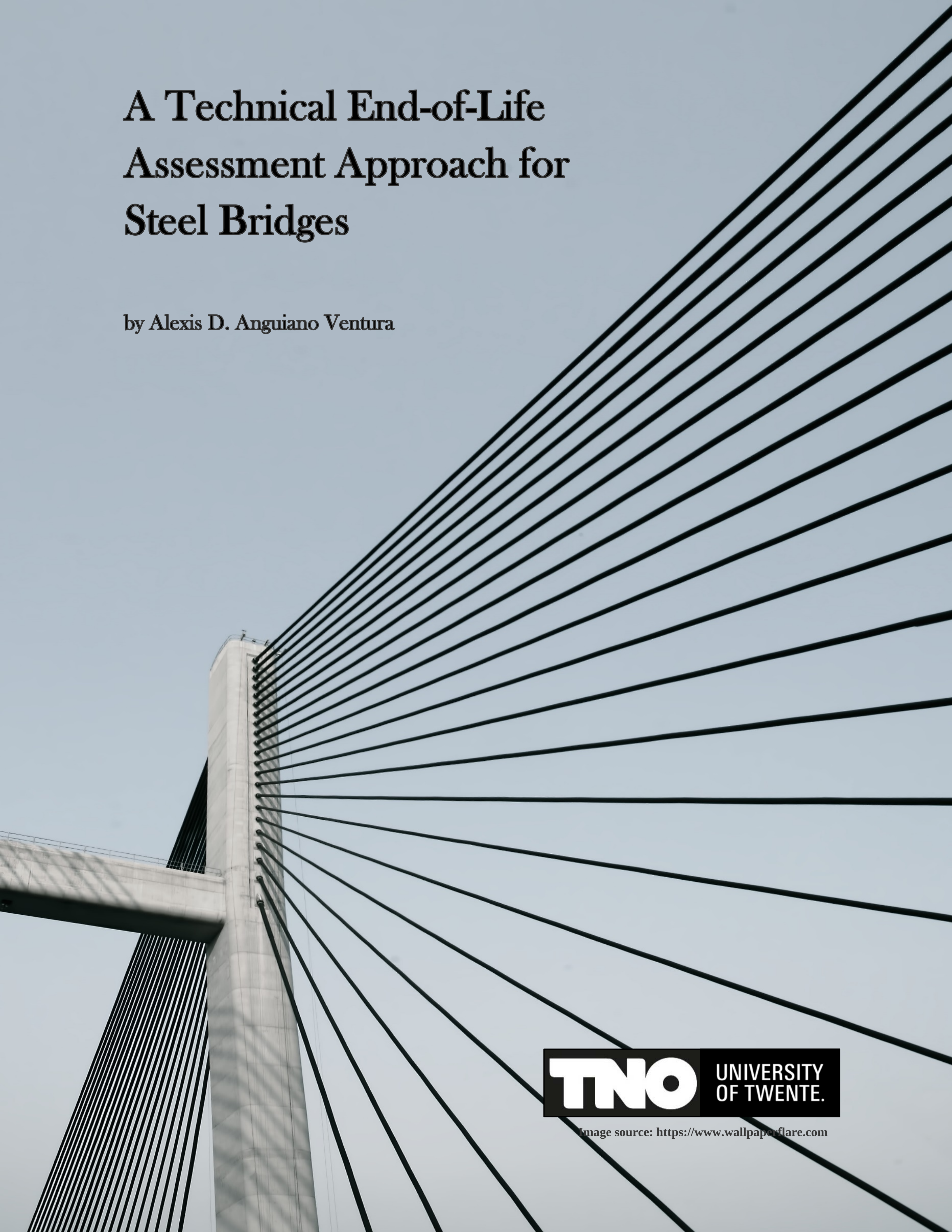
A Technical End-of-Life Assessment Approach for Steel Bridges

by Alexis D. Anguiano Ventura



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UNIVERSITY OF TWENTE.
Construction Management track,
Civil Engineering & Management, University of Twente

TNO

Master's Thesis

A Technical End-of-Life Assessment Approach for Steel Bridges

Author:
Alexis Demetrio Anguiano Ventura

Committee and Supervisors:
Dr. A. Hartmann (Andreas) – University of Twente
Ir. S.C.A. Mooren (Sander) – University of Twente
Dr. Esra Bektas - TNO

Date:
Friday, January 31st, 2025

COLOPHON

FACULTY
Engineer and technology
Civil Engineer and Management

DATE
31-01-2025

VERSION
Version #2

TITLE
A Technical End-of-Life Assessment Approach for Steel Bridges

PROJECT
Master thesis

AUTHOR(S)
Alexis Demetrio Anguiano Ventura

EMAIL
a.d.anguianoventura@student.utwente.nl

POSTAL ADDRESS
P.O. Box 217
7500 AE Enschede

WEBSITE
www.utwente.nl

FILENAME
Anguiano Ventura_MA_Engineering Technology.pdf

PREFACE

This thesis represents the culmination of my journey through the master's program in Civil Engineering and Management at the University of Twente. Reflecting on this journey, I am filled with immense gratitude of the help and guidance that have enabled me to complete this final work. Your support and belief in me have been invaluable, and I hope this work stands as a testament to your contributions.

First and foremost, I would like to express my deepest appreciation to my supervisor from TNO, Dr. Esra Bektas. Her expertise, patience, and constant encouragement guided me through every stage of this research, and her insightful feedback and steady support were essential in shaping the direction and outcome of this thesis. I would also like to extend special thanks to my colleagues and fellow researchers from the Department of Digital Built Environment and Reliable Structures at TNO. The collaborative spirit, cake of the week talks, and stimulating discussions we shared not only enriched this research but also made my internship period fulfilling and enjoyable.

I am also intensely grateful to the members of my thesis committee, Dr. Andreas Hartmann and Ir. Sander Mooren. Their valuable critiques and feedback greatly enhanced the quality of this work. Their commitment to academic excellence and their willingness to share their profound knowledge have been a true inspiration.

On a personal note, I am deeply indebted to my family and friends. To my mother, Maria Guadalupe Ventura Arellano, and my godfather, Salvador Ventura Arellano, whose unconditional love and confidence in my abilities have been a constant source of strength. Their support gave me the courage to pursue my passions wholeheartedly. To my friends, thank you for your understanding and for always being there to provide encouragement and cheerfulness when it was needed most.

Thank you all!

Alexis Demetrio Anguiano Ventura

January 2025

SUMMARY

The asset management sector in the Netherlands faces significant challenges due to aging infrastructure, increased traffic demands, and scattered data. Rijkswaterstaat manages approximately 1,145 bridges, of which 178 are steel bridges. Many of these bridges, designed for a lifespan of 80–100 years, are approaching the end of their design life. In addition to the current end-of-life assessment methods that primarily focus on aging, a technical approach can enable the necessary criteria to prioritize interventions across Rijkswaterstaat's extensive infrastructure portfolio in anticipation of increased replacement and renovation projects.

This research aimed to identify criteria and create a rule-based assessment that provides insights regarding the technical end-of-life for steel bridges at a portfolio level to aid Rijkswaterstaat in their need for prioritization within their intervention planning. This objective was tackled with a structured approach that integrated a mix of qualitative and semi-quantitative data following a research design framework. In the first stage of the research, a state-of-the-art literature review was conducted, revealing a comprehensive analysis of steel bridge typologies, frequent damages within steel structures, decomposition standards, and other current end-of-life models and tools. Concluding the literature review, a thematic coding framework was developed to systematically identify technical end-of-life criteria based on structural damages and perceived risk of failure characteristics. The development of this framework is guided by the standards outlined by the NEN 2767-4, which provides a hierarchical decomposition analysis of bridge structures, thereby enabling detailed evaluations beyond conventional global structural assessments.

The second part of the research design involved a multi-case study analysis conducted utilizing the framework. The multi-case study chapter examined four steel bridges within the portfolio of Rijkswaterstaat, which all had in common an orthotropic steel deck. This deck typology has been found critical by the asset manager due to fatigue cracking, and consequently, it was highlighted as one of the elements of interest within this research. Additionally, insights from expert interviews conducted with TNO and Rijkswaterstaat domain experts support the identification and validation of threshold values and perceived risk of failure pertinent to the technical end-of-life criteria.

The findings of the analysis establish a foundation for implementing a rule-based technical end-of-life assessment model tailored for portfolio analysis. A total of twelve criteria were deemed useful for assessing steel bridges. The identified criteria evaluate fatigue cracks within cables, corrosion in main girders, and the geometrical composition of deck plates within an orthotropic steel deck. Finally, to assess the various bridge typologies within Rijkswaterstaat's portfolio, a rule-based criteria assessment was composed. The qualitative criteria were arranged in accordance with the NEN 2767-4 following a hierarchical decomposition and the decision-tree method, focusing on structural damages within the load-bearing elements and critical building components of a steel bridge. Various examples were illustrated showcasing the technical end-of-life criteria usefulness.

Although limitations such as data availability and the consideration of only a few physical damage processes were noted, the research offers a qualitative assessment for RWS to efficiently identify steel bridge candidates to prioritize the forthcoming demands of replacing and renovating works in the Netherlands. The research concludes with the answer to the research questions, and future research recommendations to expand the knowledge within the technical end-of-life domain.

ABBREVIATIONS

DISK	Data Informatie Systeem Kunstwerken (Data Information System Artworks)
EoL	End-of-life
FE	Finite Element
FIT	Functional Inspections and Tests
HPFRC	High-Performance Fibre-Reinforced Concrete
HSC	High Strength Concrete
OSD	Orthotropic Steel Deck
RHPC	Reinforced High Performance Concrete
RWS	Rijkswaterstaat
TEoL	Technical End-of-life
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
UHPC	Ultra High-Performance Concrete
V&R	Vervanging & Renovatie (Replacement and Renovation)
WIM	Weigh-in-Motion
WRS	Weld Residual Stresses

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INTRODUCTION

The introductory chapter presents the purpose and background information that allowed this master's thesis project to be executed. The introduction will contain: the context and motivation of the project, an overview describing the background story of the project, the problem context, aims and objectives, and finally the research questions.

1.1. CONTEXT AND MOTIVATION

The research topic was selected due to its critical relevance within the infrastructure sector, specifically in the domain of asset management. Discussions revolving around the aging bridge structures in the Netherlands and the need for major interventions of these assets were an incentive to research the topic of technical end-of-life of bridges at a portfolio level. This research aims to highlight a series of criteria that give insights into the technical end-of-life of steel bridges. By determining these criteria, a rule-based assessment was extracted to analyse the portfolio of bridge assets of Rijkswaterstaat which subsequently will highlight the steel bridges close to their TEoL. Therefore, broadening the scientific knowledge within asset management and fostering a new approach to tackle this urgent infrastructure issue.

The completion of this dissertation project will fulfil the academic requirements for obtaining the Master of Science degree in Civil Engineering and Management, within the track of Construction Management.

1.2. BACKGROUND

1.2.1. BRIDGES IN THE NETHERLANDS

After the devastation caused by World War II, numerous European countries began a phase of heavy construction to rebuild the continent. Between 1950 and 1975, the Netherlands saw economic growth that had a bidirectional link to the infrastructure transportation networks within the country; as a result, there was a boost in the construction of bridges and viaducts (Xie et al., 2018). Within the Dutch territory, there is an extensive network of approximately 85,000 bridges and viaducts (Bleijenberg, 2021) (Figure **1**).

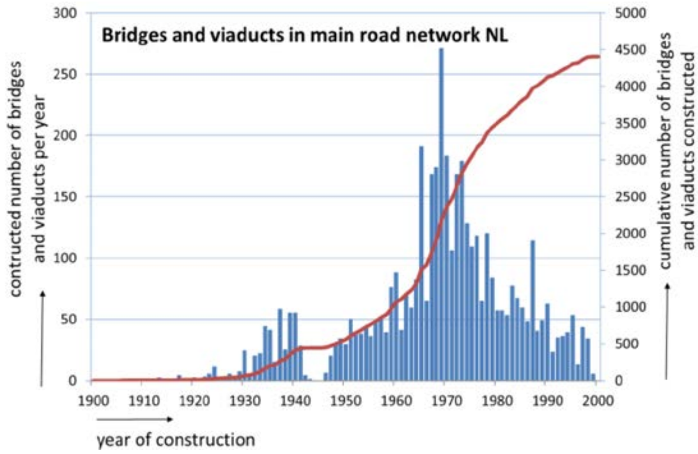

FIGURE 1: NUMBER OF BRIDGES AND VIADUCTS CONSTRUCTED PER YEAR, AND CUMULATIVE NUMBER OF BRIDGES AND VIADUCTS IN THE NETHERLANDS (BASED ON RWS DATABASE) (ABSPOEL - BUKMAN ET AL., 2023).

Bridges, both fixed or movable (Figure 2), stand out as indispensable structures that drive the economic and social growth of nations (Hartmann & Bakker, 2023). Due to their importance, understanding the risks related to aging, safety, and environmental dangers associated with the physical integrity of these structures became crucial (Chang et al., 2003).

FIGURE 2: (LEFT SIDE) MOVABLE BRIDGE – VAN BRIENENOORD BASCULE BRIDGE AND (RIGHT SIDE) FIXED BRIDGE – MOERDIJK BRIDGE A BOX GIRDER BRIDGE (ROMEIJN, 2006) AND RIJKSWATERSTAAT.

Standing as one of the entities responsible for maintaining these assets is Rijkswaterstaat (RWS), which is the executive agency of the Ministry of Infrastructure and Water Management of the Netherlands. RWS is the asset manager of approximately 1145 different bridges, including 168 movable and 977 fixed bridges (House of Representatives, 2020) of which only 178 are classified as steel bridges (De Raat et al., 2023) (Figure **3**). Although RWS's portfolio of bridges composes only 1.3% of the total amount of bridges in the country, RWS oversees the major bridges within the national highways making them one of the key infrastructure asset managers of the Dutch transport network. To ensure the functions of safety and reliability of the bridge structures within their portfolio, RWS strategically establishes intervention strategies in order to address and maintain permissible levels. The data utilized to determine these interventions is summarized within inspection reports and historical data, which then is stored in their datasets.

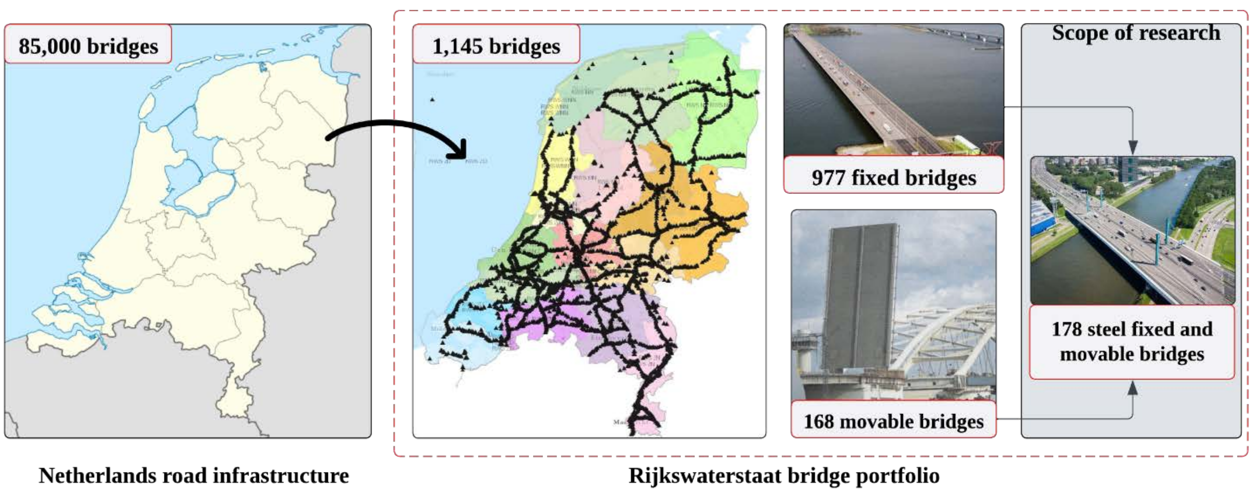

FIGURE 3: BRIDGES WITHIN THE DUTCH HIGHWAY NETWORK (RWS - GEOWEB, 2024).

