooperate on the socioeconomic and environmental model(s) to resolve capacity conflicts in cross-border sections. **Forum Role** Assist in creating the European frameworks. Participate in standardizing formats and developing security and privacy protocols for DT. **DT Implementation** Implement levels 1 and 2 of the DT according to the defined plan. Train personnel in new coordination practices and the use of digital twins and their tools. Develop and validate degradation and maintenance optimization models.
4	**DT Implementation** Transition to condition-based maintenance by applying DT level 3. The model will use standardized degradation and maintenance optimization models (approved by national authorities). Identify pilot sections for DT implementation to refine models and gather user feedback. This pilot will also help to test the federation of digital twins, focusing on data sharing and security protocols. **Forum Role** Assist the EU Railway Entity in improving frameworks. Share challenges and advice on DT with other members. Collaborate on improving coordination and maintenance practices. **Entity Role** Reach consensus on socioeconomic and environmental model(s). Coordinate with the BENEDE group on the pilot for federated DT.
5	**DT Implementation** Implement level 4 DT, incorporating feedback from pilots and forum information. Coordinate maintenance activities through DT. **Forum Role** Continue improving coordination and maintenance practices and sharing DT experiences.
6	**DT Implementation** Progress towards level 5 DT by continuously updating models. **Forum Role** Continue to collaborate on improving coordination and maintenance practices and sharing DT experiences.

ProRail is currently prepared to enter Phase 2, as the organization is already an active participant in the main railway forums. Additionally, ProRail has developed a comprehensive digitalization roadmap, divided into four strategic steps. For the period 2024-2025, ProRail has defined a detailed plan focusing on seven specific digitalization projects such as the digital design of rail infrastructure and current and complete insight into the condition of assets, among others.

5.2.5 Possible Impact of the DCF

In the following subsections, the impact of the cooperative approach is analysed by component:

EU Railway Entity

This part of the approach aims to centralize coordination and standardization efforts and provide a neutral mediator to resolve cross-border disputes. By harmonizing standards and practices, it could reduce inconsistencies and improve the overall efficiency and reliability of cross-border railway operations. As the EU Railway Entity is implemented, the main changes within the Dutch system would include the change of prioritization of maintenance and infrastructure projects, enhanced resource management and allocation and the standardization of regulations and maintenance processes.

However, it is important to remark that under the current provisions of the Proposal on the use of railway infrastructure capacity in the single European Railway Area (document number 52023PC0443), the Network Coordinator and ENIM have limited capabilities. They can only identify regulatory and maintenance practice conflicts and offer recommendations. They lack the authority to enforce these recommendations or act as a mediator, as they do not have authority over the IMs.

Regarding the prioritization of maintenance and infrastructure projects, maintenance operations and infrastructure projects in cross-border sections will be given the same level of importance as the national ones. This will be supported by transparent models developed by the Entity which consider the economic, environmental and social impact of the projects in the involved countries. This new prioritization will help to achieve the EU environmental goals and encourage a single economic area by improving the availability and reliability of the railway system.

This entity will also improve resource management and allocation. This organization will handle the cross-border projects, manage their resources, and facilitate the procedures to improve the flexibility of financial support. This centralized management will ensure better coordination and efficient use of resources across borders. The cross-border DT can also be used as a tool for monitoring projects, however, the entity should ask for authorization from the relevant IMs.

Lastly, the entity will also help with the standardization of regulations and maintenance processes. This entity would reduce and standardize regulations across the EU, ensuring consistent maintenance standards across regions. This standardization will also help to keep a high performance of the system while continuously improving these standards. However, it is important to note that the entity will primarily identify regulatory and maintenance practice conflicts and offer recommendations as previously stated.

EU Railway Forum

This forum would facilitate voluntary data sharing and continuous improvement of maintenance practices among stakeholders. It promotes collaboration without enforcing mandatory compliance, making it a cost-effective and flexible option for enhancing cross-border coordination. As the EU Railway Forum is implemented, one of the main benefits would be the standardization of maintenance processes. This standardization will help to keep a high performance of the system while continuously improving these standards.

Another benefit of participating in the forum is the access to expertise and resources. Members of the EU Railway Forum would gain access to a wider range of expertise and resources. This collective knowledge base would support the implementation of innovative maintenance solutions and the adoption of best practices, ultimately leading to better-maintained infrastructure and improved reliability.

Additionally, the forum can help open the discussion on DT implementation, focusing on how to standardize data formats and share information effectively and securely between countries. This collaboration will support ProRail and other infrastructure managers in their digitalization efforts, ensuring a unified approach across the European railway network.

The forum will also promote sustainable practices. By encouraging the adoption of standardized, efficient maintenance practices, the forum would contribute to the sustainability of the railway network. Improved maintenance processes eventually would lead to reduced resource consumption, lower emissions, and a smaller environmental footprint.

Digital Twin Application

Digital twins are a tool that offers the IMs real-time data visualization and proactive maintenance capabilities. By integrating digital systems, this approach can optimize maintenance schedules and improve decision-making. However, it requires significant initial investment and relies heavily on the availability and the quality of the data. Furthermore, successful implementation relies on the willingness of infrastructure managers to share data across borders, which can pose challenges due to varying data standards and privacy concerns.

ProRail has released its vision on digitalization for 2040, highlighting the challenges and opportunities in infrastructure digitalization. The main objective is to digitalize the railway infrastructure by 2040, which will enable the organization to better manage its resources, increase system capacity, enhance safety and reliability, and make the railway network more sustainable (ProRail, 2023). This forward-looking approach aims to use technological advancements to optimize operations and provide a more efficient and environmentally friendly transportation system.

Within this vision of digitalization, DT technology is a key component that will help achieve these goals. According to ProRail (2023), DT will allow cross-border network optimization and serve as a multi-modal development platform, enabling collaborative decision-making. DT will also act as an asset management platform, providing advanced analytics for condition-based maintenance and allowing for automatic planning and scheduling of maintenance activities. For further details, refer to the digitalization vision of ProRail document, "De visie op digitalisering van ProRail."

However, implementing this solution in ProRail would require a different contract structure, one that provides greater control over monitoring, data management, and maintenance practices, including the timing of maintenance activities.

The introduction of digital twin and condition-based maintenance will improve the monitoring capabilities, leading to better decision-making, reduced maintenance costs, and improved resource allocation. In cross-border sections, the benefits will include condition-based maintenance, which improves the reliability and availability of the railway line and optimizes maintenance schedules, reducing downtime and costs. DT will also enhance resource allocation through the use of virtual or augmented reality to facilitate field inspections and provide remote support, addressing staff shortages.

Data sharing between the relevant stakeholders is essential for optimizing maintenance and scheduling models, and enhanced data sharing through DTs will facilitate more accurate and timely maintenance decisions. Transparent models (covering degradation, socioeconomic, and environmental factors) used in a cross-border DT will be developed by the EU Railway Entity. They aim to improve decision-making and optimize the overall system by ensuring that all parties have a clear understanding of the maintenance needs and the impact of their actions on the entire network.

5.2.6 Coordination between The Netherlands and Germany: Works in Emmerich – Oberhausen

From November 2024 to May 2026, the German infrastructure manager, DB Netz, expects work on the railway line between Emmerich – Oberhausen. During these 80 weeks, DB Netz has planned the construction of a third track between the Zevenaar border and Oberhausen (ProRail, 2022). As seen in Figure 38, this line between Zevenaar and Emmerich is the cross-border railway line that connects the Netherlands and

Germany. Even though the maintenance operations occur in Germany, this affects the Dutch railway system as this line is the end or the beginning of the Betuweroute.

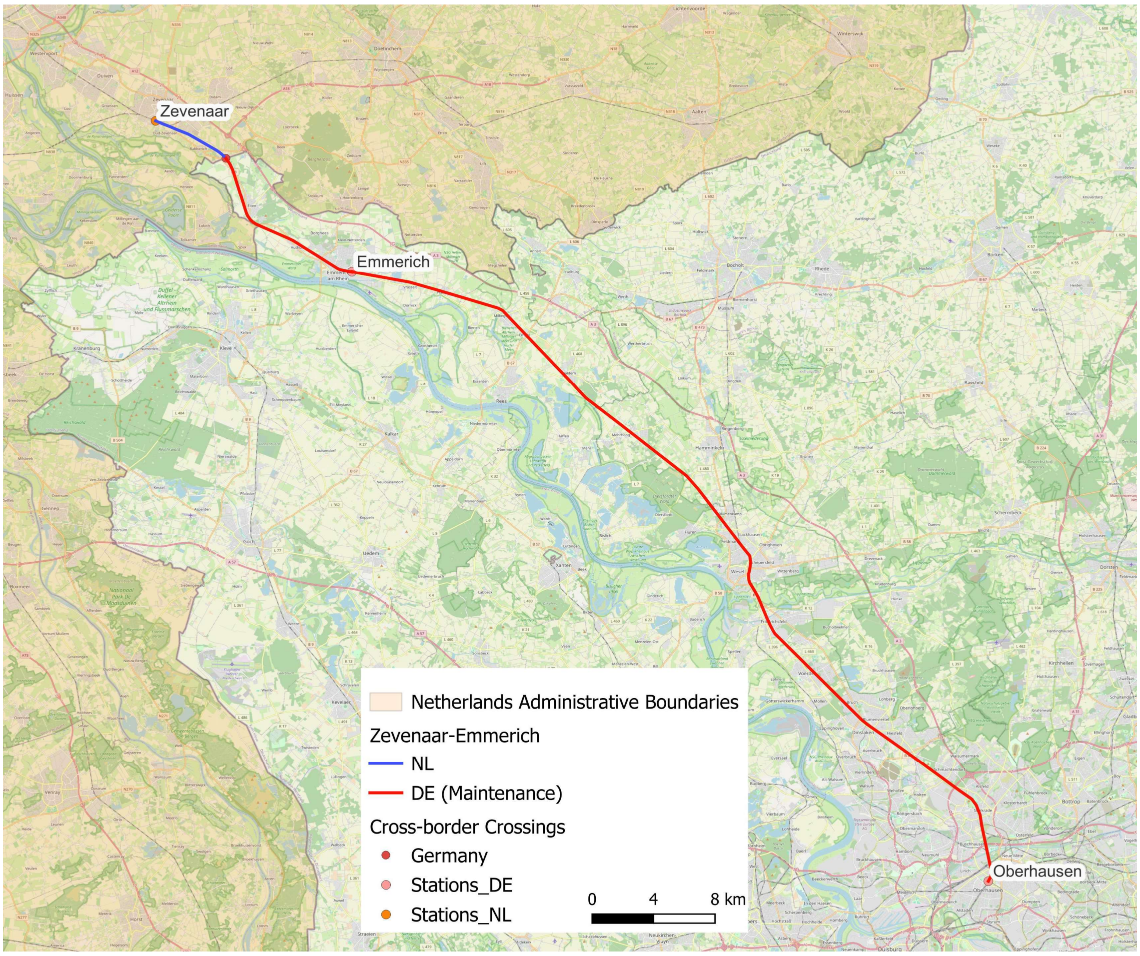


Figure 38. Case study: major maintenance works between the Zevenaar border and Oberhausen

Moreover, this line plays a major role as part of Rail Freight Corridors 1 and 8, enabling the highest freight movement totalling 36.3 million tons in 2023 (ProRail, 2024). By examining this coordination process, the case study can explore how effectively major impact maintenance activities are scheduled and organized, ultimately contributing to the overall understanding of railway maintenance practices and their impact on system performance.

The line has a standard gauge of 1435 mm and is electrified, utilizing 25 kV in the Netherlands and 15 kV in Germany. The signalling system changes from ETCS L2 in The Netherlands to PZB 90 in Germany. The line has a maximum operating speed of 120 km/h in both countries.

This line is part of the Betuweroute in The Netherlands, which is dedicated to freight traffic until Zevenaar. Beyond Zevenaar, the line supports mixed-use traffic. While in Germany, the line is also used for both freight and passenger traffic. Currently, the rail line has three tracks in The Netherlands but only two in Germany. This multi-track expansion is the main reason for the TCR.