1.2.2. The Aging Bridges Managed by Rijkswaterstaat (RWS)

Given that bridges typically have a design service life of 80-100 years (Rijkswaterstaat, 2022), statistics led RWS to conclude that the aging bridge structures within their portfolio will be reaching their design end-of-life and will require major intervention works in the upcoming decades (Hartmann & Bakker, 2023). To be able to financially cope with the required renewal and/or replacement of these aging structures, RWS has indicated forecast initiatives to prioritize major intervention strategies. One of these initiatives is the prognosis report.

The prognosis report (2022) gives an overview of the budget required to support maintenance interventions for future replacement and renovation works (Vervanging & Renovatie). Within the prognosis, a forecast of several major interventions was planned to ensure safety and accessibility to the civil infrastructures, as well as the dates they will be executed, and what resources will be required to complete the necessary interventions (Wessels et al., 2018).

By analysing these projections, the understanding of budget allocation has become crucial for decision-making for planning interventions. Currently, RWS allocates annually 1 billion euros to civil infrastructure renovations. To underline the importance of determining an efficient allocation of resources and efficient intervention strategies, by 2040-2050, the annual amount is expected to rise to 3–4 billion euros (Bleijenberg, 2021). To prioritize and optimize decision-making of which structures require an intervention, inspections, monitoring, and new propositions of assessments of the remaining service life of bridges must be conducted.

1.2.3. THE EOL WITHIN THE PORTFOLIO OF RWS

With the significant changes in the traffic environment over the years (e.g. higher load requirements, see Appendix section E), the functional performance thresholds of bridges have also changed. As a result, some bridges within RWS's portfolio have been compromised due to insufficient functional performance, limiting the functional lifespan of the infrastructure asset (Iddekinge, 2020). According to Nooij (2016), RWS has demolished 88.9% of bridges due to their functional EOL based on the functional change of the highway network. However, the current standing bridges that comply with the functional performance thresholds may not comply with the technical performance due to their aging components, degradation mechanisms, and new condition requirements, such as increased heavy traffic and technical obsolescence.

1.3. PROBLEM CONTEXT

After raising awareness of the number of steel bridge structures that are similarly reaching their design EOL, and the corresponding future economic concerns due to the forecasted interventions necessary to prolong their service life, the infrastructure authorities have been working on strategies to identify the remaining TEoL of steel bridges in a holistic manner to develop frameworks and tools to prioritize interventions for better budget allocation.

Knowing that the bridge structures in the country are the backbone of the road network, addressing this issue will help the asset managers to understand the current status of their civil infrastructure assets, consequently, providing safety and reliability to the community of road users. At the moment of the study, there is no profound analysis to determine the TEoL of bridges systematically and holistically, the current method of analysis revolves around the aging of the civil structures neglecting other relevant criteria, making a portfolio analysis unfeasible and unreliable.

The present approach by RWS to determining interventions revolves around inspection reports. These reports oversee the whole physical integrity of the asset by examining specific objects and collecting visual data, within different time frameworks (See Appendix section C). The reports exhibit the current status of the bridge components and highlight the ones that might trigger safety issues that could compromise the structure's integrity. The severity is determined by the expertise of the inspector. When an object has a high level of uncertainty, an in-depth examination is conducted which could require months. Given the large number of structures within the portfolio of RWS, the current method is inadequate due to the time-consuming and costly monitoring and analysis.

Another issue is the current datasets regarding the physical status of the bridge assets. Currently, the information is scattered within various forms of documentation within RWS organization and other regional asset managers. Each of them has different criteria to identify the TEoL making the integration of data within the infrastructure authorities complex. To address this challenge, the development of a framework derived from the current knowledge of TEoL could facilitate the identification of standardized TEoL criteria, which would mitigate inconsistencies in object categorization and condition assessments. These criteria could subsequently be organized into a rule-based model to assess their current status, thereby promoting a more unified comprehension of the TEoL for steel bridges.

Considering the importance of the steel bridge structures within the Dutch highway network, prompt identification of TEoL can result in effective decision-making strategies towards proactive interventions that enhance the safety and reliability of highway users.

1.4. MAIN OBJECTIVE

Based on the previous information, the main research objective can be established as:

Main objective: Identify criteria and create a rule-based assessment that provides insights regarding the TEoL for steel bridges at a portfolio level to aid Rijkswaterstaat in their need for prioritization within their intervention planning.

1.5. RESEARCH QUESTIONS

Based on the research objectives, the following research questions will be answered:

- What are the criteria that contribute to the TEoL of steel bridges?
- How can the TEoL rule-based criteria be utilized to aid the planning of intervention strategies for steel bridges within RWS portfolio?
- How do different bridge typologies affect the rule-based criteria?

1.6. PROJECT SCOPE

The project scope was limited only to steel bridges. A pool of 20 steel bridges was utilized for the data collection of this research based on the assignment from RWS to TNO. Consequential data derived from the case study was also deemed part of the study.

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RESEARCH DESIGN

This assignment involved a mix of qualitative and semi-quantitative research that thoroughly examined the TEoL definition, bridge decomposition and standards, influences of the TEoL, and existing TEol methods applied in other civil infrastructure assets, to develop a preliminary framework from which selected case studies were analysed to identify the TEoL criteria for steel bridges. Consequently, concluding the research with a TEoL assessment approach. In Figure 4, the research design method is illustrated within 3 main chapters:

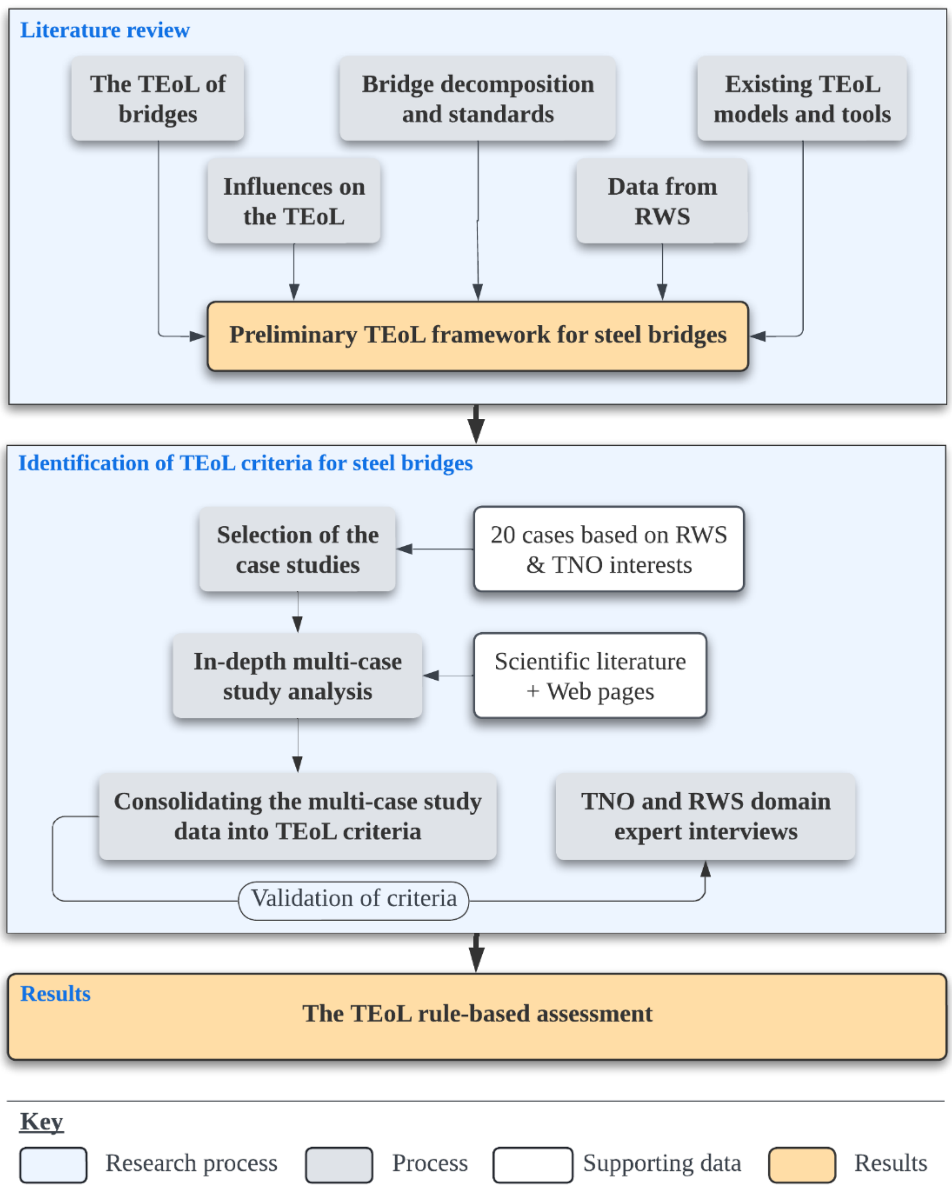

FIGURE 4: THE RESEARCH DESIGN

Literature review

This chapter describes an extensive state-of-the-art literature review within the current knowledge surrounding the topics of the TEoL of bridges, bridge TEoL influences, bridge decomposition and standards, existing TEoL methods, and data from RWS. By diving into the gap of knowledge within the portfolio-level analysis of bridges regarding the TEoL, a preliminary framework was derived based on the required information for the identification of TEoL criteria.

- **The TEoL of bridges:** This section explored and analysed multiple definitions of TEoL. After reviewing existing definitions within different assets and stakeholders, an adopted definition for bridges dictated the foundation for the TEoL rule-based criteria.

- **Influences on TEoL:** A broad analysis of potential influences pertaining to the bridge TEoL was conducted. The influences are classified as potential influences that interact externally and internally with the bridge's structural elements and critical components.

- **Bridge decomposition and standards:** This section investigated norms (e.g. NEN 2767-4), and design compositions of multiple bridge typologies in order to conclude a general element and component classification to explore in greater detail lower hierarchical component damages and not only global damages.

- **Data from RWS:** Presents a detailed analysis of the DISK dataset and the inspection reports of RWS. Due to the inaccessibility to RWS data, the inspection report section explored the data gathered in order to determine a qualitative method to assess the physical integrity of the bridge elements and components. Additionally, the data set DISK was analyzed to understand how the information was captured and stored.

- **Existing EoL models and tools:** Discussed an existing EoL schematic model which was used as the foundation of the preliminary framework. Additionally, this section illustrates existing tools that could be used as input data for the identification of TEoL criteria.

Conclusion of the literature review - Preliminary TEoL framework for steel bridges: Once all the concepts were investigated, a preliminary framework was concluded following a thematic coding approach (Gibbs, 2007). This framework was used to identify TEoL criteria candidates in the subsequent chapters.

Identification of the TEoL criteria for steel bridges

Within this chapter, the selection and analysis of multiple case studies were executed to determine TEoL criteria that led to the TEoL rule-based assessment for steel bridges.

- **Selection of Case Studies:** The selection of the multi-case studies was derived from the assignment from RWS to TNO. RWS selected 20 bridges from their portfolio to be analysed due to the high interest in the OSD. The focus attention on the deck is underlined in Appendix F, where steel bridges with a similar deck configuration had shown signs of cracking within their early service life. Additionally to the common composition of the deck, these bridges were selected due to their size, and their importance within the Dutch road network. The total selection of 4 cases from the 20 potential bridges was derived by the quantity of research available (see Appendix section J).

- **In-Depth Multi-Case Study Analysis:** In this section of the research, the 4 selected case studies were analysed utilizing the preliminary framework in order to gather data to formulate TEoL criteria candidates. Furthermore, additional TEoL criteria candidates were concluded based on the multi-case study conclusions. In total, fourteen TEoL criteria candidates were found.

  The procedure for documenting the findings followed the thematic coding approach. From the information reviewed, keywords such as fatigue, risk, deck, cables, and cracks were recorded under the specific classifications of the preliminary framework (see Appendix A).

- **Consolidating the TEoL Criteria:** Once the data was gathered from the previous sub-chapter, a consolidation process of each criterion into structured TEoL criteria was executed.

- **TNO Domain Expert/RWS Interviews:** Once the consolidated TEoL criteria were gathered, semi-structured interviews (Knox & Burkard, 2009) were executed. This section was intended to validate and open discussions for the threshold and potential risk-to-failure values of the consolidated criteria. The interviews were carried out within three sessions: two for TNO domain experts within the reliable structures department, and one with an asset manager within RWS. The complete executed process of the validation of the TEoL criteria is illustrated in Figure 5:

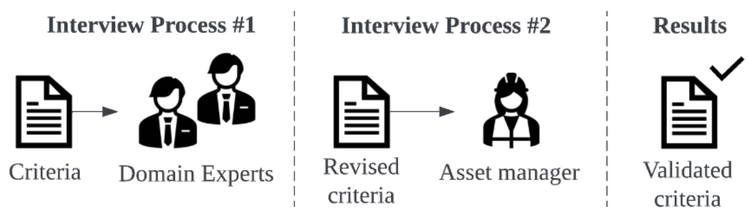

FIGURE 5: INTERVIEW AND VALIDATION PROCESS OF THE TEOL CRITERIA

  The information then was captured within text notes and audio recordings. A summarized version of the interviews and the interview process is within the Appendix section N. After following the protocol of the interview phase, the answer to the research question, what are the criteria that contribute to the technical EOL of steel bridges? was addressed.

Results

The results chapter concludes with the TEoL rule-based assessment and examples. This assessment followed a decision-tree model with a point-based system that allows ranking the assessed bridges based on the level of damages according to the availability of data inputted.

- **The TEoL rule-based assessment process:** Validated rules were arranged using the decision tree method (Song & Lu, 2015) and a point-based system (based on the perceived risk of failure of the domain experts) in order to obtain an overview of the steel bridge conditions regarding its potential TEoL. Based on the identified criteria and the arrangement of the decision tree model, an answer was given to the research question, how do different bridge typologies affect the rule-based criteria?

- **Example:** The four bridges from the multi-case study analysis were assessed utilizing the rule-based criteria in order to answer the research question, how can the TEoL rule-based criteria be utilized to plan intervention strategies for steel bridges within RWS portfolio?

3

LITERATURE REVIEW

This chapter explored the state-of-the-art TEoL ideas and concepts regarding steel bridges. The in-depth literature review dived into definitions and influences of TEoL, bridge decomposition standards and ideas, the various bridge defects, damages, potential causes, and other existing EoL models. Once the investigation within the concepts of TEoL and the portfolio-level analysis of bridges was completed, a TEoL framework was derived based on the required information for the identification of TEoL criteria.

3.1. THE TECHNICAL END-OF-LIFE

The definition of End-of-life (EoL) ranges from a wide variety of aspects and considerations, such as the state of the structure, criteria that are either met or not, trends of increasing characteristics (e.g. increasing maintenance), economic reasons, decisions of asset owners, etc. Based on these aspects, EoL can be categorized into 3 domains: Technical, Functional, and Economical (Vader et al., 2023). There are various definitions of Technical End-of-life (TEoL) in the context of civil structures. Based on the asset managers and academics working within the domain of civil structures, these definitions are meant to describe a specific moment within the service life of a structure at which a stakeholder decides to make an intervention (renovation or replacement) based on compromised parameters of an object or the whole asset.

In the research of Hartmann & Bakker (2023), the TEoL definition of bridges revolves around two connotations, the period where the bridge performance no longer complies with minimal acceptable levels, and the second, when a bridge or any of its parts cannot be repaired and performance falls below the minimally tolerable threshold. The first definition highlights the importance of maintaining the performance levels above thresholds, connotating the bridge as a whole system. The second part of the definition talks about the assessment of its components by determining if they are reparable or not.

According to Rijkswaterstaat's definition of the TEoL in the prognosis report (2022), "*The end of the technical lifespan is reached when, with regular maintenance, the legally required safety level or the agreed-upon performance can no longer be achieved*." This definition takes safety as one of its decision parameters and, additionally, mentions performance levels. According to the definition, the TEoL revolves around maintaining the performance level of components above threshold levels, making maintenance intervention strategies necessary to preserve the structure’s integrity. Within the same definition, the prognosis gives three main reasons for reaching TEoL: 1) far-reaching technical defects and change use accelerated technical defects induced by e.g. heavier traffic. 2) Applied technologies are no longer supported, making the object unfeasible to maintain. 3) Changes in standards that hinder an object to comply with the new standard of structural safety.

In the study of Bektas & Ozer (2023), the conceptualization of the TEoL for navigation locks study was defined by two key definitions; *“When a structure has serious structural defects”* and *“When a (critical) component is obsolete”*. These definitions are targeted to analyse the components of the asset, addressing the idea that if a single component reaches TEoL, the whole system reaches its TEoL. Furthermore, the concept of structural safety is mentioned, accentuating the importance of the structure’s integrity.

An important remark is that, after analysing the previous interpretation of the TEoL, only Hartmann & Bakker have a distinct definition for TEoL specifically for bridges, the other two generalized their definition based on their portfolio or their specific set of civil structures. Table 1 summarizes the definitions previously discussed.

TABLE 1: DEFINITIONS OF TEOL.

Group	Definition	Focus	Source
Academic & Asset Manager	1) The period where the bridge performance no longer complies within minimal acceptable levels 2) When a bridge or any of its parts cannot be repaired and performance falls below the minimally tolerable threshold	1) Time and Performance 2) Parts and Thresholds	(Hartmann & Bakker, 2023)
Asset Manager	1) The end of the technical lifespan is reached when, with regular maintenance, the legally required safety level or the agreed-upon performance can no longer be achieved	1) Safety and Performance	(Rijkswaterstaat, 2022)
Academic	1) When a structure has serious structural defects 2) When a (critical) component is obsolete	1) Defects 2) Component	(Bektas & Ozer, 2023)

In order to benchmark the TEoL of the bridges within this research, the adoption of a clear definition must be set. The main idea of establishing a definition of TEoL for bridges was not to create a new definition in addition to the existing ones but to set a common ground of analysis for steel bridges and start to develop a longitudinal understanding within the multiple stakeholders responsible for maintaining these assets within the Netherlands.

Based on the definitions of Table 1, the academic and asset manager's definition talks about bridge parts. These parts, according to the NEN 2676-4, were considered load-bearing elements, such as structural elements (e.g. deck, beam, cables), and building components, such as the elements bound to a specific function of the bridge that is not strictly structural (e.g. motors for movable bridges, deck plate, hanger). Figure 6 illustrates the TEoL of steel bridges and the indicators that trigger it:

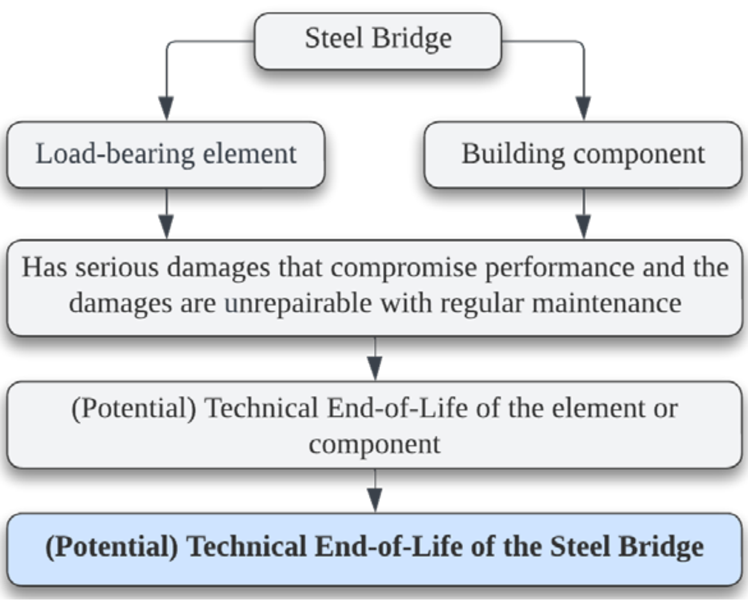

FIGURE 6: CONCEPTUALIZATION OF THE TEOL OF STEEL BRIDGES.

Figure 6 illustrates that the determining factor of the TEoL is based on the performance and the non-economic feasibility of maintaining the structure's elements and components. The composition of the TEoL for bridges incorporates two main concepts, one that asses the performance levels, and the other, that assesses if it requires a major intervention. The influences that interact with the structural or critical components of the bridge can be related to changes in regulation, aging and/or degradation mechanisms within the one or multiple bridge parts, or decision-making directly from the asset managers to make a large intervention. By identifying, classifying, and analysing these influences, TEoL criteria can be identified.

The definition of TEoL for this research also highlights the concept of potentiality within both of its outcomes, on the element and component TEoL, and the overall bridge's TEoL. Within the element and component level, this concept is given due to the level of uncertainty of the analysis. Given that the TEoL is determined by quantitative indicators such as structural calculations, and qualitative indicators such as the decision of the asset manager when considering the size of the maintenance, based only on the qualitative and semi-quantitative analysis of this research, a potential theoretical TEoL output is concluded.

On the other hand, potentiality within the TEoL of the whole bridge was coupled with two concepts:

- To determine the TEoL of the whole steel bridge, a combination of load-bearing elements and/or critical building components has to be reached. For instance, the TEoL of the bridge is potentially reached when the main girder reaches its TEoL. In the counterpart, the TEoL of the bridge would not be reached if the wearing surface had reached its TEoL.
- The structural redundancy of its critical load-bearing elements. Structural redundancy in steel bridges ensures safety by integrating design features that maintain functionality even if components fail (AISC, 2022). Within this research, a member is considered redundant if its failure alters the system's behavior without leading to collapse. As an example, a redundant cable system. If the cable system has redundancy, the TEoL of that cable would not compromise the overall structural integrity of the bridge.

<u>The scope and limitations of the TEoL definition for bridges</u>

As explained in Figure 6, the TEoL of bridges is determined by the load-bearing elements and critical components of the bridge in analysis. Once the elements and components of interest are defined, the next step is the assessment of the TEoL. The definition then diverges into two main concepts:

1) Serious damages that compromise performance, and
2) Unrepairable with regular maintenance.

The first assessment of the TEoL bridges considers defects and performance. Defects are considered as any sort of structural damages that compromise the structural integrity of the asset. Performance, on the other hand, serves as an indicator that is set to evaluate the bridge. In the research of Xie et al. (2018), various performance indicators are mentioned such as availability, functionality, safety, etc. The performance that will rule the assessment will be safety. This emphasis is justified for two reasons:

- First, it is mentioned as the "*required safety level*" in the RWS definition of TEoL.
- Secondly, the design of bridge parts adheres to the Eurocode standards, which follow design constraints that provide safe structures for users.

Therefore, safety is defined as: "*The likelihood that a system will not cause any harm to humans (injury or death) during a certain timeframe and under certain conditions*" (Rijkswaterstaat, 2017).

The second assessment addresses the inability to repair an element or component with regular maintenance. According to the prognosis report (2022), regular maintenance is described as a measure significantly smaller in scale than the V&R measures (replacement or renovation). This distinction emphasizes an economic limitation or threshold: once the investment required to replace an object reaches a certain level, the maintenance is considered a large intervention, indicating that the asset has reached its TEoL.

In summary, the TEoL of steel bridges was defined as the combination of serious damages (not repaired with regular maintenance) within its load-bearing elements and building components that compromise safety to users.

Interactions with Functional and Economical EoL

The primary focus of the research, as stated in the title, is TEoL; nevertheless, as the influences of TEoL are further discussed, the overlap between the functional and economical EoL starts to emerge. It is impossible to set them apart and rigorously analyse them without crossing each other's boundaries. This small section is an acknowledgement of the overlaps that emerge in the following chapters. The following definition is formulated to understand the entanglement of the three: The functional EoL gives the purpose, the technical EoL indicates the interventions to keep it working, and the economical EoL establishes the duration for which the infrastructure is still regarded as an asset.

3.2. INFLUENCES ON THE TEOL FOR BRIDGES

Based on the previous sub-chapter, the influences of the TEoL for bridges are internal and external influences on the bridge elements and components. External influences can be considered as environmental conditions, human-induced factors, and others that are not directly related to the physical structure. Internal influences are related to the bridge structure. These influences can be categorized and classified as follows:

TABLE 2: INTERNAL AND EXTERNAL INFLUENCES OF THE TEOL OF BRIDGES.

Influence	Category	Classification (Specific Influences)	Source
External	Environmental Factors	Weather and temperature changes	(IM-SAFE Knowledge Base, 2022)
	Traffic Loads	Increase traffic volume and loads	(Hartmann & Bakker, 2023)
	Design Limitations	New and outdated design standards and regulations	(Van der Burg, 2011)
	Human-Induced Factors	Inadequate maintenance	(C. Crawford, 2023)
Internal	Component Obsolescence	Outdated or unavailable replacement parts	(Bektas & Ozer, 2023)
	Damage Processes	Aging, fatigue, corrosion, etc.	(IM-SAFE Knowledge Base, 2022)
	Material Properties	Quality of materials and processes	(Maljaars & Vrouwenvelder, 2014)

As indicated in Table 2, the external factors come from variables that are not directly bound to the physical integrity of the bridge structure. Although these influences are stated as separated, indirectly, the external factors influence the internal. In the case of the damage processes, environmental factors and traffic loads exercise an important effect.

In the next paragraphs, the influences will be further examined illustrating the influence they have between each other and the input they covey towards the TEoL of the bridge structural elements and critical components.

3.2.1. Environmental Factors

The environment is of significant influence to take into consideration given that it is the only non-human external variable. Even though these factors cannot be controlled, they have a significant influence on the formation of damage processes of structural components of civil structures (Soo Lon Wah et al., 2018) (IM-SAFE Knowledge Base, 2022). Factors, such as rain can cause chemical damage processes, e.g. corrosion. Another factor is high-temperature fluctuations that influence the appearance of delamination, displacements, and deformations (IM-SAFE Knowledge Base, 2022).

3.2.2. Traffic Loads

Traffic loads play a crucial role in designing the structure of a bridge. These dynamic loads have a significant impact on the selection and design of the bridge structure's geometry and materials. Additionally, these loads have a correlation with safety performance standards that are determined by construction regulations and norms. In addition to the increase in traffic loads over the years, the increase in traffic intensity has also been a topic of interest (Swov.nl, 2022). In Europe, between 1995 and 2010, road freight transportation increased 36.2% (Zhou, 2013), therefore, promoting fatigue damages for road structures.

According to recent research on the renovation of several orthotropic steel decks (OSD) of bridges in the Netherlands, studies have shown that the heavy vehicle position within the deck plays a critical role in determining damage mechanisms such as fatigue cracking (Van Dooren et al., 2010). Figure 7, highlights the concentrated areas of stress where heavy vehicles interact with the deck surface.

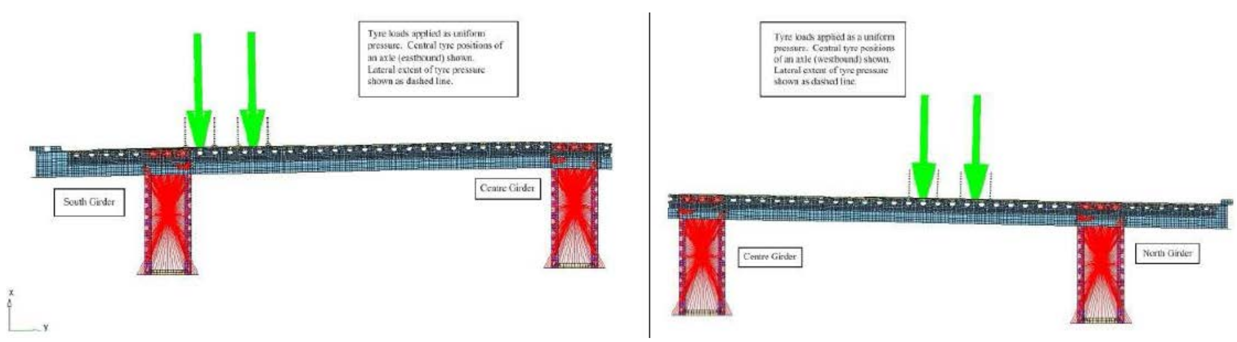

FIGURE 7: POSITION OF TRUCK LOADS (VAN DOOREN ET AL., 2010).

By identifying the vertical load, its position along the deck, and the intensity at which it interacts with the structure, numerical models have been developed to understand damage processes, in specific fatigue cracks. Figure 8 presents another example of the position of the axle load of a truck. This load can cause local deformations that translate to fatigue cracks within the upper layers of the deck and welds within the structural components of the OSD.

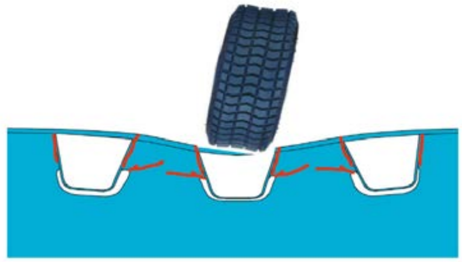

FIGURE 8: ILLUSTRATION OF OSD DEFORMATION UNDER TRUCKLOAD (LIU ET AL., 2021).

This relationship between the influence of traffic loads and the damage process of fatigue is of crucial importance to understanding the assessment of the potential TEoL for bridges, since the most prevalent condition damaging steel bridges is fatigue cracking, which mostly affects the welding joints of the deck components (Cui et al., 2024).

3.2.3. Design Limitations

The design life of movable and fixed bridges revolves around 80-100 years (Rijkswaterstaat, 2022). This design life refers to the desired planned period to which the bridge will perform its design function under assumed loads and circumstances. Over the years, these loading assumptions have changed as well as the construction codes that rule the safety thresholds that measure the bridge's performance. Within the Netherlands, the standards and codes that ruled the safety parameters for the design, load requirements, and conditions are consolidated within the Eurocodes, the Dutch building decree, the NEN standards, and other asset owner's guidelines. These regulations had undergone updates over the years to incorporate new research findings and technological advancements resulting in slimer performance thresholds.