According to DB Engineering & Consulting GmbH (2022), the rail works between Zevenaar and Oberhausen consist of:

- Expansion and upgrading of the rail infrastructure through:
    - 46 km construction of a third track adjacent to two existing ones.
    - 22 km construction of three tracks.
    - 3 km construction of a third and fourth track adjacent to two existing ones.
- Upgrades of 12 of the 15 stations on the line.
- Demolition of all 55 level crossings, enabling higher speeds.
- Upgrading/new construction of 47 railroad and road overpasses.
- Expansion of the Emmerich am Rhein electronic interlocking (EI) system.

- Capacity expansion by increasing the number of signal blocks for the sequence of trains.
- Switching of the electrification system: alternating current operation between DE and NL.
- Upgrading of all trackside equipment.

The coordination process between Germany and The Netherlands started in 2021 and it was published in 2022 in the Network Statement of DB Netz and RailNetEurope website. It followed the standard procedure for consultation of major impact TCRs.

The available capacity of the Zevenaar – Emmerich border crossing will therefore be lower until May 2026 as a result of single-track and total closures due to this work (ProRail, 2022). According to the schedule of the project (see Appendix H – Overview of Work for the 3rd Track Emmerich – Oberhausen), both tracks of the line will be closed completely for around 20 weeks (not consecutive). These partial and total restrictions on capacity will have system-wide repercussions such as traffic reallocation, and cancelled services (in both freight and passenger).

Reallocating traffic, especially freight, will significantly impact other routes by increasing congestion where freight and passenger traffic intersect. For example, diverting traffic through Venlo would result in longer waiting times at the border due to increased freight volume. Regarding passenger services, bus services will replace some of the train services (Moi, 2023). Once the works are completed, the number of daily freight trains will increase from 110 to 160 according to Moi (2023). This means almost a 50% increase in capacity in the system.

The coordination of the TCR involving the Betuweroute is a good example of good coordination due to the long-term planning which gave the involved IMs a chance to adjust their maintenance schedule to reduce the impact. This early planning allowed for pilot runs of the closing scenarios, allowing a better understanding of the implications of the closure: identifying bottlenecks, improvement points, or success factors.

Potential Benefits and Limitations of the DCF

The potential benefits and limitations of the DCF according to its components are described below:

EU Railway Entity

Some of the benefits of creating an EU Railway Entity for the case study in Zevenaar-Oberhausen are numerous and impactful. First, the coordination of the project would have been managed by this entity, efficiently clearing conflicts as it would have acted as a neutral mediator. This ensures smoother progress and less friction between the involved countries.

Additionally, the entity could provide financial and project oversight. As this project could have been considered of EU interest, it could access additional funding. Moreover, the entity could act as an auditor, ensuring that the project advances at a good pace and meets the required quality standards.

Furthermore, the creation of such an entity would facilitate knowledge sharing. Challenges and lessons learned from the project could be shared with other members, improving future coordination processes within the EU. This collaborative approach ensures that best practices are disseminated across similar projects, enhancing overall efficiency and effectiveness.

The main limitation is that the Entity proposed in document number 52023PC0443 from the EC lacks authority over the EU IMs, reducing its potential impact on standardization efforts and preventing it from acting as an effective mediator.

EU Railway Forum

One of the main benefits of the creation of an EU Railway Forum for the case study in Zevenaar-Oberhausen is sharing knowledge. In the preliminary phases of the project, the forum would facilitate information about maintenance practices and access to knowledge about similar cases. After the project is done, the forum would facilitate the sharing of challenges and lessons learned from the Zevenaar-Oberhausen project with other members. This exchange of information would improve future coordination processes by providing valuable insights and best practices. Knowledge sharing promotes a collaborative environment where member states can learn from experiences of each other, leading to more effective and efficient maintenance operations.

The main limitation of the EU Railway Forum lies in the implementation challenges. While the forum facilitates information sharing and fosters collaboration among stakeholders, its success heavily depends on the willingness and capability of each IM to implement the agreed-upon strategies and practices. Variations in national regulations, budget constraints, and differing priorities among the IMs can hinder the uniform adoption of forum recommendations. Additionally, the effectiveness of the forum is contingent on the establishment of robust communication channels and the commitment of all parties to actively participate and adhere to the shared guidelines.

Digital Twin Application

The use of digital twins for the case study in Zevenaar-Oberhausen presents several significant benefits. First, the implementation of virtual representation models, particularly 3D models during the construction phase, can greatly reduce clashes and conflicts, thereby enhancing project efficiency and saving costs. These comprehensive visual representations of the infrastructure allow for improved planning, coordination, and early detection of potential issues before they arise on-site.

Additionally, the optimization of the maintenance operations is important as this line is part of an important international freight corridor. Having a real-time monitoring system can significantly enhance maintenance decision-making and network reliability. By providing continuous, real-time data on the condition of the railway infrastructure, digital twins enable condition-based maintenance, ensuring timely and effective interventions. Moreover, the integration of virtual or augmented reality technology facilitates remote support and inspections.

Digital twins also facilitate improved coordination between the Dutch and German sides by offering a unified view of the railway infrastructure. This shared platform ensures that both parties have access to the same data, leading to more synchronized and efficient maintenance operations. Such coordination is crucial for managing cross-border railway projects effectively.

Digital twins can incorporate environmental data, helping in the assessment and mitigation of the environmental impact of maintenance activities. This capability supports the goal of sustainable railway operations and ensures compliance with environmental regulations, promoting a more environmentally responsible approach to railway infrastructure management.

Regarding limitations, the implementation of Digital Twin (DT) technology in the Emmerich–Oberhausen case study faces several significant challenges. Firstly, the high initial investment cost for instrumentation, integration, and training poses a substantial barrier. Setting up structural health monitoring systems requires advanced sensors and data acquisition devices, which are expensive. Additionally, the integration of these systems into both Dutch and German railway networks is a complex process, involving compatibility issues, differing technical standards, and extensive coordination between the two countries. The need for specialized training to ensure that personnel can effectively use and maintain the DT systems further adds to the overall cost and complexity.

Secondly, the effectiveness of DT technology is highly dependent on the availability and quality of data. Accurate models and reliable predictions hinge on continuous access to high-quality, real-time data from various sources. This necessitates standardization of data formats and protocols to ensure seamless data exchange between Dutch and German systems. The EU Railway Entity and the Railway Forum play crucial roles in facilitating this standardization process, promoting data sharing, and establishing best practices. Without consistent and high-quality data, the potential of the DT to enhance maintenance operations and optimize the railway infrastructure will be significantly undermined, limiting its overall impact and effectiveness in the Emmerich–Oberhausen corridor.

Chapter 6. Conclusion

Within this chapter, the conclusions of the thesis, the recommendations for the industry, and future research are presented.

6.1 Conclusions

The aim of this research is **to reduce the impact of maintenance operations on cross-border railway lines**. This is answered through the research questions formulated in Section 1.4.

Research Question 1: What is the current situation regarding cross-border maintenance of the railway lines in the EU?

The European railway system is governed by a combination of national and international laws, with EU regulations promoting international coordination in railway maintenance. This coordination involves bilateral or multilateral agreements or partnerships among the relevant infrastructure managers of different countries. The coordination process for cross-border maintenance operations varies depending on the type of maintenance—preventive or corrective. For corrective maintenance, the process follows the guidelines set out in the Handbook for International Contingency Management Plan. Preventive maintenance, however, requires coordination based on the anticipated impact of the operation; the greater the impact, the earlier the coordination must begin among the relevant stakeholders.

Current practice in cross-border railway asset management often results in complex situations with unique challenges. These challenges are related to the involvement of multiple stakeholders from different countries, conflicting maintenance standards, differences in regulations between countries, among others.

An assessment of cross-border railway maintenance was conducted through a questionnaire gathering expert opinions, which highlighted several key insights. First, the importance of cross-border railway lines is expected to grow in the future. Second, cross-border corrective and preventive railway maintenance were assessed across four criteria: communication and data sharing between IMs, quality of protocols, and overall coordination. Generally, corrective maintenance received higher average ratings than preventive maintenance, except in communication, where both types of maintenance were rated equally (see Figure 14 and Figure 15).

Third, there is a low willingness among IMs to increase data sharing to improve preventive maintenance coordination, with only two out of seven respondents expressing a positive disposition toward this. Finally, the main challenges were identified (see Table 7) and rated. All considered were considered significant, with scores ranging between 5 and 8 (see Figure 16). The most significant challenge is the lack of information or data from the neighbouring country.

Research Question 2: How can the current coordination mechanisms be improved to reduce the impact of cross-border maintenance operations?

Based on the current situation and the main challenges of the cross-border railway sections, a digital-cooperative framework was developed to improve the current coordination mechanisms, reducing the impact of cross-border maintenance operations. This framework has three components that can each be applied independently. However, they also complement each other, tackling all of the cross-border challenges holistically. The EU Railway Entity would serve as a centralized railway network coordinator, supported by the EU railway forum to enhance maintenance operations and standards. Additionally, the integration of Digital Twins as a digital tool would significantly improve decision-making and coordination for cross-border projects.

The three components of the framework were presented as individual solutions in the questionnaire to gather expert opinions on reducing the impact of maintenance in cross-border railway sections. Each solution addresses specific aspects of the cross-border challenges, providing a partial approach to improving maintenance coordination and efficiency across borders. These solutions were evaluated according to different criteria: impact, stakeholder acceptance, implementation complexity, cost and innovation, and future-proofing.

According to the expert opinion, the most important criteria are stakeholder acceptance, and innovation and future-proofing. The European railway forum is regarded as the best-rated solution because it could improve maintenance processes and standards without imposing mandatory compliance, allowing IMs to adopt suggestions that benefit them. Additionally, the implementation and maintenance cost of the forum is the lowest among the three solutions.

Finally, a comprehensive six-phase implementation plan for the DCF was proposed, which integrates existing initiatives to provide a clear and actionable roadmap for the organizations involved. This plan is designed to ensure a structured and coordinated approach, utilizing current efforts while paving the way for future advancements.

Research Question 3: To what extent can a digital and cooperative framework help improve the maintenance operations in cross-border lines?

The digital and cooperative framework, particularly through the implementation of DT technology, can significantly enhance maintenance operations in cross-border railway lines. Such a framework would enable real-time data visualization, predictive maintenance, and advanced analytics, optimizing maintenance schedules and reducing disruptions. By fostering collaboration and data sharing among stakeholders, this approach addresses many of the current challenges, including conflicting regulations and the lack of unified maintenance standards. The use of DTs can also automate maintenance processes and improve decision-making, thereby greatly enhancing the efficiency and reliability of cross-border railway operations.

According to the cost-benefit analysis in Section 4.2, the DCF presented significant benefits that justify its implementation despite the associated costs. The initial setup costs for the EU Railway Entity, digital twin technology, and necessary training are outweighed by the benefits of improved coordination, enhanced data sharing, and increased safety and reliability. The framework promotes efficient maintenance operations, reduces disruptions, and fosters real-time information exchange, leading to substantial cost savings and optimized resource use. Furthermore, it supports the digitalization of infrastructure, contributing to environmental and socioeconomic goals by reducing the carbon footprint and enhancing regional connectivity.

Finally, the game theory analysis in Section 4.3 illustrated the impact of the DCF between two neighbouring countries. The cooperation between the two countries (or a coalition) implied saving time which also meant fewer line closures. Reducing the number of line closures due to TCRs enhances both the availability and reliability of train services, making them more attractive to passengers and freight operators.

6.2 Recommendations for Researchers

Future research should focus on conducting a comprehensive cost analysis of the cooperative approach and its components, including the European Railway Entity, the European Railway Forum, and Digital Twin technology. Furthermore, investigating the long-term socioeconomic and environmental impacts of a fully implemented framework can provide a deeper understanding of its benefits. This includes quantifying the reductions in service disruptions, economic benefits from improved reliability, and the environmental advantages of optimized maintenance practices.

One limitation in this thesis is the simplified treatment of the cost of possession in the game theory analysis, which does not account for the societal and environmental costs of line closures—factors that are crucial yet challenging to quantify. Future research should address this by incorporating these costs into the analysis to provide a more accurate and holistic assessment of the impact of the framework.

Another limitation of this research was the low number of responses to the questionnaire because the data may not accurately represent the diversity of perspectives and experiences of all stakeholders involved in cross-border railway maintenance. Despite the low number of responses, the insights provided by these experts are still highly valuable, given their specialized knowledge and experience. Their input provides critical, high-quality insights that are deeply informed by practical experience, which can be just as valuable as larger quantities of less informed responses. For future research, extending the data collection period would likely increase the number of responses, enhancing the robustness of the thesis.