As an example, within the research of van der Burg (2011), noticeable changes within the steel design standards for plate buckling were observed between the NEN 6771 and the NEN-EN 1993 1-5. The conclusion was that the NEN-EN 1993 1-5 gave higher buckling capacity than the NEN 6771. This example illustrates that within the transition between the NEN 6771 to the NEN-EN 1993 1-5 in the early 2000s, there have been changes in the considerations of safety thresholds over the design of steel structures.

In addition to the transitions and updates of the codes and standards, the components designed for the initial assumed loads have certain materials and geometries that might not be able to cope with the current load requirements due to other external influences and damage processes such as degradation due to aging. Despite time-dependent changes in material properties, losing bearing capacity is associated with safety performances and cannot be compromised.

3.2.4. Human-Induced Factors

Once a bridge structure is completed and enters its operational phase, degradation mechanisms will start to act upon the infrastructure reducing its performance. To preserve the structures' integrity, maintenance must be executed. The maintenance strategies are a consequence of the decision-making processes of the asset managers and heavily rely on inspection reports. Bridge inspection reports are crucial for the prompt identification of potential damage within the bridge before they cause a catastrophic failure. During these inspections, the structural and critical components are carefully examined for indicators of any signs of damage processes (Under Bridge Platforms, 2024).

In 1976, in the state of Ohio in the US, due to an unforeseen fracture of an eye bar at a pin connection the Silver Bridge collapsed causing a total human loss of 46 (Figure **9**). This cable-stayed bridge was the first bridge within the US territory to utilize an eye bar-link suspension system. According to the failure analysis, the eye bar 330 technically failed due to an unforeseen fracture in combination with stress corrosion and fatigue over its entire 40 years of service life (C. Crawford, 2023).

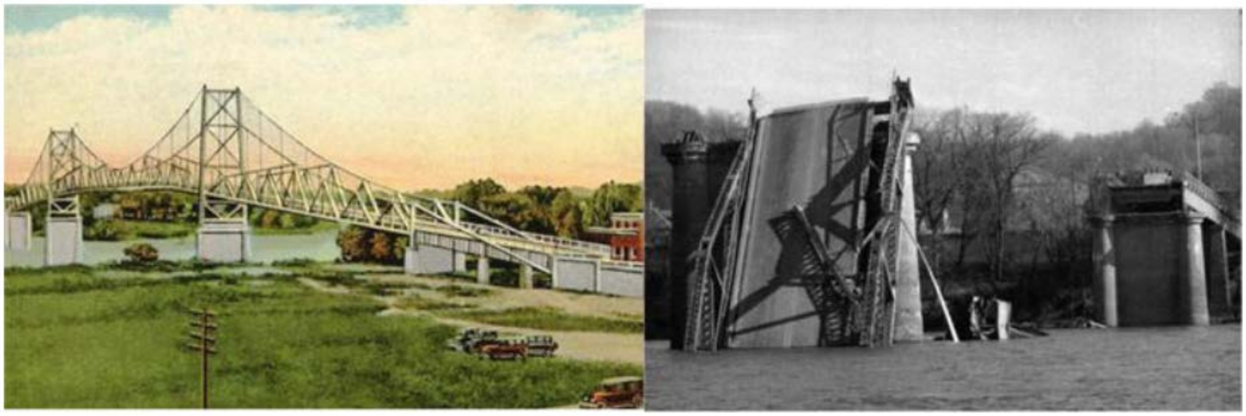

FIGURE 9: THE SILVER BRIDGE IN 1928 (LEFT IMAGE), AS FAILED IN DECEMBER 1967 (RIGHT IMAGE) (C. CRAWFORD, 2023).

This case illustrates the high importance of performing a proper inspection, highlighting that in combination with degradation mechanisms such as aging and fatigue, unforeseen failures can be avoided if proper maintenance is executed.

3.2.4.1. Poor maintenance

Following, are two examples of poor maintenance within steel bridges:

Poor application of HSC

High-strength Concrete (HSC) is a type of concrete distinguished by its high compressive strength (> 60 MPa), and low water-to-cement ratio. This concrete mixture provides an improvement in mechanical properties of the element, such as durability, stiffness, and high compressive strength. This type of concrete can also be cost-effective in the long term due to the lower maintenance costs (Shah & Ribakov, 2011).

Based on the mechanical properties of the HSC, this mix has been proven useful for maintenance interventions in the OSD (Buitelaar & Braam, 2008). In a case study of the Moerdijk Bridge, HSC was applied to reinforce the deck plate, which exhibited cracking. However, during the placement of the new pavement layer, a de-bonding defect occurred due to improper application of the mix, leading to interconnection issues among the components (Buitelaar & Braam, 2008).

Poor Welding

In the composition of an OSD, the troughs, the deck plate, and the crossbeams, are all interconnected through welded joints. The welded components, particularly at the intersections of trough-to-deck plates, are susceptible to stress concentrations due to traffic-induced loads and weld residual stresses (WRS) generated during the welding process (Zhong et al., 2023). Therefore, poor execution of a weld, in combination with heavy traffic loads, can initiate cracks in the weld, such as in the case study of the Moerdijk bridge (Buitelaar & Braam, 2008).

According to the qualitative experiment of Wu et al. (2019), three scenarios of welded connections between the trough and the deck plate were explored utilizing a finite element (FE) model. The results concluded that the weld shape profiles affect the fatigue resistance of the joint. Specifically, the concave weld designated as Type "B" (Figure 10) demonstrated a 16% increase in fatigue resistance compared to weld Type "A," while weld Type "C" showed a 3.2% decrease relative to weld Type "A."

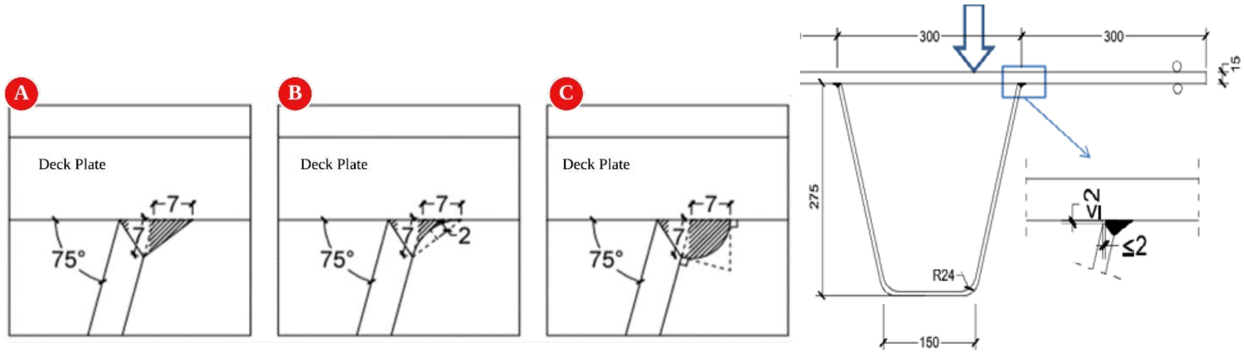

FIGURE 10: SKETCH OF THE WELD PROFILE USED IN THE STUDY AND THE LOAD APPLICATION (WU ET AL., 2019)

3.2.5. COMPONENT OBSOLESCENCE

According to Hartmann & Bakker (2023), the concept of functional obsolescence as the result of changes in the function of the asset, leads to an insufficient performance level of a critical component that can no longer meet the new demands, directly compromising safety (e.g. increasing the load capacity of an old bridge). As stated in the previous sub-chapter, the boundaries of this research are coupled within the TEoL, not functional EoL. Even though, it is important to mention that due to a change in a higher conceptual level, the asset is affected within its technical components.

Another definition of obsolescence is described as the state of a critical component that is unrepairable or is no longer produced (not in stock) (Bektas & Ozer, 2023). This definition is in direct context to a technical conceptualization of obsolescence. Following, is a theoretical example:

- Technical obsolescence in combination with aging can result in a technically outdated critical component that is no longer in the market, and/or one of its pieces is out of stock. This could be an example of a component of a mechanical element of the bridge's mechanical room.

It is difficult to provide a specific example of technical obsolescence within the structural and critical components of a steel bridge without delving into functional obsolescence given that the only critical components that can become obsolete are mechanical components of movable bridges that serve a specific function.

3.2.6. DAMAGE PROCESSES

The main reason a bridge can potentially reach its TEoL is due to a singularity or combination of elements or components that have damages. Damage, as defined by Gorse et al. (2020), is a physical destruction that reduces the utility, service, or value of an element or component due to the actions of human interaction (e.g. usage of heavy lorries, in the context of vehicles crossing the bridge) or the environmental effects (e.g. corrosion). Based on Figure 11, the typical damages of steel bridges revolve around corrosion deterioration and fatigue damages attributed to environmental factors and stress ranges caused by traffic loading (So et al., 2012). As with any construction material exposed to variable environmental conditions, damage processes give rise to various degradation mechanisms. Over time, aging materials in combination with increased load stresses result in unsafe structures.

Within the IM-SAFE knowledge base (2022), four different damage processes are distinguished: Physical, Chemical, Biological, and Design and Construction Issues. Within the physical processes lies relevant influences of interest for the TEoL of bridges, such as the aging of materials and fatigue. Within the Appendix section A, a table illustrates the array of multiple damage processes to bridges and the performance indicators that trigger them.

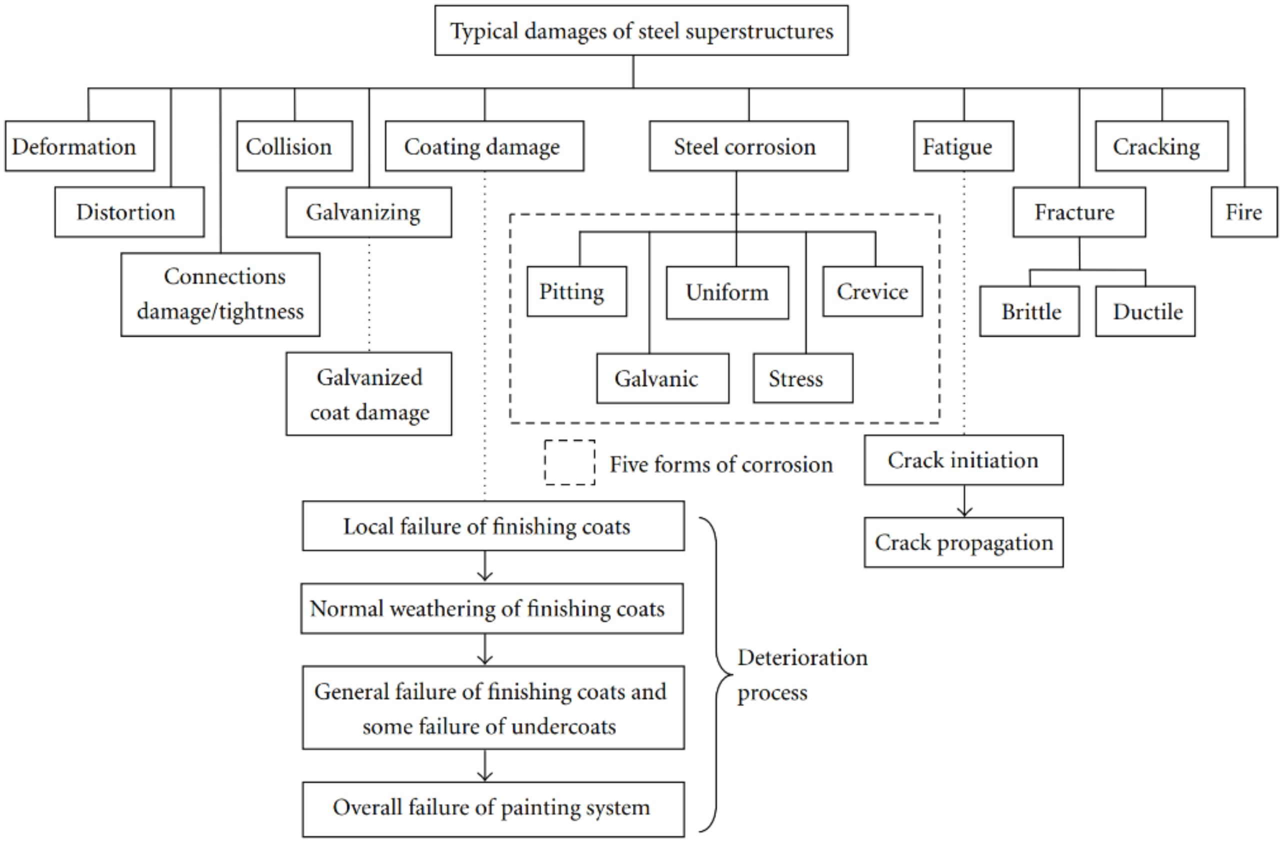

FIGURE 11: TYPICAL TYPES OF DAMAGES OF STEEL SUPERSTRUCTURES (SO ET AL., 2012)

3.2.6.1. FATIGUE

The development of microscopic cracks into macro cracks as a result of repeated tensile stress application is known as fatigue damage (U.S. Department of Transportation, 2016). Within the structural components of a bridge, fatigue cracks are usually presented in welded components or within single load-bearing elements. After a considerable amount of load variation, fatigue is what causes cracks to form and ultimately leads to complete fracture. Therefore, within the service life of a structure, fatigue cracks can be categorized into fatigue crack initiation, fatigue crack propagation, and final failure (Shankar Gupta, 2019). Based on the research of Zerbst et al. (2012), the 3 phases of fatigue cracks are described:

<u>Fatigue Crack Initiation (or nucleation)</u>

In the initial phase, the nucleation first develops due to the accumulation of irreversible plastic deformation. This considers the element's pre-existing conditioning, which is regarded as a defect and can include inclusions, pores, scratches, sharp corners, etc. From this stage on, the evolution of the cracks is dependent on the influences of heavy loading cycles and environmental-related defects (e.g. corrosion) This stage includes most of the overall fatigue life for non-welded elements.

Fatigue Crack Propagation

The cracks can be classified as mechanically short cracks in the second phase as they get bigger and, as a result, propagate more steadily.

Final Failure (Fracture)

The element fractures when the fatigue crack lengthens to the point where it lowers its capacity to fulfil its function representing a complete breakage of the wire.

Figure 12, summarizes the previous stages of fatigue cracks, from nucleation up to fracture based on the length scale:

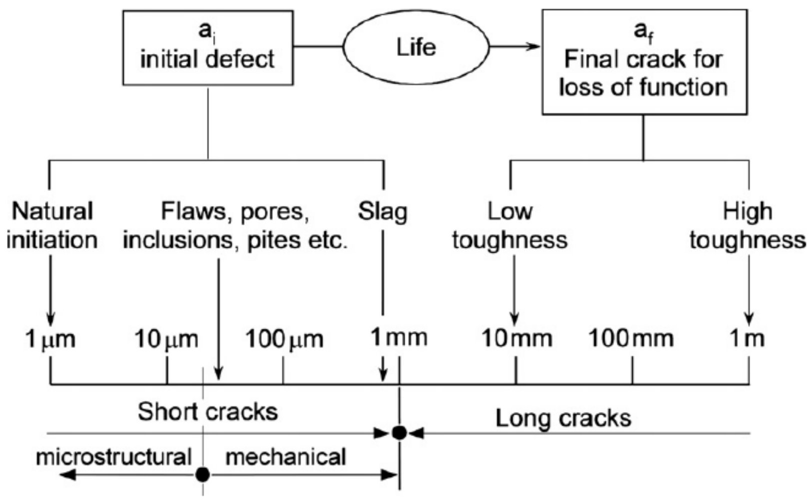

FIGURE 12: LENGTH SCALES OF THE LIFE CYCLE OF A COMPONENT SUBJECTED TO CYCLIC LOADING (ZERBST ET AL., 2012).

Considering the potential for fracture based on fatigue crack length on load-bearing elements that could directly impact safety, fatigue cracks are significant damages to take into account when discussing TEoL for bridges.

Fatigue crack in welded connections

Fatigue cracking has been a persistent challenge in steel structures for many years, largely due to the presence of welded connections (Qian & Abruzzese, 2009). Welded connections, while providing necessary continuity and strength, often introduce stress concentrations that can become initiation sites for fatigue cracks under cyclic loading conditions. In the context of OSDs, these initial cracks, combined with the repetitive stress from traffic loads can lead to the progressive development of cracks in the deck plate.

According to the research of Shankar (2019) and Ji et al. (2013), for the OSD welded connections, there are four types of possible crack paths:

- Crack I (Toe-deck crack): starts at the weld toe in the deck plate and propagates through the deck plate.
- Crack II (Root-deck crack): starts at the weld root and propagates through the deck plate.
- Crack III (Toe-trough crack): starts at the weld toe in the trough web and propagates through the trough web.
- Crack IV (Weld root crack): starts at the weld root and propagates through the weld trough.

A depiction of the crack types is indicated in Figure 13:

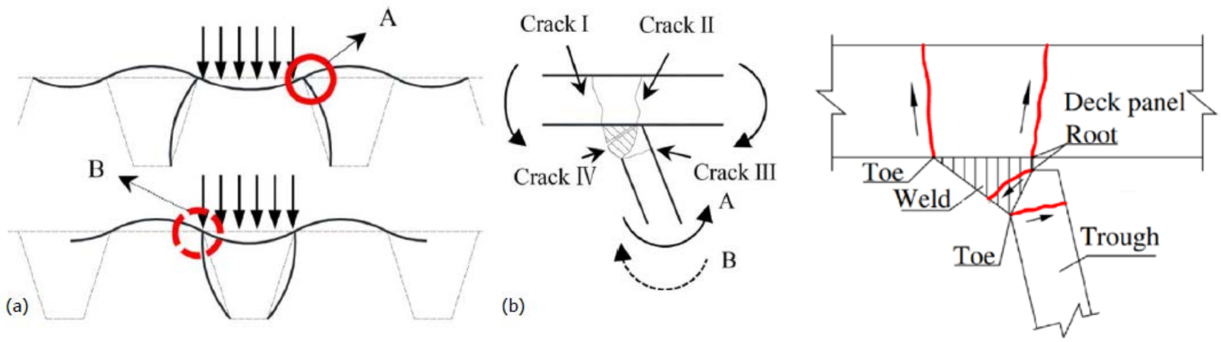

FIGURE 13: ILLUSTRATION OF THE DEFORMATION AND CRACKS OF THE BRIDGE DECK (A) REPRESENTATIVE LOADING SCENARIOS AND THE CORRESPONDING DEFORMATIONS (B) TYPICAL FATIGUE CRACK PATTERNS AND TERMINOLOGY (SHANKAR GUPTA, 2019) (JI ET AL., 2013)

<u>Crack propagation</u>

The threat level to traffic safety posed by cracks in the OSD is determined by factors such as the phase of crack propagation, the crack length, and the crack's location within the surface plate. According to Figure 14, image “1”, there are two longitudinal fatigue cracks within the deck plate of the OSD. In this context, cracks originate at the root of the longitudinal fillet weld between the trough wall and the deck plate, specifically at the intersection of the crossbeam and the continuous closed trapezoidal stiffeners. After the initiation phase, the crack grows vertically (Figure 15 – phase 2), once it reaches the deck plate surface, it starts to grow horizontally (Figure 15 – phase 3). These types of cracks are considered of high threat to traffic safety (Romeijn, 2006) (Shankar Gupta, 2019). Due to the nature of this crack type, the propagation results in large invisible or undetected until they reach the surface of the deck plate. Research from Romeijn (2006) indicates that the length of the cracks in the bottom of the deck plate are usually four times smaller than the one on the top side.

The deck plate fatigue crack within image “2”, illustrates a similar crack pattern to the one in image “1”, the only difference is the location within the OSD. The one in image “2” is located in the middle section between the crossbeams of the OSD. It is also distinguished that this type of crack starts from the weld root, and it propagates in the longitudinal direction (Figure 15 – phase 3). This type of crack is not considered a threat to traffic safety (Romeijn, 2006).

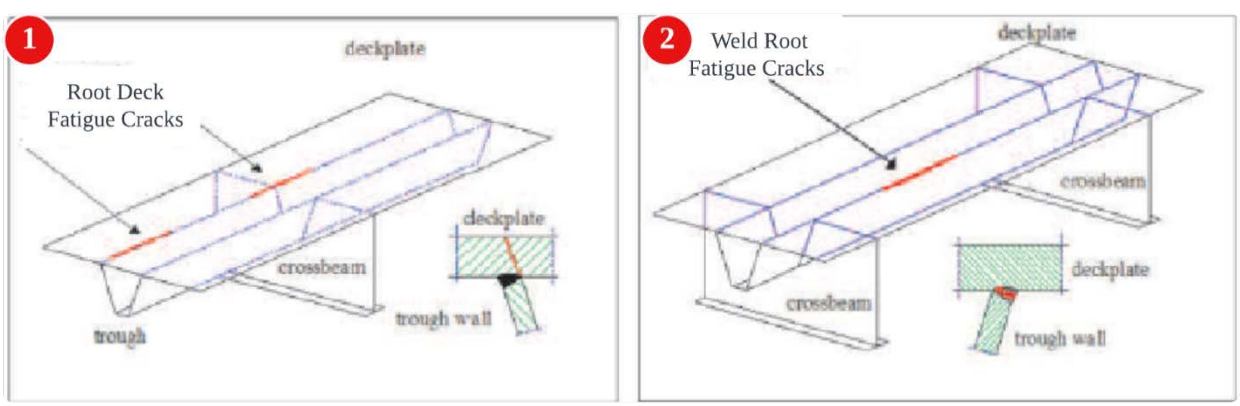

FIGURE 14:FATIGUE CRACKS IN THE DECK PLATE (1) AND IN THE LONGITUDINAL FILLET WELD BETWEEN DECK PLATE AND TROUGH (2) (ROMEIJN, 2006)

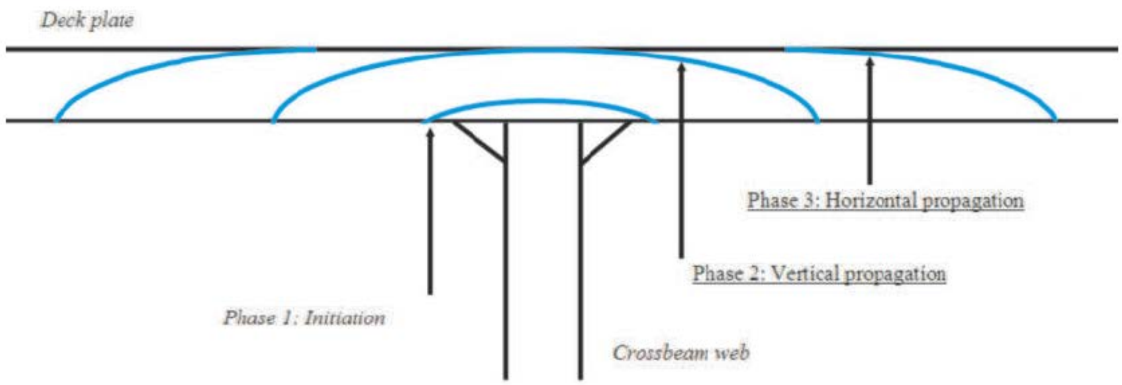

FIGURE 15: CRACK GROWTH PHASES FOR DECK PLATE CRACK (ROMEIJN, 2006).

3.2.6.2. CORROSION

Corrosion is the other common deterioration process that affects steel structures. The loss of cross section area in steel elements and components is caused by this degradation mechanism in conjunction with environmental phenomena, which has a substantial effect on the bridge's reliability, particularly in relation to safety and durability (Gocál & Odrobiňák, 2020). This degradation mechanism is relevant to steel infrastructure since, in developed countries, yearly corrosion-related damages account for 3.1% to 3.5% of GDP. These costs are essentially the direct cost of materials, equipment, and services involved in maintenance and replacement (Hays, 2010).

The deck, the cables, and the girders are the load-bearing parts and components of steel bridges that are impacted by corrosion. Within the design manual of OSD by the U.S. Department of Transportation (2012), corrosion can be initiated within the ribs of the deck, or within the ribs of a box girder due to condensation. Additionally, it causes de-bonding by a cascading effect brought on by water penetration due to crack formation in the deck plate induced by fatigue.

<u>Corrosion in steel wires</u>

This damage is usually localized where condensation of moisture and failures of the external protective sleeve are present (Gao et al., 2023). This type of damage is prone to be present within the anchoring, where the lower part of the cable is attached (Figure 16). Other factors that trigger this damage are temperature, pH, salinity, oxygen content, wetting conditions, and applied loads (Yu et al., 2022).

After the extensive analysis of Gao et al. (2023), it has been determined that aged steel wires exhibit a significantly higher corrosion rate than new wires, particularly when the protective coatings fail, and fatigue damage is present. On the other hand, another research on cable-stayed bridges revealed that brittle fractures and severe wire corrosion can be found in new bridges between 4 to 6 years of age (Betti et al., 2016). This demonstrates that corrosion damages are not exclusive to older bridges and underscores the importance of early detection for preserving the structural integrity of the bridge. Furthermore, as corrosion progresses, there is a dramatic decrease in the ultimate strain of the wires. This reduction in ultimate strength becomes exponential, especially when the cross-sectional area diminishes to less than 40% of its original size (Gao et al., 2023).

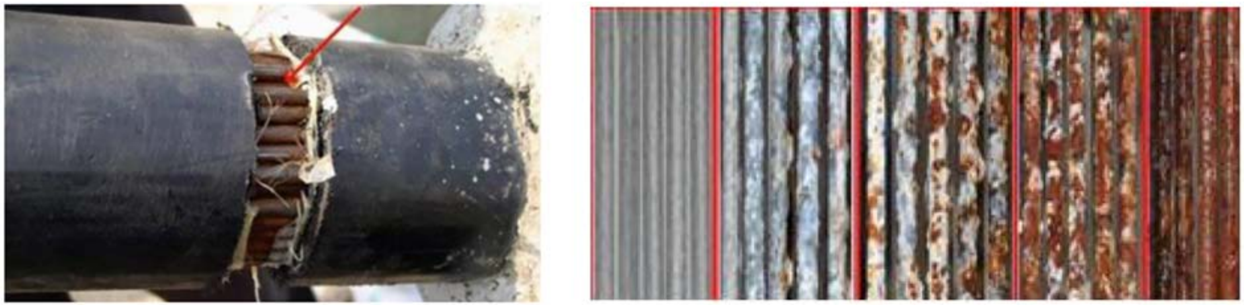

FIGURE 16: SCHEMATIC OF THE CORROSION DAMAGE OF BRIDGE CABLE (YU ET AL., 2022).

TABLE 3: EAMPLES OF DAMAGES OF STEEL BRIDGE ELEMENTS AND COMPONENTS.

Functional Component	Bridge Element	Element properties	Bridge Component	Defects and Damage	Possible Causes	References
Super-structure	Cables	High-strength steel wires + wrap + supports	Main cable	Corrosion of wires	Damaged of protective wrapping + humidity	(Betti et al., 2016)
			Hanger rope	Fracture cracks	lamination due to Manufacturing process	(Maljaars & Vrouwenvelder, 2014)
			Eye-bar	Fatigue cracks	Stress cracking + Degradation	(C. Crawford, 2023)
				Corrosion	Degradation + Humidity	
Deck	Deck	Orthotropic Steel Deck (OSD)	Deck plate	Fatigue cracks	Deck plate thickness + increased load	(Den Blanken et al., 2012), (U.S. Department of Transportation, 2012), (Zerbst et al., 2012)
				Rutting		
				Shoving		
				Delamination		
				Corrosion	Water penetration	
				Degradation of surface (durability)	Direction (transversal) of ribs	
			Trough - Open / Closed	Fatigue cracks	Poor welding + increased load	
				Corrosion	Water penetration	
			Crossbeam	Fatigue cracks	Poor welding + increased load	
					Accumulated stress (no cut-out)	
				Corrosion	Water penetration	

As mentioned in previous chapters and illustrated in Table 3, the most common defects within steel bridges, mainly in the superstructure elements, are fatigue cracks and corrosion. These prevalent damages are correlated with increased heavy traffic loads, human-induced factors, and environmental factors.

3.2.7. Material Properties

Within the design phase of a civil project, after the load calculations are complete, the definition of the necessary element is performed. This selected element must display material properties and a defined geometry that complies with the load calculations and construction standards. Then, within the execution phase, the element can be made in-situ or purchased by a manufacturer. Depending on which method is used, different assessments are undertaken to ensure the quality of the element.

In the case study of the Ewijk bridge, a manufacturing problem was detected in the composition of the suspension cables (Maljaars & Vrouwenvelder, 2014). During the bridge's assessment, fractures were found in multiple wires of the bridge due to large initial defects. In the civil infrastructure domain, a defect is strictly a divergence from the intended condition of a component (Viana da Rocha, 2013). The report concluded that throughout the manufacturing process, lamination was formed during the rolling process of the full lock wire.

3.2.7.1. Lamination

Laminations are elongated, linear imperfections or extended cracks that typically run parallel to the surface of metal products. These defects frequently occur in materials manufactured through rolling or drawing processes, such as wires. Laminations, which indicate separations or discontinuities within the material, can significantly compromise the mechanical properties and structural integrity of the metal (Adewole & Bull, 2016). The research of Maljaars and Vrouwenvelder (2014) defines lamination as a defect derived from wrinkles on the surface of the steel wire originating from the manufacturing rolling process which are then smoothed into the wire's surface.

3.3. Bridge Decomposition and Standards

Based on the previous influences of TEoL, the theoretical criteria that may result in the potential TEoL for bridges can be identified in various hierarchical levels of element classification of the bridge, dependent upon the influence with which the element in question is interacting. To gain a more comprehensive understanding of the relationship between the complete bridge system, and the lower hierarchical elements of a bridge, a decomposition was introduced in accordance with NEN 2767-4.

3.3.1. Different Bridge Typologies

Based on the definition on the research report for maintenance and management of bridges in Amsterdam (2015) "*A bridge is a movable or fixed connection between two points separated by water, a road or otherwise*". Within the territory of the Netherlands, there are various types of steel fixed and movable bridges, some examples are swivel bridges, vertical-lift bridges, bascule bridges, arch bridges, beam bridges, cable-stayed bridges, suspension bridges, and truss bridges (Transportation and Public Works Information Department, 1979; Van den Berg & Nijenhuis, 2006).

In the book of Bridge Engineering by Weiwei & Teruhiko (2017), an extensive analysis of multiple bridge typologies was conducted. In the following paragraphs, their research findings of typical bridge typologies will be explained:

Cable-Stayed Bridge

This civil structure is desired for lengthy spans, with an approximate range of 150 to 600 meters. The typical structural system of this bridge typology is composed by a pylon that transfers the loads to the foundation, a deck (e.g. girder), and the cables.