Additionally, future research should emphasize collaborative efforts and the implementation of pilot testing for new digital twin technologies. Encouraging collaboration between academic institutions and industry stakeholders is crucial to enhancing railway data availability and model accuracy. Such partnerships can use the strengths of both academia and industry, leading to more robust and comprehensive research outcomes.

Implementing pilot tests for new digital twin technologies is essential for gathering user feedback and making necessary adjustments before full-scale deployment. This approach helps mitigate operational disruptions and addresses technical challenges early in the process, ensuring that the technology is well-adapted to real-world conditions and requirements.

Further research is required in developing degradation models, maintenance optimization, and scheduling models. For maintenance optimization and scheduling models, it is essential to account for environmental and socioeconomic factors to understand the implications of line closures. These factors include the potential environmental impact of rerouting and the socioeconomic consequences for users and businesses affected by maintenance activities. Finally, integrating all of these models to create a cohesive and functional digital twin system is crucial for advancing the railway sector.

6.3 Recommendations for the Industry

One of the recommendations is to provide clear mandates and flexible funding for cross-border transportation projects. The European Union should issue directives and allocate funding to encourage cooperation among countries. Providing incentives to railway infrastructure managers will promote the prioritization of international projects and offer flexibility in funding these projects.

Additionally, ENIM and the future network coordinator should aim to define international maintenance standards. Establish and adopt international standards for maintenance operations and data formats to address issues related to data compatibility and interoperability between the railway systems of different countries. Uniform quality of track across the EU will guarantee the availability and safety of the network. Policymakers should strive to harmonize technical and operational standards across EU member states, ensuring consistency and efficiency in cross-border railway maintenance operations.

One of the main limitations of this research is the data availability. Data sharing between stakeholders is essential for the improvement of the planning and coordination of maintenance operations however IMs and maintenance contractors limit the information shared. To address the limitation of data availability, it is recommended that stronger incentives and clearer regulations be established to encourage IMs and maintenance contractors to share data more openly.

Regarding The Netherlands, ProRail must advance its digitalization goals, beginning with defining DT and its parameters and establishing the standards for its national implementation. By doing so, ProRail can be one of the pioneers of the application of DT technology at a European level, setting a benchmark for other countries to follow. This initiative will not only enhance the efficiency and effectiveness of railway maintenance within the Netherlands but also facilitate the integration of DT models across Europe, promoting interoperability and collaboration among European railway infrastructure managers. Another recommendation for ProRail is to adopt a new contract structure that offers enhanced control over monitoring, data management, and maintenance practices. This new structure will help with the transition to condition-based maintenance. Furthermore, it will enable better long-term planning and coordination of maintenance activities, ensuring improved efficiency in managing cross-border railway operations.

Regarding the application of DT, the coordination tool is just a small part of its capabilities. To make digital twins feasible and attractive, more of its capabilities should be exploited: structural health monitoring, diagnostics and prognosis, data visualization, etc. The coordination application is not enough to make it attractive and viable for infrastructure managers however it is essential within its functions. If digital twins are considered unviable or expensive, it is recommended to develop alternative digital frameworks that promote data sharing among infrastructure managers while ensuring data security and privacy measures. Enhanced data sharing will improve maintenance planning and decision-making in cross-border operations.

Another promising area for future research in the subject of digital tools is the application of AI translation technologies. Utilizing AI translation can significantly enhance communication between IMs, particularly in traffic operations. This tool would help to reduce or even eliminate language barriers, encouraging more efficient and effective cross-border collaboration.

Finally, by addressing these recommendations, both researchers and industry professionals can work towards more efficient and coordinated cross-border railway maintenance operations, ultimately enhancing the reliability and sustainability of railway transport across Europe.

Bibliography

#CrossBorderRail. (2024). *Homepage - #CrossBorderRail*. Retrieved March 24, 2024, from #CrossBorderRail Website: https://crossborderrail.trainsforeurope.eu/

Alqatawna, A., Sánchez-Cambronero, S., Gallego, I., & Rivas, A. (2023). BIM-centered high-speed railway line design for full infrastructure lifecycle. *Automation in Construction, 156*, 105114. doi:10.1016/j.autcon.2023.105114

Armijo, A., & Zamora-Sánchez, D. (2024). Integration of Railway Bridge Structural Health Monitoring into the Internet of Things with a Digital Twin: A Case Study. *Sensors, 24*(7), 2115. Retrieved from https://doi.org/10.3390/s24072115

Bhutada, G. (2022, February). *Comparing the carbon footprint of transportation options*. Retrieved from Visual Capitalist: https://www.visualcapitalist.com/comparing-the-carbon-footprint-of-transportation-options/

CBS. (2022, June). *Nearly 7 percent more rail freight transport in 2021*. Retrieved from CBS.nl: https://www.cbs.nl/en-gb/news/2022/22/nearly-7-percent-more-rail-freight-transport-in-2021

CBS. (2024, April). *Goods transport; modes and flows of transport to and from the Netherlands*. Retrieved from CBS.nl: https://opendata.cbs.nl/#/CBS/en/dataset/83101ENG/table?dl=A40F5

CEN. (2017). NEN-EN 13848-5:2017. *Railway applications - Track - Track geometry quality - Part 5: Geometric quality levels - Plain line, switches and crossings*. Brussels: European Committee for Standarization.

Ciccone, A., Di Stasio, S., Asprone, D., Salzano, A., & Nicolella, M. (2022). Application of OpenBIM for the management of existing railway infrastructure: Case study of the Cancello–Benevento Railway line. *Sustainability*. Retrieved from https://doi.org/10.3390/su14042283

DB Engineering & Consulting GmbH. (2022, December 11). *Three-track upgrade Emmerich – Oberhausen*. Retrieved June 10, 2024, from DB E&C. DB Engineering & Consulting Website: https://db-engineering-consulting.com/en/projects/three-track-upgrade-emmerich-oberhausen-2/

Directorate-General for Mobility and Transport. (2023, January). *Connecting Europe by train: 10 EU pilot services to boost cross-border rail*. Retrieved March 11, 2024, from Mobility and Transport: https://transport.ec.europa.eu/news-events/news/connecting-europe-train-10-eu-pilot-services-boost-cross-border-rail-2023-01-31_en

Directorate-General for Mobility and Transport. (2023, September). *Rail Transport: New harmonised EU standards to support cross-border rail*. Retrieved March 11, 2024, from Mobility and Transport: https://transport.ec.europa.eu/news-events/news/rail-transport-new-harmonised-eu-standards-support-cross-border-rail-2023-09-08_en

Directorate-General for Mobility and Transport. (n.d.). *European Network of Rail Regulatory Bodies (ENRRB)*. Retrieved May 29, 24, from European Commission - Mobility and Transport Web Site: https://transport.ec.europa.eu/transport-modes/rail/market/regulatory-bodies/european-network-rail-regulatory-bodies-enrrb_en

Dirnfield Turocy, R. (2022, June). Digital Twins in Railways. Retrieved May 14, 2024, from https://www.researchgate.net/publication/361724633_Digital_Twins_in_Railways

Doubell, G. C., Kruger, K., Basson, A. H., & Conradie, P. (2022). The potential for digital twin applications in railway infrastructure management. In *Lecture notes in mechanical engineering* (pp. 241-249). Retrieved from https://doi.org/10.1007/978-3-030-96794-9_22

European Commission – Directorate General for Mobility and Transport. (2022, July). Rhine Apline: Fifth Work Plan of the European Coordinator. Retrieved from https://transport.ec.europa.eu/document/download/0a1af8c6-a572-495d-9e2a-3019b0f9a285_en?filename=5th_workplan_ralp.pdf

European Commission. (2023, July 11). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of railway infrastructure capacity in the single European railway area, amending Directive 2012/34/EU and repealing Regulation (EU) No 913/2010*. Retrieved from EUR-Lex: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0443

European Commission. (2023, October 10). *Total length of the railway lines in use in the European Union (EU-27) from 1990 to 2021 (in kilometers) [Graph]*. Retrieved April 2024, 2024, from Statista: https://www.statista.com/statistics/451812/length-of-railway-lines-in-use-in-europe-eu-28/

European Commission. (2024, May 30). *About PRIME*. Retrieved from Prime Infrastructure Homepage: https://wikis.ec.europa.eu/display/primeinfrastructure/About+PRIME#AboutPRIME-Subgroups

European Commission. (2024). *TENtec Interactive Map Viewer*. Retrieved from Mobility and Transport: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html

European Commission. (n.d.). *Mobility Stategy*. Retrieved December 6, 2023, from Mobility and Transport: https://transport.ec.europa.eu/transport-themes/mobility-strategy_en

European Commission. (n.d.). *Trans-European Transport Network (TEN-T)*. Retrieved December 10, 2023, from Mobility and Transport: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en

European Commission, Directorate-General for Mobility and Transport. (2021). Long-distance cross-border passenger rail services : final report. Publications Office of the European Union. Retrieved from https://data.europa.eu/doi/10.2832/019365

European Commission: Directorate-General for Mobility and Transport. (2022). *Analysis accompanying the impact assessment for the revision of Regulation (EU) N° 1315/2013 on Union guidelines for the development of the trans-European transport network : executive summary to the final report.* Retrieved March 11, 2024, from Publications Office of the European Union: https://data.europa.eu/doi/10.2832/63968

European Investment Bank. (2023). Cross-border infrastructure projects: The European Investment Bank's role in cross-border infrastructure projects. European Investment Bank. Retrieved from https://www.eib.org/attachments/lucalli/20230107_cross_border_infrastructure_projects_en.pdf

European Parlament. (2024). *2023/0271(COD) : Single European railway area: use of railway infrastructure capacity*. Retrieved July 7, 2024, from Legislative Observatory of the European Parlament Web site: https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2023/0271(COD)&l=en

European Parliament; Council of the European Union. (2010, September 22). *Regulation (EU) No 913/2010 of the European Parliament and of the Council of 22 September 2010 concerning a European rail network for competitive freight.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02010R0913-20140101

European Parliament; Council of the European Union. (2012, December). *DIRECTIVE 2012/34/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 November 2012 stablishing a single European railway area.* Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02012L0034-20190101&qid=1712091202355

European Rail Infrastructure Managers (EIM). (2019, May 20). *PRIME*. Retrieved from EIM Web site: https://eimrail.org/document/prime/

European Union Agency for Railways. (2022). *Cross-border rail transport potential.* Luxembourg: Publications Office of the European Union. doi:10.2821/375922

European Union Agency for Railways. (2023, Febraury 7). *About the Agency*. Retrieved from European Union Agency for Railways Web site: https://www.era.europa.eu/can-we-help-you/faq/289

Eurostat. (2023, November 15). *Rail freight transport slightly down in 2022*. Retrieved March 12, 2024, from Eurostat - News articles: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20231115-2

Forum Train Europe. (n.d.). *Forum Train Europe - Organisation*. Retrieved May 29, 2024, from Forum Train Europe Web site: https://www.forumtraineurope.eu/organisation/forum-train-europe

Galván-Nuñez, S., Alishio, R., & Johnson, C. (2024, March). Digital Twins in Railroad Freight Research: The FAST Vision. *Cyber and Digital Information in Railway Engineering and Operations Workshop*. Maryland, United States of America.