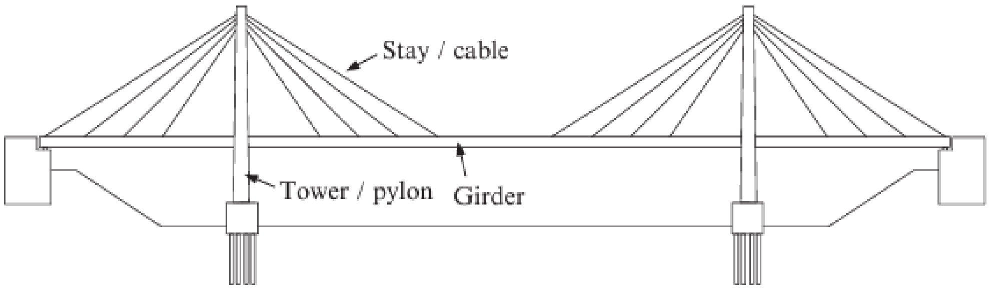

FIGURE 17: A TYPICAL CABLE-STAYED BRIDGE (WEIWEI & TERUHIKO, 2017).

Truss Bridge

A truss is a load-carrying superstructure that acts as a beam subject to axial forces. Its elements react to load in tension and compression. Its elements respond to dynamic loads in tension and compression. Within this system, the joints or connections are the most important structural component.

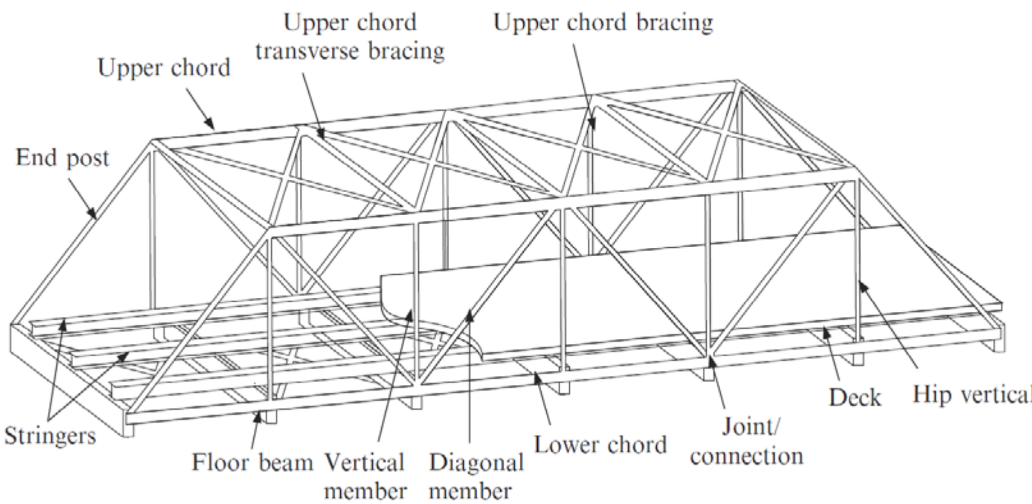

FIGURE 18: TRUSS BRIDGE TERMINOLOGY (WEIWEI & TERUHIKO, 2017).

Arch Bridge

This bride typology is distinguished by a curved structure supported by abutments at each end, and it functions by transferring dead and live loads vertically onto the foundation. The advantages of this bridge typology are that the cross-section is subject to compression. On the other hand, the disadvantages are heavy deadweight and relatively high deck height.

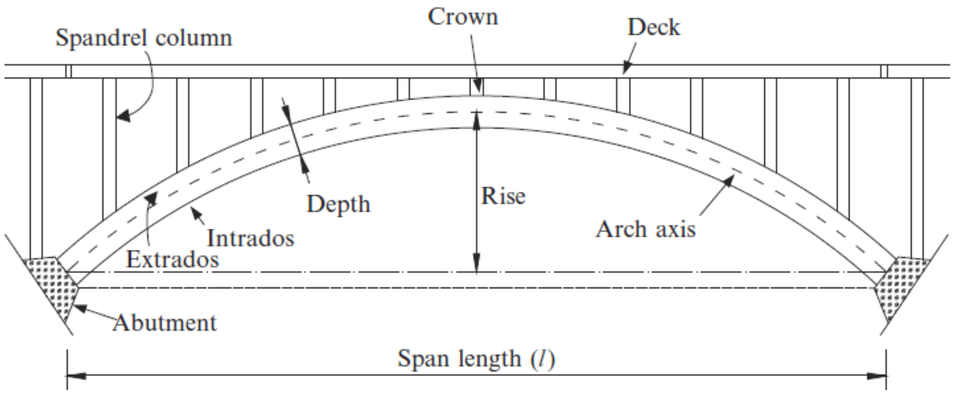

FIGURE 19: ARCH NOMENCLATURE (WEIWEI & TERUHIKO, 2017).

Suspension Bridge

Similarly to the cable-stayed bridge, the suspension bridge is a structure in which the deck is supported by main suspension cables on a vertical suspender. Within this typology, the main load-carrying member are the cables.

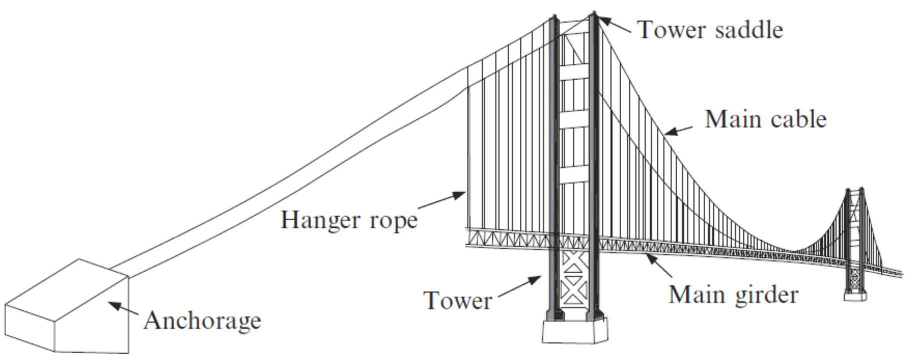

FIGURE 20: SUSPENSION BRIDGE COMPONENTS (WEIWEI & TERUHIKO, 2017).

Based on previews information, Table 4 compiled diverse bridge typologies by categories (fixed and movable) and classifies their composition by their main structural elements:

TABLE 4: GENERAL BRIDGE DCOMPOSITION OF MAJOR BRIDGE TYPOLOGIES AND THEIR MAIN STRUCUTRAL ELEMENTS.

Category	Typology	Main structural elements
Fixed - Bridge	Arch Bridge	Deck, abutment, arch, columns.
	Beam bridge	Deck, main girder, abutment, bearing.
	Cable-Stayed Bridge	Deck, cables, pylon.
	Suspension Bridge	Deck, main girder, tower, saddle, hanger rope, anchorage, main cable.
	Truss bridge	Deck, joint/connection, vertical and diagonal members, floor beam, stringers.
Movable - Bridge	Bascule bridge	Deck, main girders, abutment, bearing.
	Vertical-lift Bridge	Deck, vertical and diagonal members, towers, joint/connection, rope/cables.

Table 4 exhibits the deck, cables, and girders as the main structural elements of most of the bridge typologies. Important non-structural components of movable bridges, such as counterweights and hydraulic mechanical motors, could also potentially cause TEoL due to technical obsolescence.

3.3.2. Decomposition of RWS based on NEN 2767-4

Within the different typologies of bridge structures, there are structural subsystems that conform the core system project, such as, foundation, substructure, and superstructure (Mitchell, 2017). This idea can englobe a subsystem categorization for easy analysis of bridges, but this research intends to investigate the component level. To be able to generalize the criteria to all the bridge typologies within RWS portfolio a clear decomposition of the bridge components must be set. Component level is defined as; a distinctly identifiable part of an object composed of one or more elements and intended to serve a specific objective (IM-SAFE Knowledge Base, 2022). To state the bridge components, the NEN 2767-4 will be used. This national standard follows the method of determining the condition of buildings, infrastructures, and other management objects. Based on the decomposition of RWS, in accordance with the NEN 2767-4, the following standard levels of decomposition were utilized in this specific hierarchy:

TABLE 5: HIERARCHICAL LEVELS PROVIDED BY NEN 2767-4 AND EXAMPLES (VIANA DA ROCHA, 2013).

Level		Examples
Area data	(1) Main system	Highways network
	(2) System	Ring road system Amsterdam
	(3) System part	Highway between interchanges A and B
	(4) Object	Bridge, tunnel and road section
Decomposition	(5) Element	Piers, bearings and pavement
	(6) Building component	Top layer, expansion joint seal

By utilizing the RWS standard decomposition method for the identification of TEoL criteria, an alignment of data was set for data collection. Further in the research, the elements and components of interest within the steel bridges were discussed and selected.

In addition to the decomposition based on the NEN 2767-4, the bridge can be categorized by major functional components. As suggested in the Bridge Inspector's Reference Manual (2023), most bridges can be divided into several major components:

- The deck, as the main load-bearing element that is has direct contact with the traffic load.
- The superstructure is composed of a set of structural elements that carries the dead and live loads that interact with the bridge (e.g. girders, trusses, cables).
- The substructure, as the elements that support the superstructure and transfer the loads to the foundation (e.g. piers, abutments, wing walls).

The thought behind the additional categorization of bridge elements and building components is to propose a method to organize the elements in a way that identification, understanding of load distributions, material-specific damages and defects, and effective inspections can be issued.

3.3.3. Building Components of a Steel Bridge Deck

Building on the preceding, the main load-bearing components are listed in Table 4 highlighting the deck as one of the main structural elements used in all bridge typologies. The OSD is of particular relevance in the

RWS portfolio due to its strong utilization and its attributes such as lightweight, high load-bearing capacity, and fast construction, making it a relevant element of interest for this research.

Orthotropic Steel Deck (OSD)

The OSD is a steel structure deck design developed in the 1930s. The design is composed of an orthogonal transverse crossbeam and a thin steel deck plate that rests on top of a series of longitudinal stiffeners set near apart. This structure then connects to longitudinal girders that transfer the dead load of the OSD and traffic load to the foundation. Figure 21, illustrates the composition of the OSD:

Compared to a concrete deck, the OSD structure presents several advantages and disadvantages within the design of a bridge. The advantages include its low weight, which is beneficial for long-span applications, and its fast construction process. However, the disadvantages encompass high prefabrication costs and susceptibility to fatigue (Pavlovic, 2023).

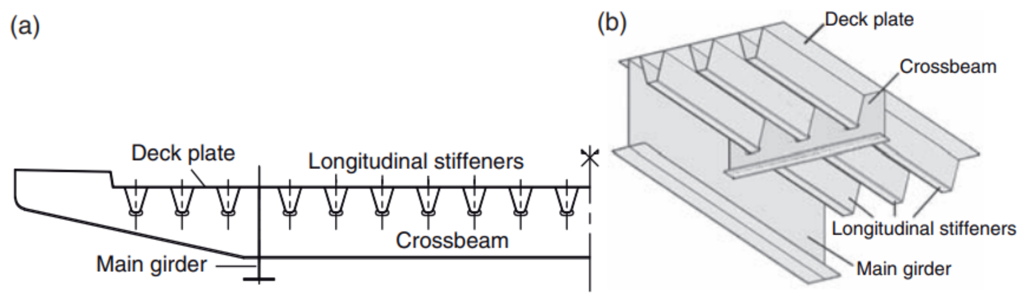

FIGURE 21: ORTHOTROPIC STEEL BRIDGE DECK COMPONENTS: (A) CROSS SECTION, (B) UNDERSIDE VIEW (DE FREITAS ET AL., 2011).

Longitudinal stiffeners, also called ribs or toughs can have different geometries (Figure 22). These components alongside the deck plate are responsible for transferring the live loads to the crossbeams. Depending on the design requirements and composition of the OSD, the troughs can have an open or closed geometry. Closed troughs have high torsion resistance, bending stiffness, and are typically used within steel deck compositions that have exposed the lower side of the deck, usually for 3-5m spans. On the other hand, open troughs have a low torsion resistance and are commonly used within closed decks as stiffeners to the deck walls of box girder webs and bottom flanges, usually for spans between 2-3m (Pavlovic, 2023).

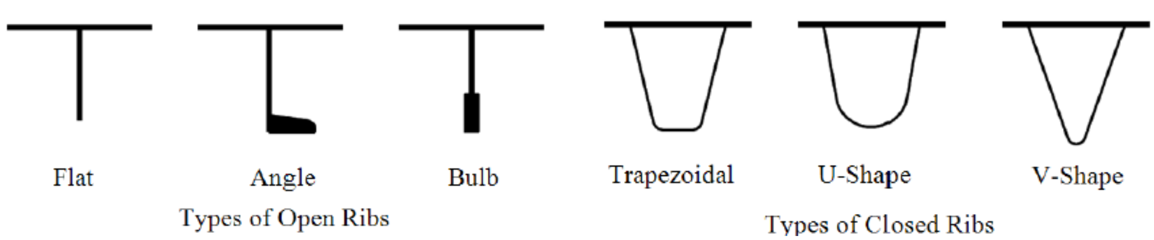

FIGURE 22: COMMON RIB TYPES FOR ORTHOTROPIC DECKS INCLUDING CLOSED AND OPEN RIBS (U.S. DEPARTMENT OF TRANSPORTATION, 2012).

Closed and open troughs, along with the cross beams and the deck plate, are welded together to form a single, unified load-bearing element within the structural system. Over the years, this preferred deck solution has faced several challenges caused by increased traffic load, and technical advancements such as the addition of the cut-outs in the lower portions of the closed ribs (Figure **23**). This modification was implemented to alleviate the accumulated stress that arises between the crossbeam and the trough (U.S. Department of Transportation, 2012).

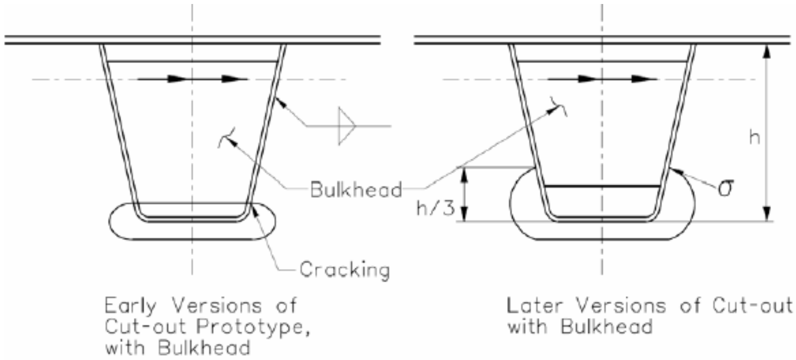

FIGURE 23: EARLY VERSIONS OF STRESS RELIEF CUT-OUT SHAPES FOR THE TRAPEZOIDAL SHAPED RIB (U.S. DEPARTMENT OF TRANSPORTATION, 2012).

The closed troughs, when in combination with the crossbeams, suffer from high secondary stress directly in the bottom side of the trough, which can be mitigated by cutouts. Due to the addition of these new degrees of freedom, the welding becomes complicated, thus, the weld quality declines. To reduce stress concentration, the innovative idea of bulkheads was introduced to the reliability of OSDs (Zhu et al., 2018) (Romeijn, 2006). Figure 24, illustrates two types of bulkhead applications:

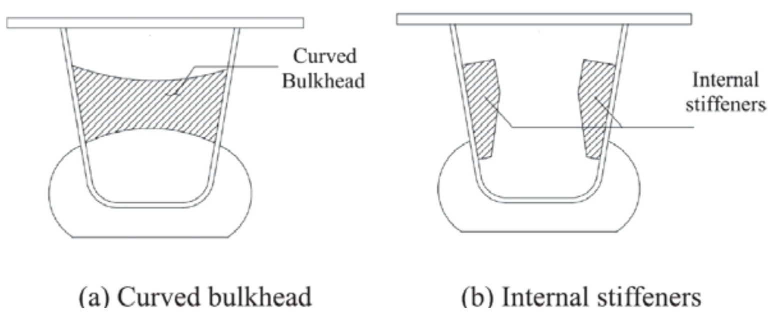

FIGURE 24: TWO BULKHEAD SHAPES (ZHU ET AL., 2018).

Zhu et al. (2018) conducted a qualitative analysis investigating the fatigue behaviour of bulkheads within closed U-troughs. Their study concluded that incorporating these reinforcements significantly diminishes tensile stress at the trough-to-crossbeam connections, thereby enhancing the fatigue life of the deck.

3.4. Existing EoL Models and Tools

Given the considerable number of civil infrastructure assets that need to be replaced or renovated, asset managers and owners, in collaboration with academia, are actively seeking effective solutions to this urgent challenge. Currently, there are models proposed for use in different civil infrastructure projects, such as, navigation locks. Therefore, this section investigated and deconstructed these models, to subsequently developed a foundation for a preliminary TEoL framework for bridges, alongside an investigation into the essential information needed to analyse a portfolio of assets. The next paragraphs examined current EoL models and tools that could provide input for the assessment of specifically the TEoL for steel bridges.

3.4.1. EoL of Navigation Locks

In the multi-case study of Bektas & Ozer (2023), a model was developed to determine the technical, functional, and economical EoL of the navigation locks managed by RWS based on object-specific aging components and objectified sets of conditions. The research provides analysis of under which condition a navigation lock becomes potential for reaching its EoL and enables this analysis on portfolio level through a rule-based semantic model developed based on utilizing knowledge on domain judgments. This research by Bektas & Ozer gives path to a similar TEoL model analysis for specifically bridge assets within the portfolio of RWS.

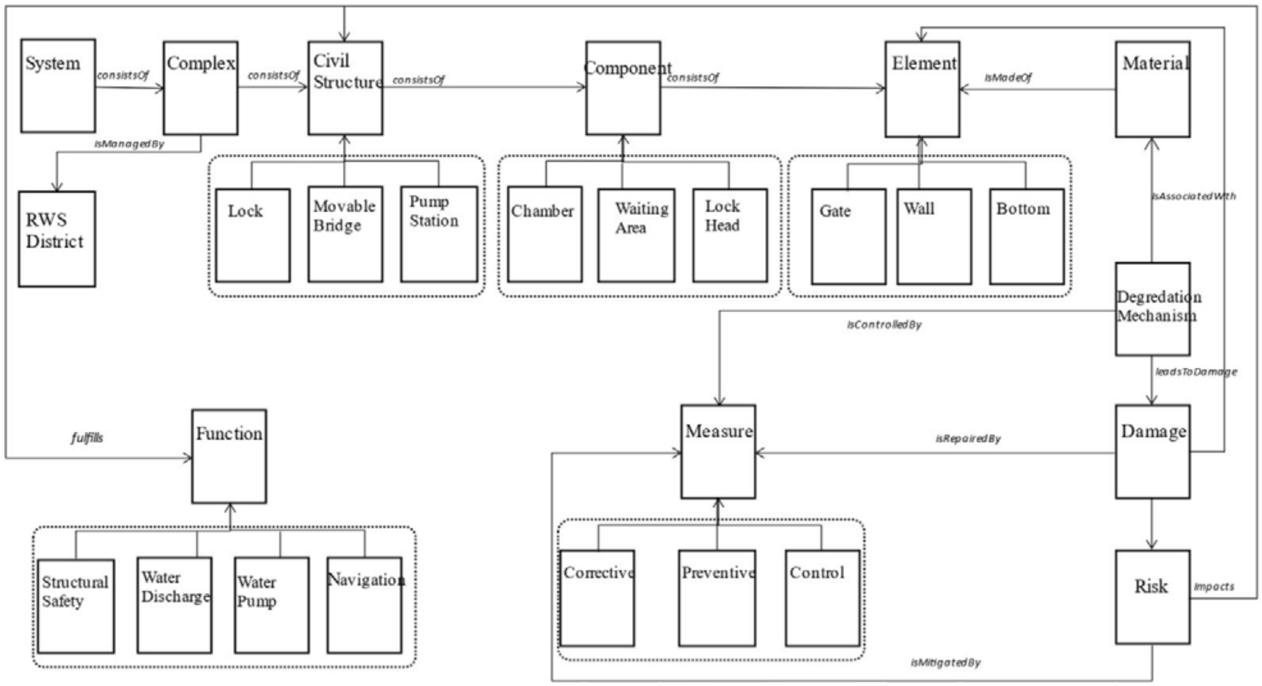

FIGURE 25: THE TOP-MODEL OF THE INFORMATION MODEL (SIMPLIFIED SCHEMATIC ILLUSTRATION FOR MAIN CONCEPTS - EXCLUDING DATA PROPERTIES AND CARDINALITY CONSTRAINS) (BEKTAS & OZER, 2023).

Figure 25 illustrates the model's hierarchical decomposition which is based on the NEN 2767-4. Additionally, material properties, degradation mechanisms, damages, and risks are considered.

3.4.2. Quick Scan Tool

The "Quick Scan" is a tool developed by van Es and Maljaars (2017) for the Dutch research organization TNO. This tool allows users to quickly assess the structural safety of a bridge. The quick scan evaluates the structural integrity of a bridge using valid construction standards, static control based on the unity check formula, and fatigue control data. The tool is a spreadsheet that changes as the user enters new data and assumes the data that is missing.

The unity check is a qualitative assessment under the NEN standard that evaluates the structural integrity of the bridge by examining the ratio of the acting load to the designed load-bearing capacity. This ratio determines if the bridge is within permissible safety limits, therefore the ratio must be less than or equal to 1 (De Vlieger, 2011).

$$Unity\ Check = \frac{Acting\ load}{Designed\ load - bearing\ capacity}$$

EQUATION 1: UNITY CHECK EQUATION.

Currently, this tool does not calculate the fatigue of OSD. In the near future, a module is scheduled to be introduced that estimates the lifespan of OSD road decks based on the number of vehicle crossings and the detection of first cracks on bridges with a comparable deck. At the time of this research, this type of tool is not suitable for a portfolio analysis since it requires specific load data that is not always available and the evolving procedure that it has.

3.4.3. Condition Measurement

Based on NEN 2767-1, the condition score is a measurement that takes place on the basis of qualifying and quantifying defects in an element and component level (NEN 2767-1, 2011). This score is intended to measure the real state of an asset. To determine the condition score, damages are evaluated based on severity, intensity, and magnitude. These indicators combined create a condition score which ranges on a qualitative scale from 1 to 6.

TABLE 6: DESCRIPTION OF CONDITION SCORES (NEN 2767-1, 2011).

Condition score	Description	Explanation
1	Excellent condition	Occasional minor defects
2	Good condition	Occasional onset of aging
3	Reasonable condition	Locally visible aging Functional performance of construction and installation parts is not at risk
4	Moderate condition	Functional performance of construction and installation parts occasionally at risk
5	Poor condition	The aging is irreversible
6	Very bad condition	Technically ready for demolition

The condition score is an approach that could be used to identify TEoL criteria, not necessarily the score but the damage evaluation that is used to determine the score. By analysing each structural and critical component of a bridge and assigning a damage score, a risk assessment can be done. This damage score ranges also on a qualitative scale from 1-6, defining 1 as “No damage” and 6 as a “direct threat to safety or performance”. This qualitative method in conjunction with the data from case studies and articles were used for the development of the preliminary framework.

3.4.4. Aging Curve

The aging curve is a graphic analysis approach described in NEN 2767-1 that depicts the ratio between the condition score and the technical lifespan of a component. This graph is used when there is an absence of conditional data on a component regarding observable defects that are subject to wear and tear. In these extreme cases where there is no data, the condition score is determined using the aging curve (Figure 26).

Further research could look into the feasibility of using this graph inversely, to determine the remaining technical lifespan based on the current condition score. This method can therefore be used to examine the TEoL of bridge components at the portfolio level since the timeframe of assessment is short, and it only requires the condition score.

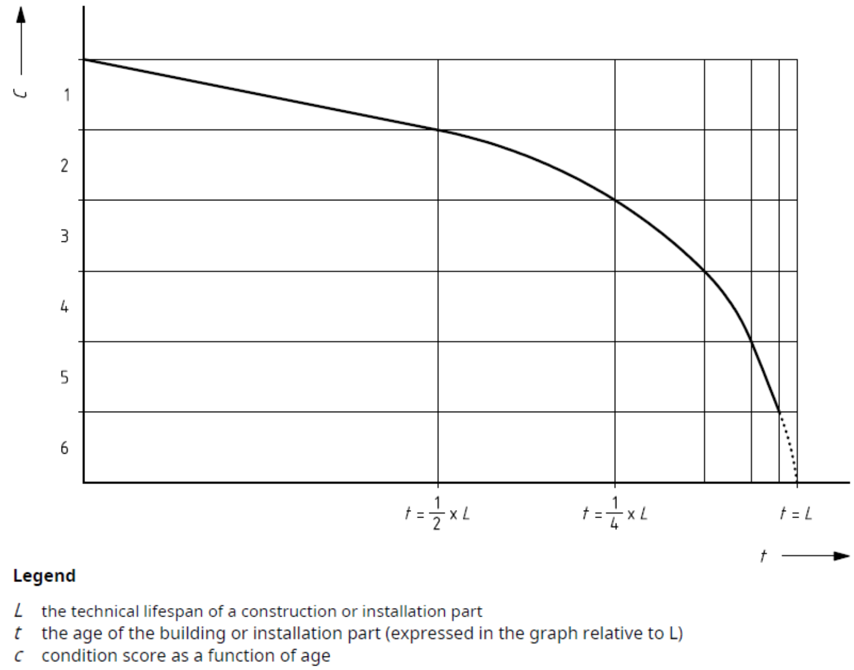

FIGURE 26: CONDITION PROGRESSION AS A FUNCTION OF THE (RESIDUAL) LIFESPAN (NEN 2767-1, 2011).

3.5. DATA FROM RWS

According to the research of Viana da Rocha (2013), the database DISK is a single-user system used exclusively to support processes within RWS. Within this database, inspection data, project data, maintenance measures, costs, and other relevant information regarding their assets are stored. The collected data then is used for maintenance optimization, prioritization, and programming. Figure 27, exemplifies the input and output within DISK.

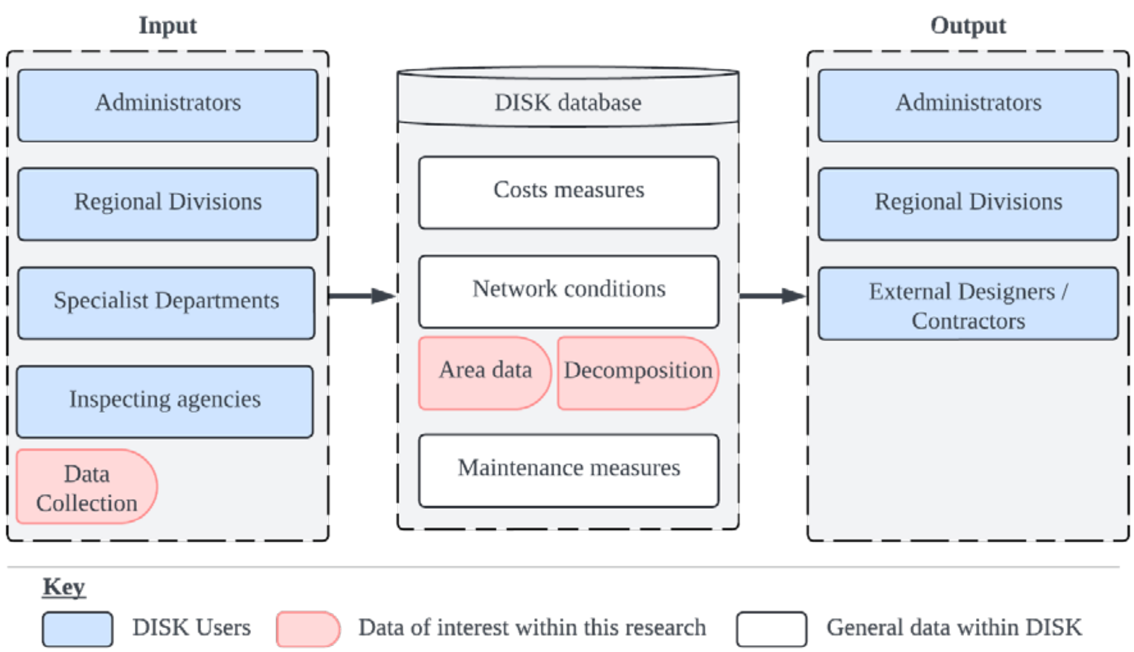

FIGURE 27: RELATIONSHIP AND LOGIC BETWEEN THE INSPECTION REPORTS AND THE DATABASE DISK BASED ON THE RESEARCH OF (VIANA DA ROCHA, 2013).

The data of interest is within the input data and the database itself. In the following sub-sections, the inspection data, as well as the network conditions of DISK were further explored.

3.5.1. DISK

The Data Informatie Systeem Kunstwerken (DISK) is a database developed by RWS that consolidates inspection report data and maintenance planning information for various infrastructure assets, including bridges, locks, and viaducts. DISK was developed to manage the structural conditions of these assets, provide a direct overview of object-specific status (condition assessment), evaluate network conditions, calculate cost measures, and facilitate efficient data maintenance and management. This includes data for maintenance programming through optimization and prioritization of maintenance activities at a network level (Viana da Rocha, 2013).

TABLE 7: RESUME OF DISK DATA USAGE (VIANA DA ROCHA, 2013).

	Name	DISK/ MIOK
Usage information	**Aspect**	**Description**
	For budget preparation	Yes, costs are fed into the network planning system
	For setting of performance standards (e.g. target average condition states)	The structure quality index *(see assessment inspection on structure level)* is used as a KPI on network level.
	For matching funding sources	Not in the system. Matching funding sources is a feature of the network planning system (RUPS).
	For managing special (overweight) transports (e.g. granting permits to cross)	Basic data like design class and results of assessments on capability for overweight transport is in the system. Operations for special transports are treated in another system using this data .
	Additional	-

There are different people involved in storing and data collection within DISK. As explained in Figure 27, object inventory data is managed by administrators (central and/or regional), or by authorized users (e.g. designers or inspection teams). Direct administrators only perform the inspection planning and clustering. Inspection and intervention data are exclusively collected and stored by inspection agencies. Direct information from DISK was not utilized within this research due to being unable to gain authorization to access RWS's data. Therefore, only the process and the protocols were utilized. In Figure 27, the Network conditions are based on the NEN 2767-4 (Table 5) within the DISK database schematic. This concept is divided into Area data and Decomposition. The Area data encompass the Management Object – Level 4 that describes the general characteristics of the infrastructure asset, in this context, the bridge. Within the Decomposition, Level 5 – Element, and Level 6 – Building Component data were gathered (see Appendix section □B). Following, the utilized data for each of the decomposition levels is described:

<u>Level 4 – Management Object</u>

This level describes the general characteristics of the bridge, which include, description and identification, location, network where it is located, and year of construction.

TABLE 8: SUMMARY OF LEVEL 4 - MANAGEMENT OBJECT DATA FOR PRELIMINARY FRAMEWORK.