Gamon, W., & Naranjo Gómez, J. M. (2019). Main Problems of Railway Cross-Border Transport Between Poland, Germany and Czech Republic. *Sustainability*, 11. Retrieved from https://doi.org/10.3390/su11184900

Infrabel; ProRail; ACF/CFL; SNCF Réseau; DB Netz AG; SBB Infrastruktur AG; BLS Netz AG; ÖBB Infrastruktur AG; RFI S.p.A; SŽ Infrastruktura. (2023). *Capacity Strategy 2027.* RailNetEurope - Capacity Strategies. Retrieved from https://rne.eu/wp-content/uploads/231215_Common-pilot-Capacity-Strategy-TT-2027_v1.0.pdf

Jeong, D.-Y., Baek, M.-S., Lim, T.-B., Kim, Y.-W., Kim, S.-H., Lee, Y.-T., . . . Lee, I.-B. (2022). Digital Twin: technology evolution stages and implementation layers with technology elements. *IEEE access, 10*, 52609-52620. doi:10.1109/access.2022.3174220

Jere, N., Sušilović, D., Ford-Alexandraki, E., & Xenellis, G. (2024). *Key figures on European transport : 2023 edition.* Luxembourg: Publications Office of the European Union. doi:10.2785/4866

Kaewunruen, S., AbdelHadi, M., Kongpuang, M., Pansuk, W., & Remennikov, A. M. (2022). Digital Twins for managing railway bridge maintenance, resilience, and climate change adaptation. *Sensors, 23*(1), 252. doi:10.3390/s23010252

Klugman, C. (2018, June). A Europe without internal borders? Free movement of persons. European Parliamentary Research Service. Retrieved March 8, 2024, from https://www.europarl.europa.eu/RegData/etudes/BRIE/2018/621815/EPRS_BRI(2018)621815_EN.pdf

Lundgren, A., Löfving, L., & Westin, L. (2023). *Cross-border transport infrastructure planning in the Nordic Region – An introduction.* doi:http://doi.org/10.6027/R2023:3.1403-2503

Marrone, S., De Donato, L., Dirnfeld, R., Somma, A., De Benedictis, A., Flammini, F., . . . Vittorini, V. (2023). Towards AI-assisted digital twins for smart railways: preliminary guideline and reference architecture. *Journal of Reliable Intelligent Environments, 9*(3), 303–317. doi:10.1007/s40860-023-00208-6

Ministerie van Infrastructuur en Waterstaat. (2018, February 23). *Organisation of public transport*. Retrieved from Mobility, Public Transport and Road Safety | Government.nl: https://www.government.nl/topics/mobility-public-transport-and-road-safety/public-transport/organisation-of-public-transport

Moi, J. (2023, December 22). *Betuweroute vanaf eind 2024 ruim anderhalf jaar grotendeels gesloten*. Retrieved May 6, 2024, from fd. Website: https://fd.nl/samenleving/1501303/betuwelijn-eind-volgend-jaar-80-weken-gesloten

Nederlands Normalisatie-instituut. (1999, November). Railway applications - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS):Part 1: Basic requirements. CENELEC.

Nilsson, J.-E., & Nyström, J. (2014). *Mapping railways maintenance contracts – the case of Netherlands, Finland and UK.* VTI. Retrieved April 18, 2024, from https://www.diva-portal.org/smash/get/diva2:771921/FULLTEXT01.pdf

NS. (2022). *Perfomance on mail rail network and the high-speed line*. Retrieved from NS - Anual Report 2022: https://2022.nsannualreport.nl/annual-report-2022/our-activities-and-achievements-in-the-netherlands/performance-on-the-main-rail-network-and-the-highspeed-line/international-connections

Offenbacher, S., Neuhold, J., Veit, P., & Landgraf, M. (2020). Analyzing major track quality indices and introducing a universally applicable TQI. *Applied Sciences, 10*(23), 8490. doi:10.3390/app10238490

OpenRailwayMap. (2024). *OpenRailwayMap*. Retrieved from https://www.openrailwaymap.org/index.php?style=standard&lat=51.58248&lon=15.6501&zoom=3&mobile=0

OpenStreetMap. (n.d.). *OpenStreetMap*. Retrieved April 9, 2024, from OpenStreetMap Web Site: https://www.openstreetmap.org/#map=7/52.117/6.031

PRIME. (n.d.). *2021PRIME Benchmarking report.* Retrieved May 5, 2024, from Prime Infrastructure Homepage: https://wikis.ec.europa.eu/display/primeinfrastructure?preview=/44167372/93979322/PRIME%20External%20Report%202021.pdf

ProRail - Capacity Management. (2022). *Timetable Redesign: Capacity Strategy 2026 Netherlands.* Retrieved April 15, 2024, from https://www.prorail.nl/siteassets/homepage/samenwerken/vervoerders/documenten/ttr-capacity-strategy-timetable-2026_netherlands-v2.pdf

ProRail - Capacity Management. (2023). *Timetable Redesign: Capacity model 2025 Netherlands.* Retrieved April 14, 2024, from https://www.prorail.nl/siteassets/homepage/samenwerken/vervoerders/documenten/netwerkverklaring-2023/ttr-capacity-model-timetable-2025.pdf

ProRail. (2023, November). *De visie op digitalisering van ProRail: Spoor naar morgen.* Retrieved from ProRail Web site: https://www.prorail.nl/siteassets/homepage/over-ons/ict/prorail-visie-op-digitalisering-1.pdf

ProRail. (2023, December 8). *Network Statement 2025*. Retrieved May 4, 2024, from ProRail Web Site: https://www.prorail.nl/siteassets/homepage/samenwerken/vervoerders/documenten/netwerkverklaring-2025/network-statement-2025---initial-issue-version-8-december-2023.pdf

ProRail. (2024). *Ontwikkeling spoorgoederen in Nederland 2023 vergeleken met 2022.* Retrieved May 5, 2024, from https://www.prorail.nl/siteassets/homepage/over-ons/organisatie/pr-jaarrapport-ontwikkeling-spoorgoederenverkeer-in-nederland-2023_v3.pdf

ProRail. (n.d.). *Aannemers kleinschalig onderhoud*. Retrieved from ProRail - Aannemers: https://www.prorail.nl/samenwerken/leveranciers/aannemers/onderhoudsaannemers

ProRail. (n.d.). *Onze klanten*. Retrieved April 15, 2024, from ProRail - Vervoerders: https://www.prorail.nl/samenwerken/vervoerders/onze-klanten

ProRail. (n.d.). *Overzicht werkzaamheden ten behoeve van Derde spoor Emmerich – Oberhausen 2024.* Retrieved May 6, 2024, from Informatiepakket werkzaamheden Duitsland Website: https://www.prorail.nl/siteassets/homepage/projecten/zevenaar-oberhausen/pr_overzichtkalender-werkzhdn-2024-derde-spoor-duitsland_web.pdf

RailNetEurope. (2021, April 16). Handbook for International Contingency Management. Viena. Retrieved from https://rne.eu/wp-content/uploads/2022/10/ICM_Handbook.pdf

RailNetEurope. (2022). *TCR - Guidelines.* Retrieved February 2024, from RailNetEurope Web site: https://rne.eu/wp-content/uploads/2022/10/TCR-Guidelines.pdf

RailNetEurope. (2023). *RFC Network*. Retrieved from RailNetEurope: https://rne.eu/corridor-management/rfc-network/

RailNetEurope. (2023, November 23). *Role of network coordinator in view of proposed set-up of "European rail international capacity allocation body"*. Retrieved May 30, 2024, from RailNetEurope - News Web site: https://rne.eu/role-of-network-coordinator-in-view-of-proposed-set-up-of-european-rail-international-capacity-allocation-body/

RailNetEurope. (2024, January 10). *Launch of Preparations for Implementation of Draft Regulation on Use of Rail Infrastructure Capacity*. Retrieved from RailNetEurope - News Web site: https://rne.eu/launch-of-preparations-for-implementation-of-draft-regulation-on-use-of-rail-infrastructure-capacity/

RailNetEurope. (n.d.). *Incident Management*. Retrieved April 4, 2024, from RailNetEurope: Traffic Operations: https://rne.eu/traffic-management/incident-management/

RailNetEurope. (n.d.). *RNE Approach and Structure*. Retrieved May 29, 2024, from RailNetEurope Web site: https://rne.eu/organisation/rne-approach-structure/

RailNetEurope. (n.d.). *Temporary Capacity Restrictions tool*. Retrieved April 8, 2024, from RailNetEurope Website: https://rne.eu/it/rne-applications/tcr-tool/

Ryan, J., & Wretstrand, A. (2020). Improving Coherence in a Cross-Border Public Transport System: Lessons from the Greater Copenhagen Region. *Sustainability*. doi:https://doi.org/10.3390/su12156208

Sahilbhutada. (2023, May 28). *Case Studies and Real-World Examples of Digital Twin Implementation*. Retrieved from Medium Website: https://medium.com/@sahilbhutada28/case-studies-and-real-world-examples-of-digital-twin-implementation-fa650eed06c0

Spanevello, T. (2021, July 1). *Digital twins: Accelerating the digital transformation in the rail sector*. Retrieved May 31, 2024, from Global Railway Review: https://www.globalrailwayreview.com/article/120887/digital-twins-rail/

Statista. (2023, August 24). *Market share of rail freight companies the Netherlands 2017*. Retrieved from Statista- Rail Transport: https://www.statista.com/statistics/1043680/market-share-of-rail-freight-companies-the-netherlands/

The European Parliament And The Council Of The European Union. (2013, December). Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU. Official Journal of the European Union. Retrieved March 24, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013R1315

The European Parliament And The Council Of The European Union. (2016, May). DIRECTIVE (EU) 2016/797 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the interoperability of the rail system within the European Union. Official Journal of the European Union . Retrieved March 24, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016L0797

Thelen, A., Zhang, X., Fink, O., Lu, Y., Ghosh, S., Youn, B. D., . . . Hu, Z. (2022). A comprehensive review of digital twin — part 1: modeling and twinning enabling technologies. *Structural and Multidisciplinary Optimization*. Retrieved from https://doi.org/10.1007/s00158-022-03425-4

United Nations. (n.d.). *Goal 11 - Target and Indicators*. Retrieved February 24, 2024, from United Nations - SDGS Web Site: https://sdgs.un.org/goals/goal11#targets_and_indicators

United Nations. (n.d.). *Goal 9 - Target and Indicators*. Retrieved December 20, 2023, from United Nations - Department of Economic and Social Affairs: https://sdgs.un.org/goals/goal9#targets_and_indicators

Vieira, J., Clara, J., Patrício, H., Almeida, N., & Poças Martins, J. (2022). Digital Twins in Asset Management: Potential application use cases in rail and road infrastructures. In *Lecture notes in mechanical engineering* (pp. 250–260).

Yan, B., Yang, F., Qiu, S., Wang, J., Cai, B., Wang, S., . . . Hu, W. (2023). Digital twin in transportation infrastructure management: a systematic review. *Intelligent Transportation Infrastructure, 2*. Retrieved from https://doi.org/10.1093/iti/liad024

Appendix

Appendix A – Map of the Rail Freight Corridors

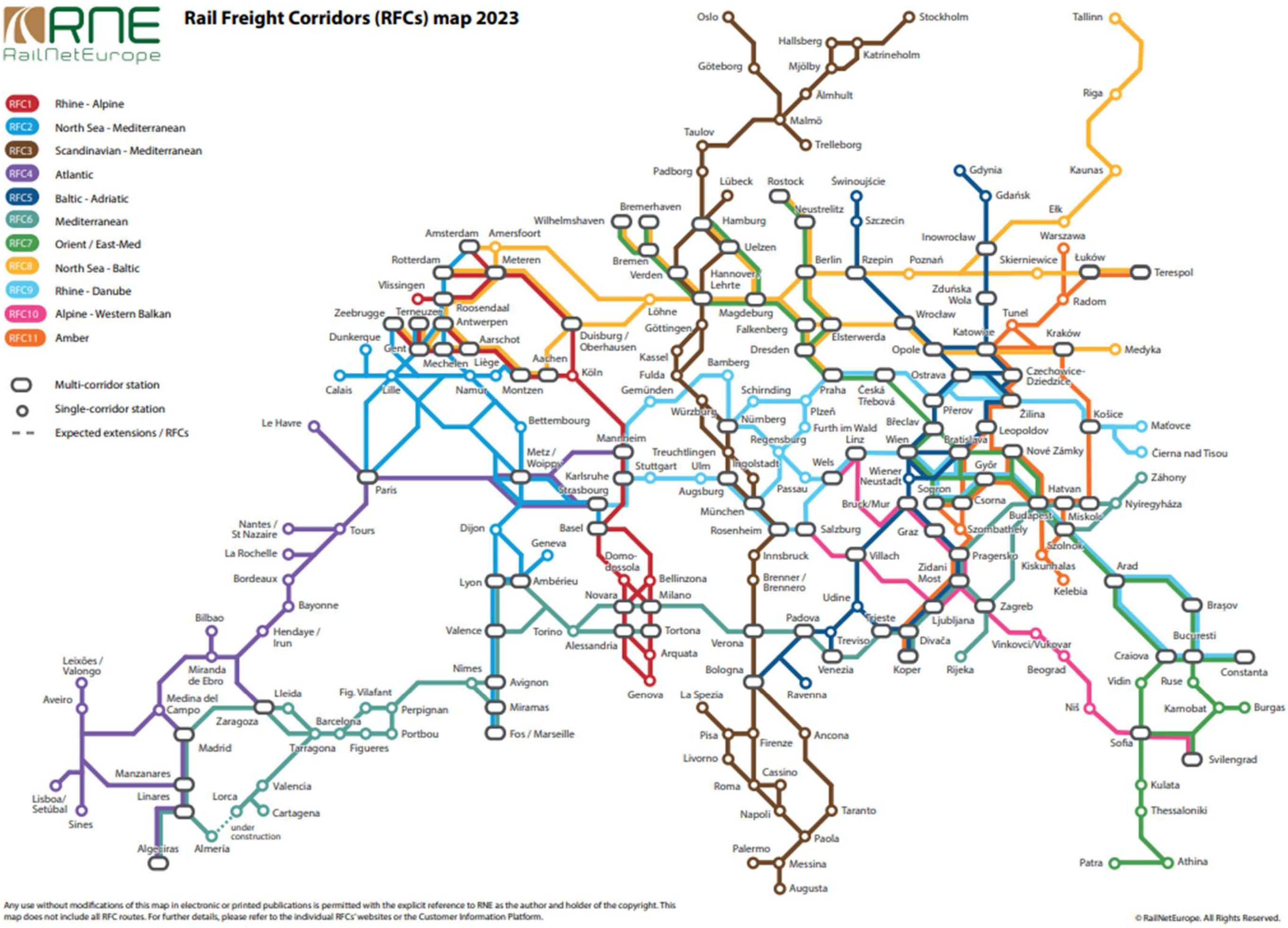


Figure 39. Rail Freight Corridors (source: RailNetEurope, 2023)

Appendix B – ICM Process Map

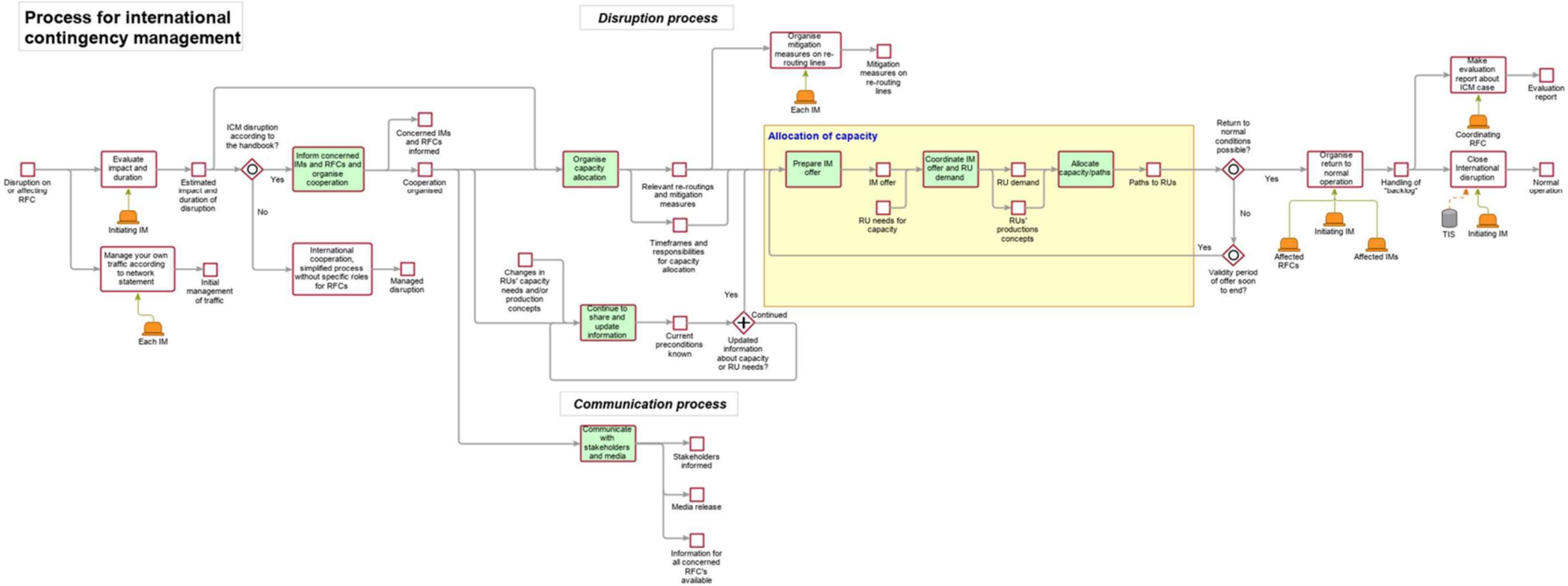


Figure 40. ICM overall process map (source: RailNetEurope, 2021)

Appendix C – Communication Process Map

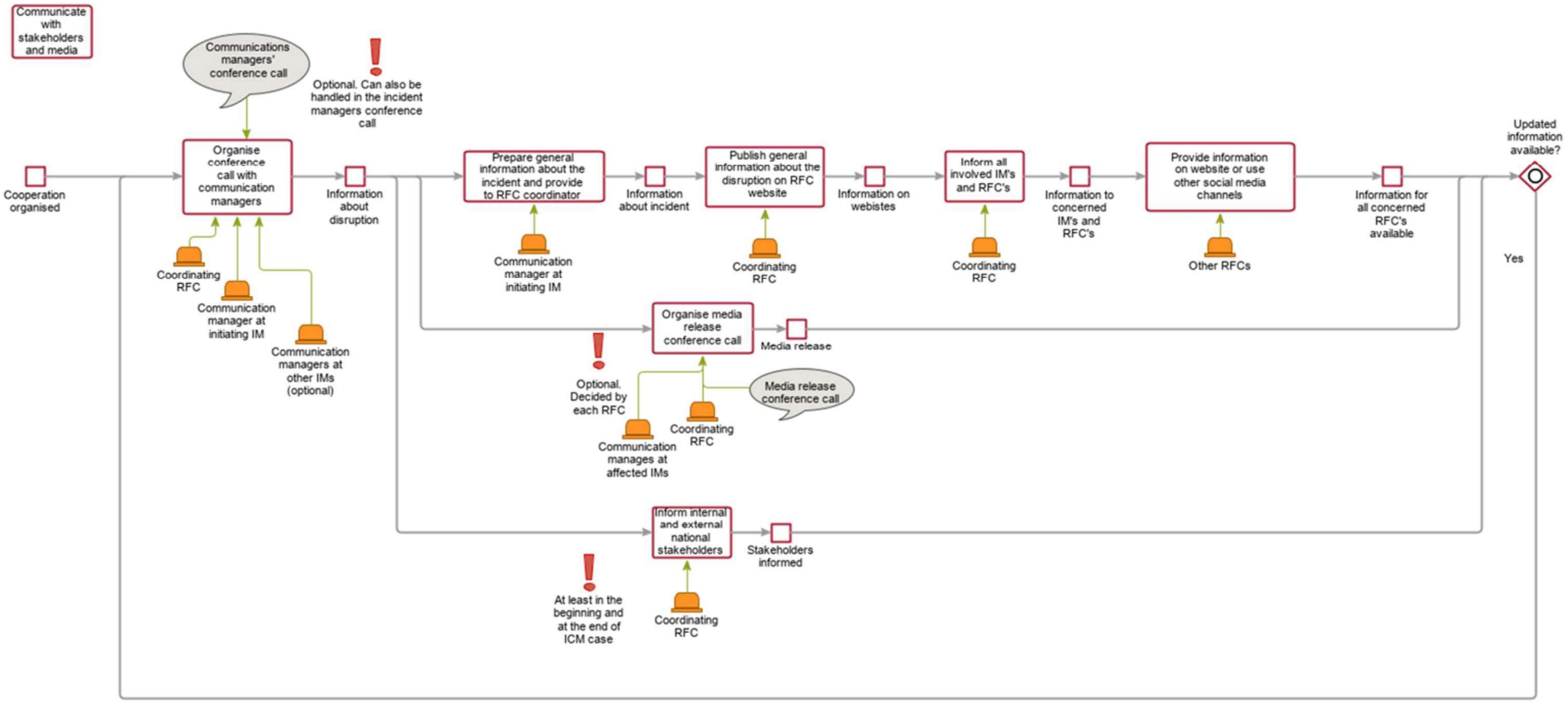


Figure 41. ICM communication process map (source: RailNetEurope, 2021)

Appendix D – Rating of Challenges of Cross-border Maintenance Operations

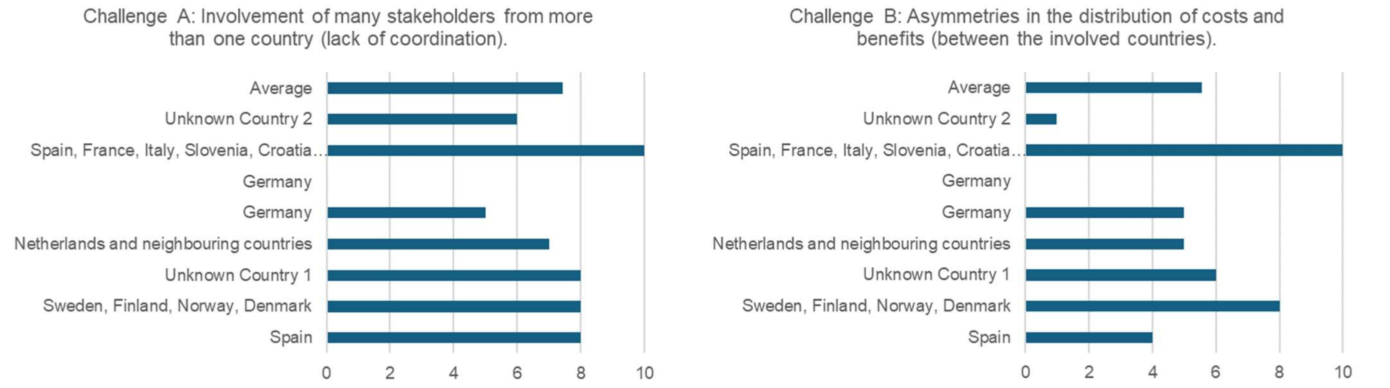


Figure 42. Rating of challenges A and B

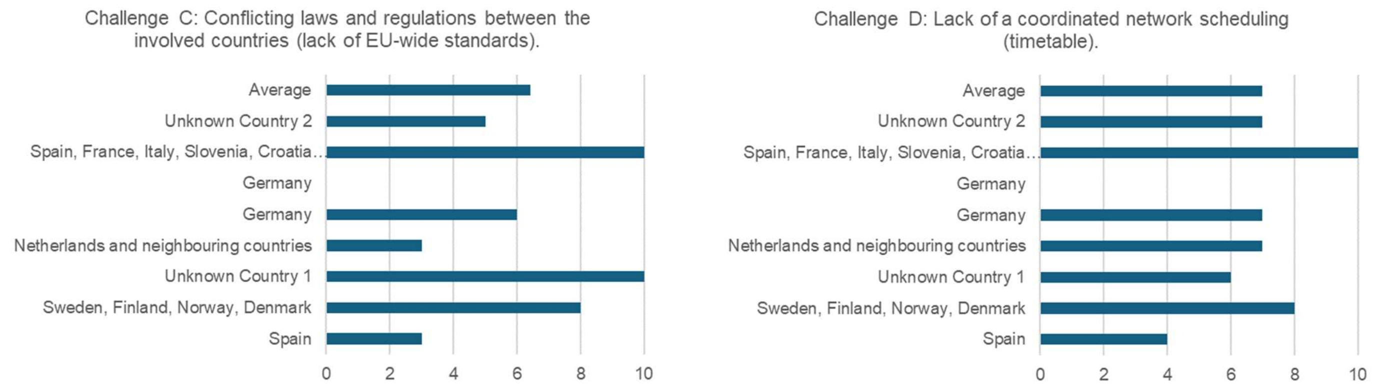


Figure 43. Rating of challenges C and D

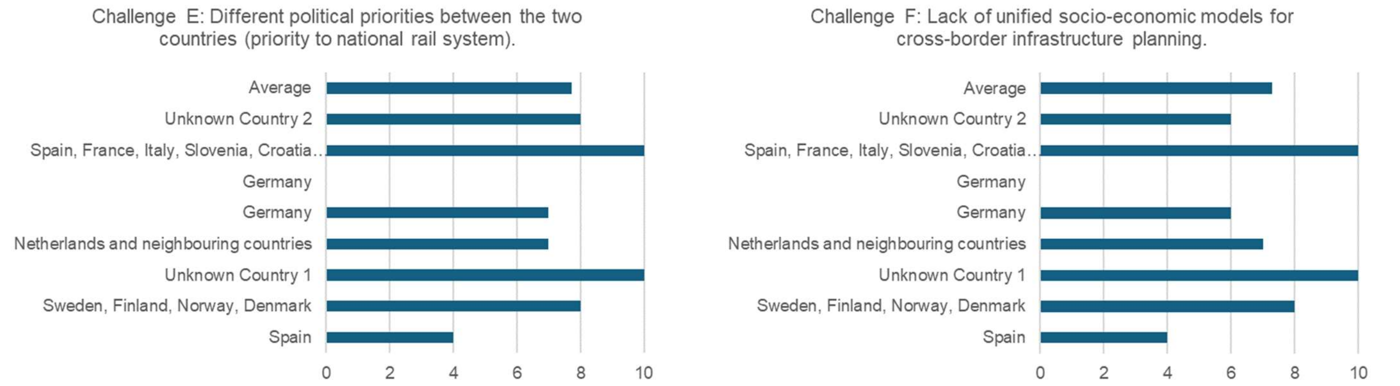


Figure 44. Rating of challenges E and F

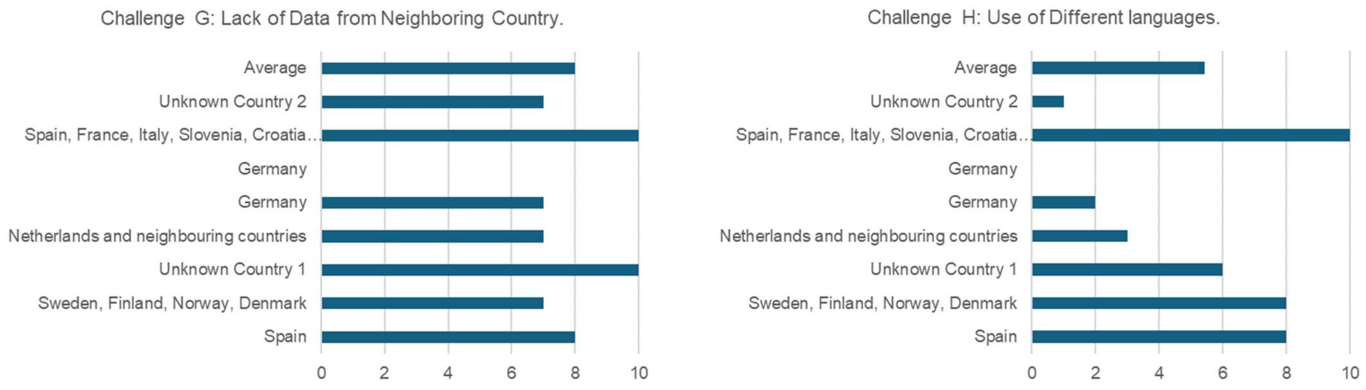


Figure 45. Rating of challenges G and H

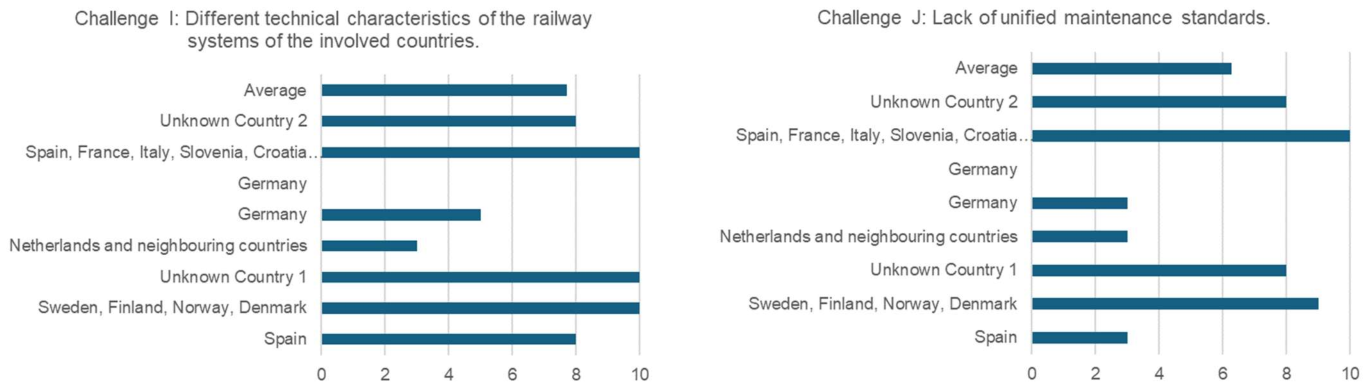


Figure 46. Rating of challenges I and J

Appendix E – Shared Track Degradation Model

A cooperative approach could be exemplified by employing a shared degradation model to coordinate maintenance operations. The decision to perform maintenance is supported by degradation models specific to railway components.

In Scenario B, both countries must perform maintenance operations to maintain the railway system in optimal condition. The following considerations apply to this simplified model:

- The data used to create this scenario is synthetic and based on actual data on the Dutch railway network.
- The degradation model of the track is going to be linear. Also, the same degradation model will be the same after applying the maintenance operation.
- The expert system will follow the EN-13848-6 only measuring the performance according to the standard deviation of the longitudinal level. However, other track characteristics should be monitored in parallel to determine if maintenance is applied to maintain the safety of the system.
- The EN-13848-6 is chosen as it provides a European standard rather than regulations specific to any single country, ensuring a comprehensive view of the railway system. It is important to mention that if the involved IMs have stricter regulations regarding the performance of the railway system, those regulations should be complied with at all times.
- This system will follow the rule that if the standard deviation surpasses a certain threshold (defined by EN-13848-6), maintenance will be applied to the system for the system to remain safe. This threshold should be defined by the relevant IMs as it would become the criteria for when to perform maintenance operations.
- Maintenance leads to a consistent improvement in performance, quantified by a reduction in the standard deviation of the longitudinal level. Different levels of maintenance are applied based on the country and specific needs.
- The planning horizon for the model will be set at three years, aligning with the coordination process for medium, high, and major TCRs, which begins at least two years in advance.
- The model does not consider clustering with other maintenance operations.
- The model assumes that both involved countries are willing to share sufficient data for the required analysis and adhere to the same maintenance standards.

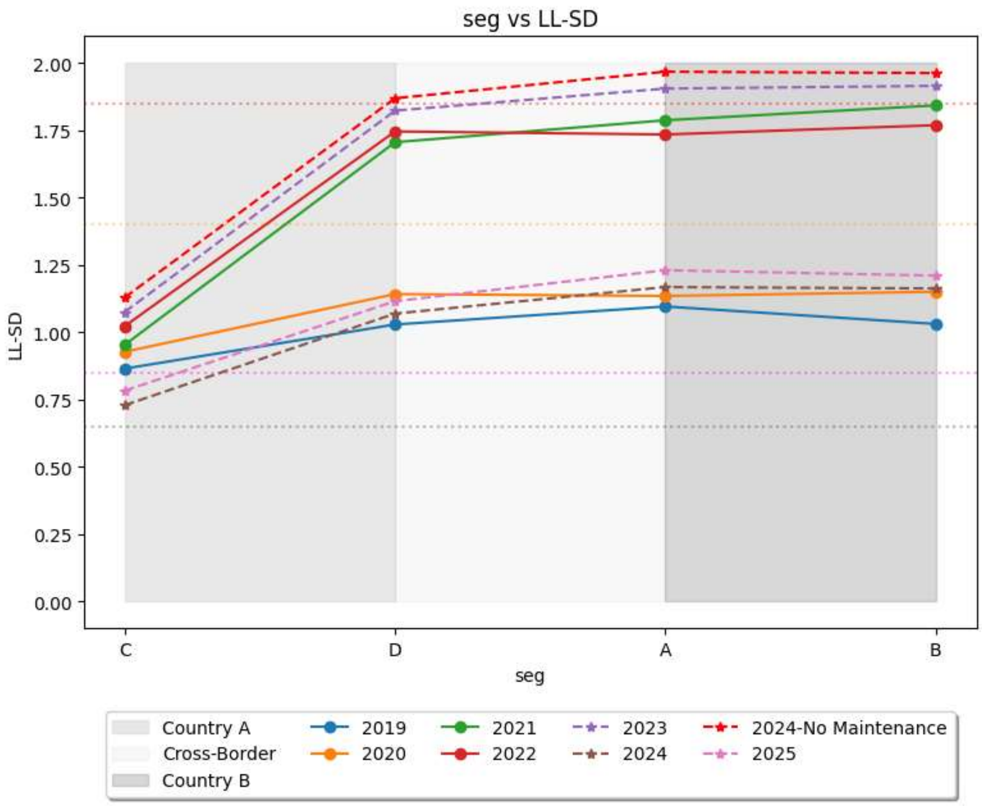


Figure 47. The standard deviation of the longitudinal level of different track segments in two bordering countries

As seen in Figure 47, the track quality reached the D level (according to EN-13848-6) in segment D in 2022, meaning it is approaching a critical condition. By 2023, the track quality would have deteriorated further to the E level, which is at the intervention limit, necessitating immediate maintenance. So as indicated in scenario B both countries performed maintenance in the first year, which generates the need for coordination between the relevant stakeholders to minimise the disruption within the railway system.

The dashed red line in Figure 47 illustrates a hypothetical scenario where no maintenance is conducted in 2024. It shows that the LL-SD values continue to increase, indicating further deterioration of track quality, which would lead to more severe consequences in the following years.

Finally, Figure 47 demonstrates the critical importance of maintenance operations to prevent further deterioration of the railway track. It highlights that coordinated maintenance efforts between the countries, especially in cross-border sections, are essential to maintaining the safety and reliability of the railway system. By using such a cooperative model, the optimization and coordination of maintenance can be significantly improved, ensuring the railway system remains in good condition through effective maintenance operations.

Appendix F – Numerical Example of a Coalition Game

A numerical example is presented to illustrate the coalition game model. It will follow the next conditions:

- For simplicity, one kilometre of track on each side of the border is going to be studied. The possession time will be one month on each side of the border.
- The maintenance cost and revenue on the TAC are based on the 2021 PRIME Benchmarking report (PRIME, n.d.). The values used are the average of the EU.
- The cost of maintenance and renewal is on average €88 000 per main track-kilometre per year.
- The possession cost is simplified to the revenue loss from the TAC due to the line closure. On average, the possession cost amounts to €60,000 per main track-kilometre annually.
- The $C_{Possession\_AB}$ is going to be simplified as the cost of only closing the line one time, which represents the positive impact of effective coordination between the two countries.

The value functions for each coalition are:

$v(\emptyset) = 0$

$v(\{A\}) = -C_A = \frac{-88\ 0000}{12} + (\frac{-60\ 000}{12} * 2) = -17\ 333.33$

$v(\{B\}) = -C_B = -17\ 333.33$

$v(\{A,B\}) = v(\{B,A\}) = -C_{AB} = (\frac{-88\ 0000}{12} * 2) + \frac{-60\ 000}{12} = -19\ 666.66$

Marginal Contribution of Country A

$$v(\{A\}) - v(\emptyset) = -C_A - 0 = -17\ 333.33$$

$$v(\{A,B\}) - v(\{B\}) = -C_{AB} + C_B = -2\ 333.33$$

$$\phi_A = \frac{1}{2}[-17\ 333.33 + (-2\ 333.33)]$$

$$\phi_A = \frac{1}{2}[-C_A + (-C_{AB} + C_B)]$$

$$\boldsymbol{\phi_A = -\ 9\ 833.33}$$

The average marginal contribution for Country A is **€ 9 833.33**

Marginal Contribution of Country B

$$v(\{B\}) - v(\emptyset) = -C_B - 0 = -17\ 333.33$$

$$v(\{A,B\}) - v(\{A\}) = -C_{AB} + C_A = -2\ 333.33$$

$$\phi_B = \frac{1}{2}[-C_B + (-C_{AB} + C_A)]$$

$$\phi_B = \frac{1}{2}[-17\ 333.33 + (-2\ 333.33)]$$

$$\boldsymbol{\phi_B = -\ 9\ 833.33}$$

The average marginal contribution for Country B is **€ 9 833.33**

Coalition vs No coalition

The total cost of maintenance for the coalition is **€19 666.66**, while the cost of maintenance for both countries operating independently is **€24 666.66** due to the additional line closure. This simple exercise demonstrates the benefits of cooperation: both countries achieve cost savings, and the Shapley value ensures a fair distribution of these savings. It is important to note that this calculation excludes the environmental and socioeconomic impacts on users due to the line closure.

Appendix G – Rail Freight Corridors in The Netherlands

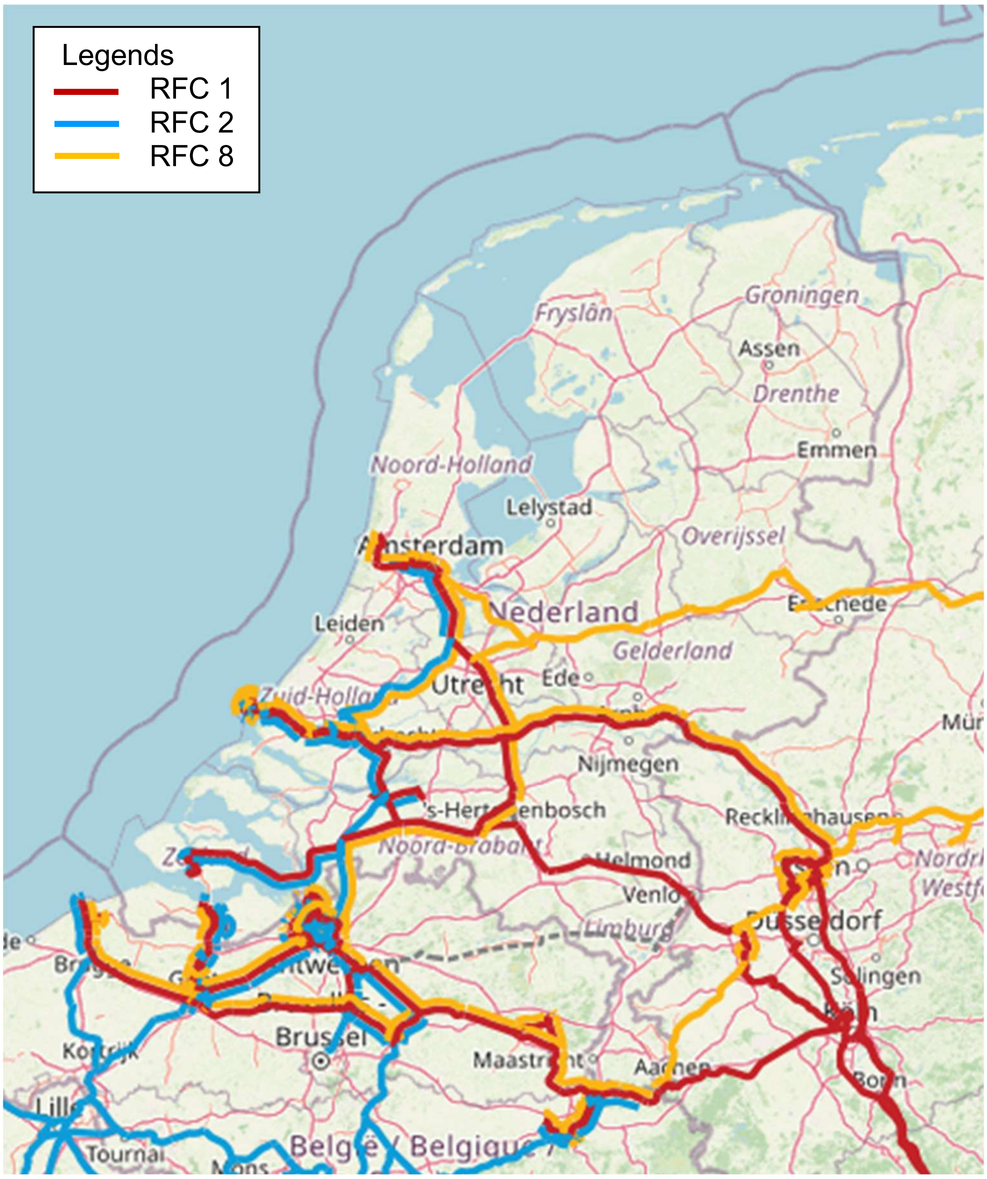


Figure 48. Rail freight corridors in The Netherlands (source: European Commission, 2024)

Corridor	Main route of the international freight corridor	Main route in the Netherlands
Rhine – Alpine	Zeebrugge – Antwerp / Terneuzen / Amsterdam / Vlissingen / Rotterdam – Duisburg – [Basel] – Milan – Genoa	Maasvlakte – Kijfhoek / Amsterdam Westhaven / Amsterdam Houtrakpolder / Vlissingen Sloe > Meteren – Zevenaar (border)
North Sea – Mediterranean	Dunkirk / Rijsel / Liege / Paris / Amsterdam – Rotterdam – Terneuzen / Zeebrugge / Antwerp – Luxembourg – Metz – Dijon – Lyon / Basel – Marseille	Maasvlakte/Amsterdam – Kijfhoek – Roosendaal (border)
North Sea – Baltic	Wilhelmshaven / Bremerhaven / Hamburg / Amsterdam / Rotterdam / Ghent / Antwerp – Aachen / Prague / Berlin – Warsaw – Terespol (Polish – Belarusian border) / Kaunas – Riga - Tallinn	Maasvlakte – Kijfhoek – Meteren – Zevenaar (border) Amsterdam Westhaven / Amsterdam Houtrakpolder > Amersfoort – Oldenzaal (border) Roosendaal (border) – ’s Hertogenbosch – Utrecht – Amersfoort – Oldenzaal (border).

Figure 49. International freight corridors in The Netherlands (source: ProRail, 2023)

Appendix H – Overview of Work for the 3rd Track Emmerich – Oberhausen

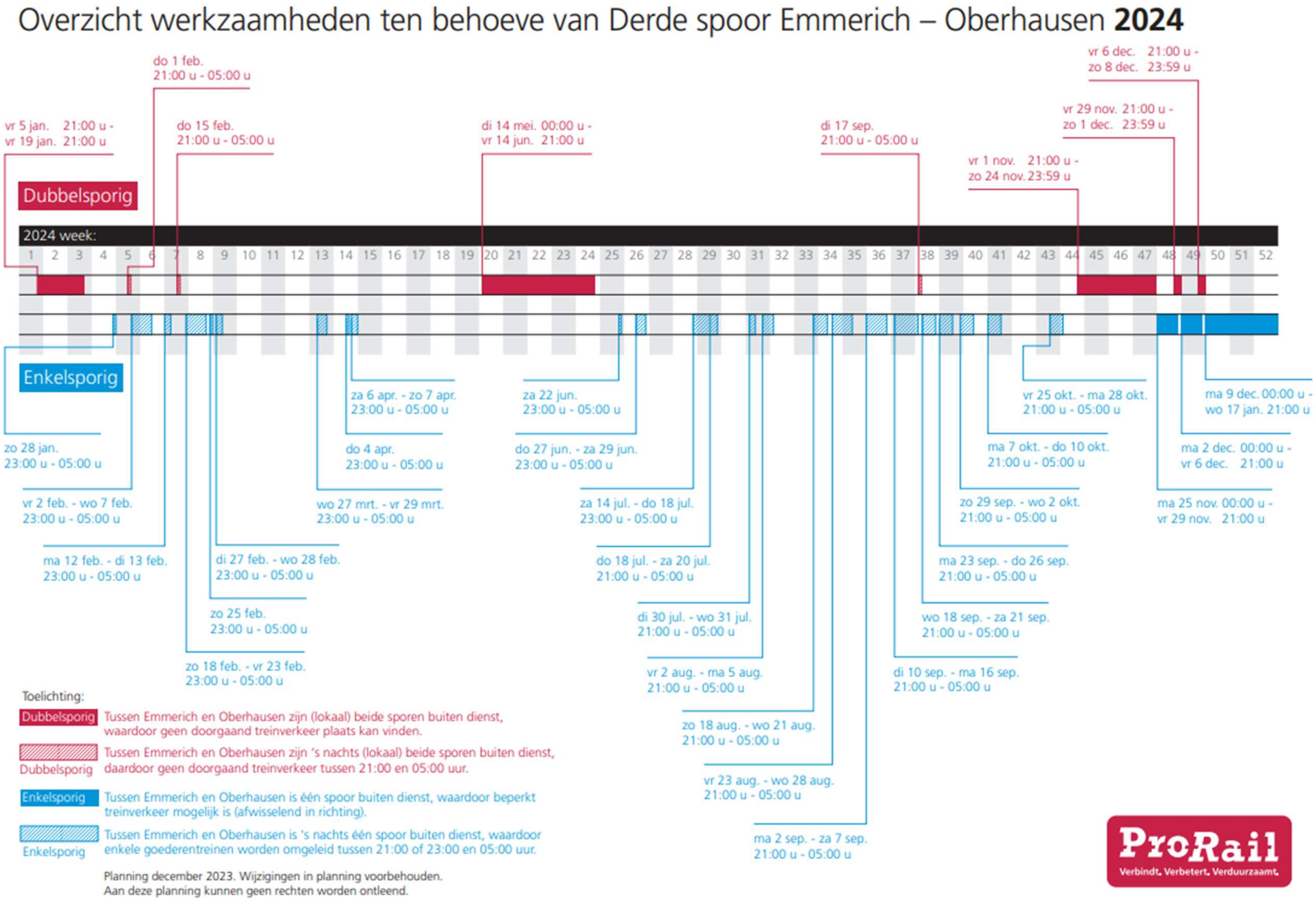


Figure 50. Overview of work for the 3rd track Emmerich – Oberhausen 2024 (Source: ProRail, n.d.)

Appendix I – Questionnaire about Cross-border Maintenance Operations

Cross-Border Maintenance Operations in Railway

My name is Jose Stradi. I am a second-year master's student in civil engineering, specializing in Traffic and Transportation Engineering, at Delft University of Technology in The Netherlands.

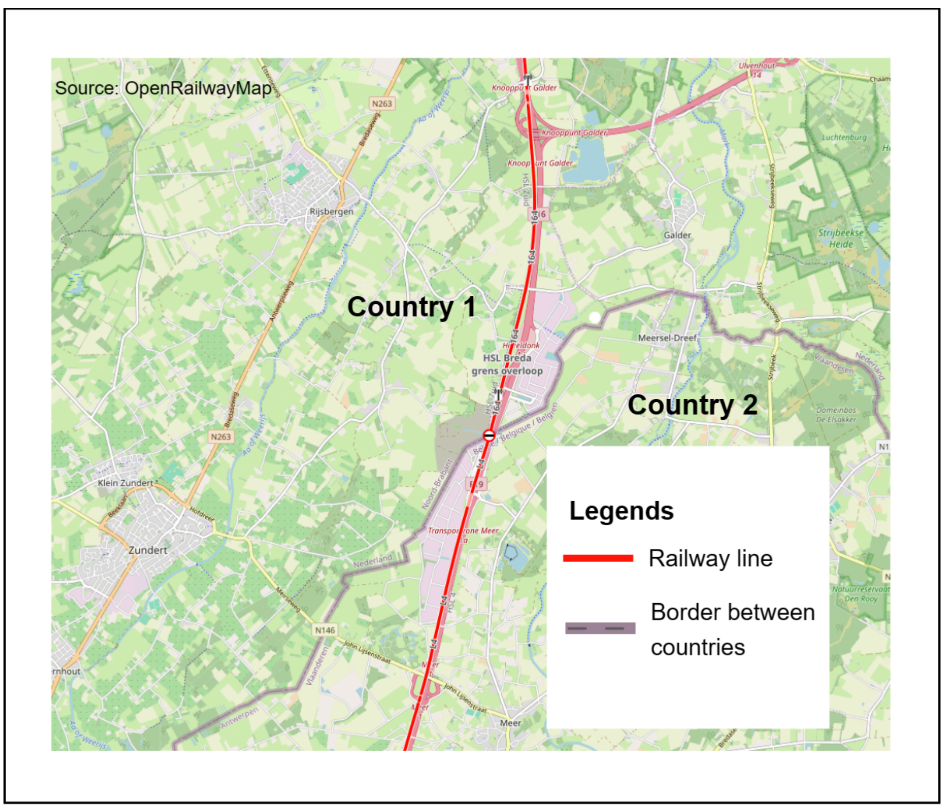
I am investigating cross-border railway maintenance operations in the European Union (EU). The goal is to assess existing coordination practices to mitigate disruptions caused by cross-border maintenance operations and identify challenges and opportunities for improving the coordination of these operations.

In cooperation with colleagues from the IAM4RAIL project, we developed a questionnaire that can be answered in about 15 minutes.

The answers will be analyzed and included in a public report and my thesis. Participation in this study is entirely voluntary, and you can withdraw at any time. You are free to omit any of the questions. To the best of our abilities, your answers in this study will remain confidential. To minimize any potential risks, we will maintain your anonymity, which means no personal information will be collected. All data will be securely stored in a server from TU Delft.

DEFINITION: Railway Cross-Border Sections

A cross-border section is defined as a segment of railway infrastructure that connects two different countries. The next figure shows an example of a cross-border section between The Netherlands (Country 1) and Belgium (Country 2).



Cross-Border Sections in your Country

1. Please indicate the country or countries to which your answers will be related.

2. What is the importance of the railway cross-border lines in your selected country?

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely important

3. Do you think their importance will increase in the near future? Explain briefly why.

4. In your selected country, how would you rate the availability and performance of cross-border railway lines in previous years?

Mark only one oval.

- ◯ Excellent: Cross-border lines have consistently performed well and are readily available.
- ◯ Good: Cross-border lines are generally reliable, but there have been occasional issues.
- ◯ Fair: Cross-border lines face challenges, but they are still operational.
- ◯ Poor: Cross-border lines have significant availability or performance issues.
- ◯ Not Sure / No Opinion

5. How has the availability of railway cross-border lines been in previous years in your selected country? Is this performance similar to regular lines?

6. What sort of agreements are in place for the management of railway cross-border lines in your selected country?

Mark only one oval.

- Standard EU protocol (same agreement for all countries)
- Multilateral agreements between the involved countries
- Other: ____________________

DEFINITION: Maintenance

According to the EN50126:

Maintenance: The combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function.

Preventive Maintenance: The maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.

Corrective Maintenance: The maintenance carried out after fault recognition and intended to put a product into a state in which it can perform a required function.

Preventive Maintenance

According to the EN50126, it is the maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.

7. Who are the key stakeholders involved in preventive maintenance operations for cross-border railway lines in your selected country?

   Please select one or more options:

Check all that apply.

- [ ] Railway infrastrucutre managers
- [ ] Rail freight corridors
- [ ] Railway undertakers
- [ ] Maintenance contractors
- [ ] Other: ____________________

8. If you added "Other (s)" key stakeholders. Please describe briefly the main function(s) that these stakeholders perform.

____

____

____

____

____

9. What are the three main challenges that preventive maintenance faces in cross-border sections in your country? Please give a brief explanation with an example (if possible).

10. How would you rate the following aspects when evaluating the preventive railway maintenance operations in cross-border lines in your country? Rate from **1** (bad) to **10** (excellent).

Mark only one oval per row.

	1	2	3	4	5	6	7	8	9	10
Comunication between infra managers	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Data sharing between infra managers	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Quality of the current standard protocols for cross-border preventive railway maintenance	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Overall / Global Coordination	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

11. According to the TCRs (temporary capacity restrictions) guidelines from Rail Net Europe (TCR-Guidelines.pdf (rne.eu)), the following information should be available to the relevant stakeholders:
a) Planned days.
b) Time of day, and, as soon as it can be set, the hour of the beginning and the end of the capacity restriction.
c) Section of line affected by the restriction.
d) Where applicable, the capacity of diversionary lines.
e) Criteria for which trains of each type of service should be re-routed with a preliminary allocation of the remaining capacity to the different types of train services to the extent known.

Is this information enough to coordinate the maintenance operations? If not, please add the additional information you consider necessary.

12. As a stakeholder, would you be open to sharing additional data (such as track geometry) to optimize the maintenance operations for cross-border railway lines?

Please select one of the following options:

Mark only one oval.

- Yes, I am willing to share relevant data to improve maintenance efficiency.
- No, I prefer not to share additional data beyond what is currently exchanged.
- Not Sure / No Opinion

Corrective Maintenance

According to the EN50126, it is the maintenance carried out after fault recognition and intended to put a product into a state in which it can perform a required function.

13. Who are the key stakeholders involved in corrective maintenance operations for cross-border railway lines in your selected country?

Please select one or more options:

Check all that apply.

- [ ] Railway infrastrucutre managers
- [ ] Rail freight corridors
- [ ] Railway undertakers
- [ ] Maintenance contractors
- [ ] Other: ____________________

14. If you added "Other (s)" key stakeholders. Please describe briefly the main function(s) that these stakeholders perform.

15. What are the three main challenges that corrective maintenance faces in cross-border sections in your country? Give a brief explanation or an example.

16. How would you rate the following aspects when evaluating the corrective railway maintenance operations in cross-border lines in your country? Rate from **1** (bad) to **10** (excellent).

Mark only one oval per row.

	1	2	3	4	5	6	7	8	9	10
Comunication between infra managers										
Data exchange between infra managers										
Quality of the current standard protocols for cross-border corrective railway maintenance										
Overall / Global Coordination										

Challenges in Railway Cross-Border Maintenance Operations

Railway cross-border maintenance operations encounter various challenges, which can impact rail transportation.

In this section, you will rank the following challenges (shown in the table below) according to their significance level.

	Challenge
A	Involvement of many stakeholders from more than one country (lack of coordination).
B	Asymmetries in the distribution of costs and benefits (between the involved countries).
C	Conflicting laws and regulations between the involved countries (lack of EU-wide standards).
D	Lack of a coordinated network scheduling (timetable).
E	Different political priorities between the two countries (priority to national rail system).
F	Lack of unified socio-economic models for cross-border infrastructure planning (*1).
G	Lack of data or information from the neighbouring country (i.e. stable timetable with the defined TCRs).
H	Use of different languages.
I	Different technical characteristics of the railway systems of the involved countries (*2).
J	Lack of unified maintenance standards.
K	Other:
(*1) Models applied in transport and infrastructure planning are usually developed in a national context to calculate scenarios and impacts within national borders. As such, they are not designed to function in a cross-border context. (*2) For example, various signalling and power systems and various vehicle types.	

Challenges in Railway Cross-Border Maintenance Operations

17. Challenge A: Involvement of many stakeholders from more than one country (lack of coordination).

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

18. Challenge B: Asymmetries in the distribution of costs and benefits (between the involved countries).

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

19. Challenge C: Conflicting laws and regulations between the involved countries (lack of EU-wide standards).

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

20. Challenge D: Lack of coordinated network scheduling (timetable).

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

21. Challenge E: Different political priorities between the two countries (priority to national rail system).

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

22. Challenge F: Lack of unified socio-economic models for cross-border infrastructure planning.

Models applied in transport and infrastructure planning are usually developed in a national context to calculate scenarios and impacts within national borders. As such, they are not designed to function in a cross-border context.

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

23. Challenge G: Lack of data or information from the neighbouring country (i.e. stable timetable with the defined TCRs).

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

24. Challenge H: Use of different languages.

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

25. Challenge I: Different technical characteristics of the railway systems of the involved countries. For example, various signalling and power systems and various vehicle types.

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

26. Challenge J: Lack of unified maintenance standards.

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

27. Challenge H: Other.
If you think there is a challenge that was not part of the previous options, please indicate it below.

____

28. Challenge H: Other.
(Only respond to this if you provided an answer to the previous question.)

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Leas	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Most significant

29. Please provide a brief comment explaining the most and the least significant challenges.

____
____
____
____
____

Solutions for Cross-Border Maintenance Operations

30. Which are the most urgent actions you would suggest to improve the maintenance operations of cross-border lines?

Possible Solutions

This research is exploring three possible solutions for improving the coordination of maintenance operations in cross-border lines.

Solution 1: Create a European entity to manage and resolve cross-border conflicts.

Solution 2: Establish a forum for infrastructure managers to enhance cross-border guidelines/agreements.

Solution 3: Create a new frameworks based on digital applications, transparent models and data sharing to support maintenance decisions in cross-border lines.

Rating Criteria

In the following questions, these solutions will be rated according to the next criteria:
1. Impact: If the solution is implemented to what extent do you expect a (positive) impact on coordination of maintenance operations.

2. Stakeholder acceptance: If the solution is implemented to what would be the level of acceptance and support from relevant stakeholders, including infrastructure managers, railway operators, and regulatory bodies.

3. Implementation complexity: If the solution is implemented to what would be the complexity and ease of implementation for each solution, considering factors such as technological requirements, regulatory compliance, and organizational readiness.

4. **Cost**: Assess the financial implications of implementing each solution. It considers the costs associated with setting up and maintaining the proposed mechanisms.

5. Innovation and future proofing: Assess how innovative and future-ready each solution is, considering its ability to utilize new technologies, adapt to evolving industry trends, and promote ongoing improvement in cross-border maintenance practices.

31. **Solution 1**: Create a European entity to manage and resolve cross-border conflicts.

Rate this solution for improving the coordination of maintenance operations in cross-border lines according to:
1. Impact: From **1** (least impact) to **10** (most impact).
2. Stakeholder acceptance: From **1** (least accepted) to **10** (most accepted).
3. Implementation complexity: From **1** (least feasible) to **10** (most feasible).
4. Cost: From **1** (lowest cost) to **10** (highest cost).
5. Innovation and future proofing: From **1** (least innovative) to **10** (most innovative).

Mark only one oval per row.

	1	2	3	4	5	6	7	8	9	10
Impact										
Stakeholder acceptance										
Implementation complexity										
Cost										
Innovation and future proofing										

32. **Solution 2**: Establish a forum for infrastructure managers to enhance cross-border guidelines/agreements.

Rate this solution for improving the coordination of maintenance operations in cross-border lines according to:
1. Impact: From **1** (least impact) to **10** (most impact).
2. Stakeholder acceptance: From **1** (least accepted) to **10** (most accepted).
3. Implementation complexity: From **1** (least feasible) to **10** (most feasible).
4. Cost: From **1** (lowest cost) to **10** (highest cost).
5. Innovation and future proofing: From **1** (least innovative) to **10** (most innovative).

Mark only one oval per row.

	1	2	3	4	5	6	7	8	9	10
Impact										
Stakeholder acceptance										
Implementation complexity										
Cost										
Innovation and future proofing										

33. **Solution 3:** Create a new frameworks based on digital applications, transparent models and data sharing to support maintenance decisions in cross-border lines.

Rate this solution for improving the coordination of maintenance operations in cross-border lines according to:
1. Impact: From **1** (least impact) to **10** (most impact).
2. Stakeholder acceptance: From **1** (least accepted) to **10** (most accepted).
3. Implementation complexity: From **1** (least feasible) to **10** (most feasible).
4. Cost: From **1** (lowest cost) to **10** (highest cost).
5. Innovation and future proofing: From **1** (least innovative) to **10** (most innovative).

Mark only one oval per row.

	1	2	3	4	5	6	7	8	9	10
Impact	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Stakeholder acceptance	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Implementation complexity	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Cost	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Innovation and future proofing	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

34. Please rate the **importance** of each criterion for evaluating the proposed solutions to improve coordination of maintenance operations in cross-border railway lines.

Use a scale from 1 to 10, where:
1 indicates **least important**.
10 indicates **most important**.

Mark only one oval per row.

	1	2	3	4	5	6	7	8	9	10
Impact	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Stakeholder Acceptance	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Implementation Complexity	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Cost	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
Innovation and Future-Proofing	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

35. Please include here any comments about these three solutions.

Thank you for your time!

I would like to express my sincere gratitude for participating in this questionnaire on cross-border rail maintenance operations. Your insights and expertise have provided me with a deeper understanding of the challenges and opportunities in this field. Thank you once again for your invaluable participation and collaboration.