Level 4 - Management Object	
1. Nomination and references	Name DISK code Description
2. Management property	Province
	Municipality

4. Network	Highway network (dry)
9. Historical data	Year of construction Designer name

Level 5 – Element

This level will collect the element's description data, material properties, and localization within the bridge.

TABLE 9: SUMMARY OF LEVEL 5 - ELEMENT DATA FOR PRELIMINARY FRAMEWORK.

Level 5 - Element	
1. Nomination and references	Description and name
2. Design properties	Material of object Tech description Length
3. Geographic properties	Position of element (L, M and R)

These selected data entries are based on the knowledge from the literature review. Degradation processes can be explored by collecting data such as material qualities, and localized fatigue stresses can be reported based on the element's position within the bridge.

Level 6 – Building Component

The lowest hierarchical level will collect information such as the name and design properties.

TABLE 10: SUMMARY OF LEVEL 6 - BUILDING COMPONENT DATA FOR PRELIMINARY FRAMEWORK.

Level 6 - Building Unit (Component)	
1. Nomination and reference	Name
2. Design properties	Material Form Name of manufacturer Tech description

3.5.2. Inspection Reports

An inspection involves the visual assessment of the physical components of an infrastructure, incorporating verifications, measurements, tests, and supervision. This process is crucial for obtaining an up-to-date, reliable, and comprehensive understanding of the infrastructure's condition, the associated risks, and the management strategies required to mitigate them (Rijkswaterstaat, 2021). In Appendix section C, RWS inspection types and timeframes are illustrated. Regarding the content of the inspection report, individual condition assessments of specific structural elements and components must be directly linked to the respective element or component.

The importance of the inspection reports within the study was to understand what type of information is captured and how this information can be utilized or arranged to analyse the TEoL of bridges at a portfolio level. Within this study, the inspection data for any of the multi-case study bridges was not available. The available inspection report data was a template to help understand how the information is registered.

3.6. The Preliminary TEoL Framework for Steel Bridges

Based on the information from previous sub-chapters, Figure 28 illustrates the preliminary framework that was used for the analysis of the bridge case studies:

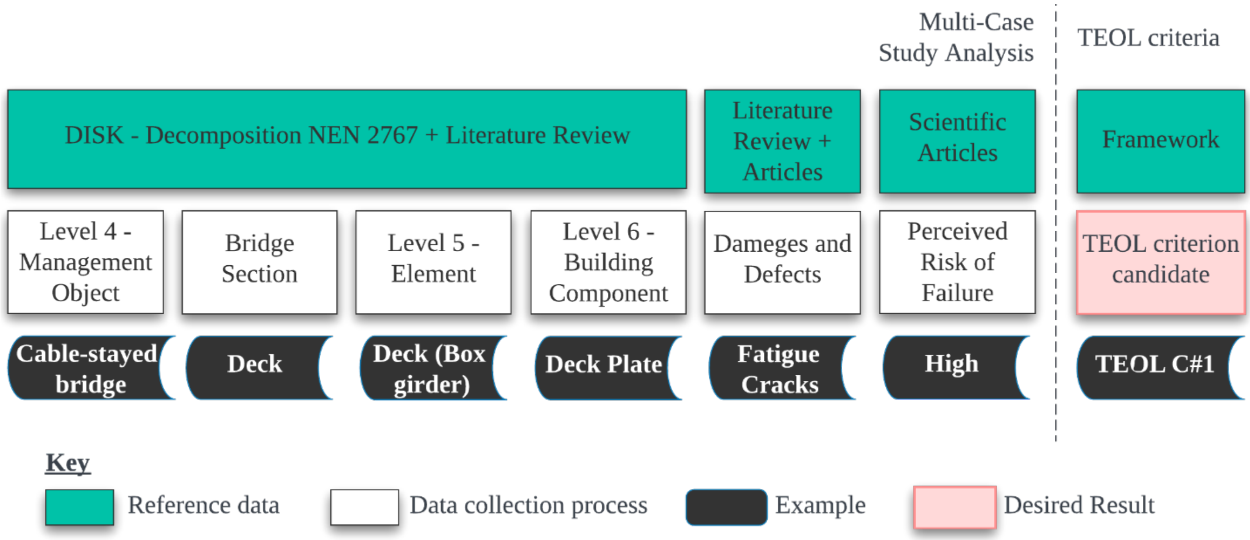

FIGURE 28: SCHEMATIC MODEL FOR THE CASE STUDY ANALYSIS WITH AN EXAMPLE.

This framework was fundamentally based on the information model developed in the research of Bektas and Ozer (2023) for navigation locks. The framework from Figure 28 is composed of 3 main sections: The decomposition, damage and defects, and the perceived risk of failure. The framework utilized a thematic coding approach, which is a form of qualitative analysis that identifies concepts that are alike or have the same idea into categories (Gibbs, 2007). From the information reviewed, keywords such as fatigue, risk of failure, deck, cables, and cracks were recorded under the specific classifications of the framework.

The first section integrated the decomposition standard from the NEN 2767-4 and the main bridge sections from the Bridge Inspector's Reference Manual (2023). This combination was made to potentially identify any cascade effects where the condition of one element may influence or deteriorate the condition of another. Such review can be key for identifying vulnerabilities that are not apparent when analysing isolated elements or components of the bridge.

The second section, "Damages and Defects" was dedicated to the properties of the observed damages, identifying potential causes, and establishing threshold levels if relevant data was mentioned within scientific articles or reports. This section also examined the complex interplay between internal influences, such as the ones mentioned in the sub-chapters of Damage Processes and Material Properties, and external influences like Human-Induced Factors and Traffic Loads. This section was incorporated to provide a potential technical limit state or threshold value, that could be utilized to identify TEoL criteria.

The final section, "Perceived Risk of Failure" was constructed based on the protocol of the Inspection Reports and the data required for the Condition Measurement. This was completely a qualitative assessment that relied on the professional judgment and observations of the inspector, which correspond to the damage level that is used to determine the condition score. According to the research of da Rocha (2013), the qualitative scale of damage levels is as follows:

1. No damage
2. Limited damage
3. Moderate damage
4. Much damage
5. Advanced damage
6. Direct threat to safety or performance

This scale was summarized as, High (damage score 6), Medium (5-4), and Low (2-3). This qualitative data was only registered if it was found within any of the case study analysis or scientific literature. In the event that data and literature were not available, the level of risk was estimated based on the author's tone. This data was of key importance since it emphasizes the potential risk of failure of the element or component, a concept coupled with safety, highlighting it as one of the primary indicators mentioned in the definition of TEoL.

The outcome of the preliminary framework was a data set that once condensed, a set of TEoL criteria candidates was created. These candidates were then validated in order to determine the validated TEoL criteria for the rule-based assessment.

4

IDENTIFICATION OF TEOL CRITERIA FOR STEEL BRIDGES

Within this chapter, the preliminary TEoL framework was utilized to assess four steel bridges (see Appendix section J). The data collected from the case studies was then consolidated into structured and concise TEoL rules which were then used for the validation phase.

4.1. In-Depth Multi-Case Study Analysis

This sub-chapter illustrates and analyses real-world examples of steel bridges that are currently under the research program set up by RWS called Replacement and Renovation (V&R), bridges that already underwent a major intervention or that are planned to have a major intervention. Each of the analysed bridges will exhibit a brief description, images of the civil infrastructure asset, geometrical data, the TEoL framework, and an extensive analysis of the damages and defects discovered. Figure 29, indicates the selected case studies and their location within the Netherlands:

Figure 29: Overview of the selected case studies.

4.1.1. Case Galecopper Bridge

The Galecopper Bridge is a double cable-stayed bridge managed by RWS located in Utrecht within the A12 highway (Figure 30). Being the second busiest bridge in the Netherlands with over 220,000 vehicles per day, the steel bridge is of critical importance to the transport network. The bridge is composed of 3 spans, a main span of 180m and two 70m spans, with a total length of 320m, and a width of 34m per direction (6 lanes in each direction, 12 in total). The bridge is composed of an OSD, steel pylons, 6 main girders, steel cables, reinforced concrete abutments, and piers (Figure 31). During the period of 2013 and 2015, the bridge underwent renovation, and replacement works to extend its service life for 30 years. The major intervention was executed due to the increase in cracks based on inspections in the 90's (Abspoel‐Bukman et al., 2023) (Structurae.net, 2023a).

According to the information gathered by TNO (2012), the south side of the OSD has round troughs, while the north side has trapezoidal trough profiles, and the main span has 4 cross beams. This information gives an insight into the geometrical composition of the OSD, which will be considered for the analysis. Until 2009, the north span had road deck plate cracks (Den Besten, 2012).

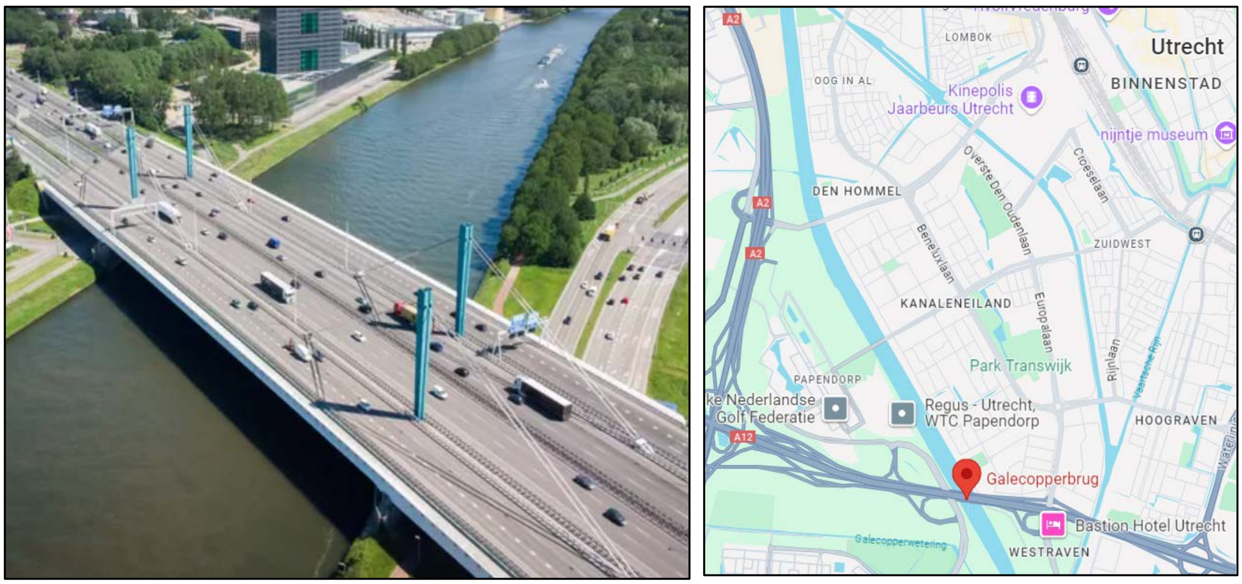

FIGURE 30: AERIAL PHOTO OF THE A12 AND THE GALECOPPER BRIDGE BY KOEN LAUREIJ, AND GOOGLE MAPS.

Based on the research and findings of Den Blanken et al. (2012) and Abspoel-Bukman et al. (2023), the Galecopper bridge had additional damages other than the ones located on the deck plate. During the first intervention around 2015, corrosion damage was found within the cables. Below, the intervention and the research findings will be further elaborated, including the decomposition of the defect elements, possible causes, and potential risks of failure.

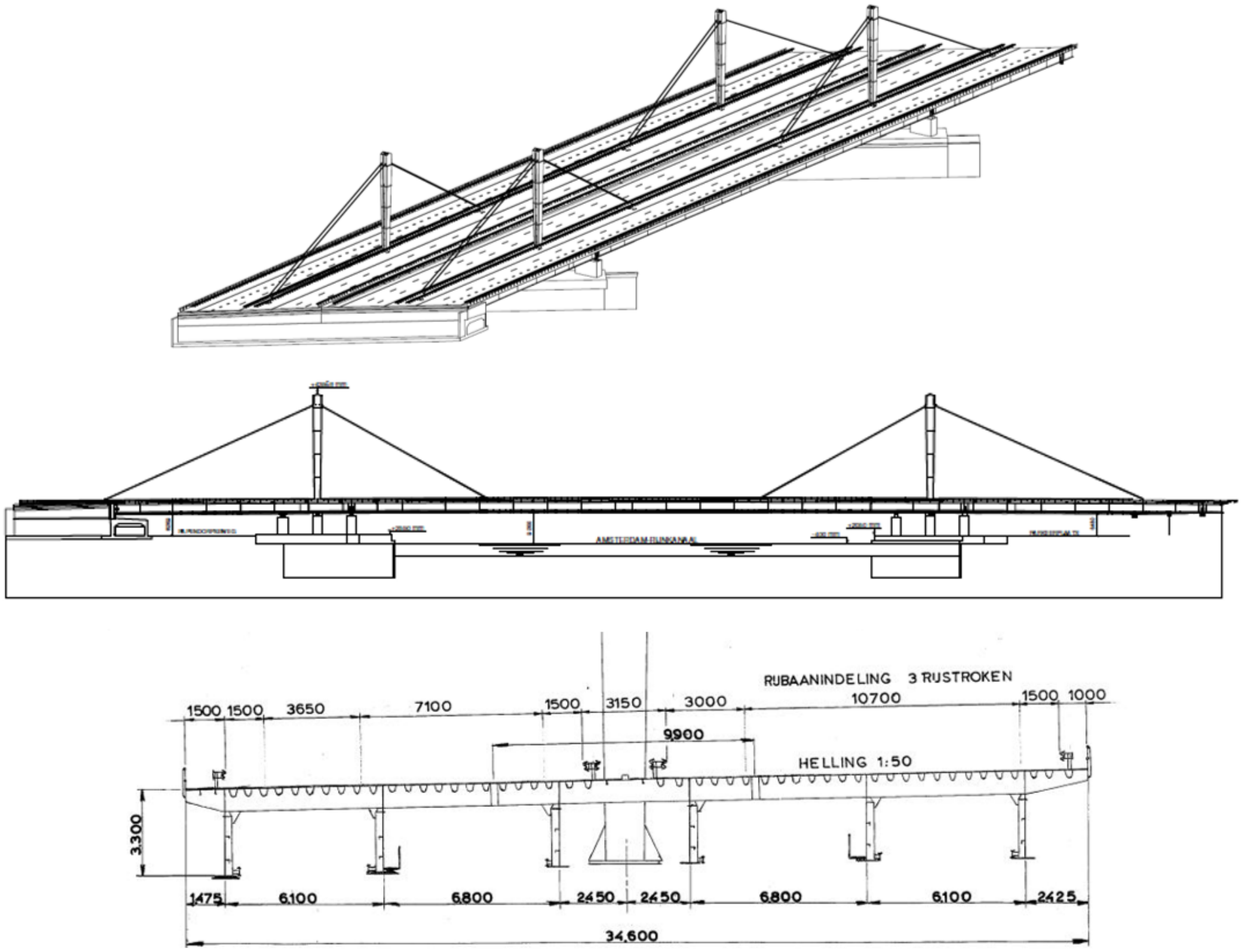

FIGURE 31: EXISTING STRUCTURAL SYSTEM OF THE GALECOPPER BRIDGE (DEN BLANKEN ET AL., 2012).

<u>Intervention 1:</u>

Before the first intervention, Den Blanken et al. (2012) exposed that the steel deck of the bridge suffered from fatigue cracks dated all the way back to the 90s. During the period of 2009, cracks were spotted within the road surface of the asphalt, identifying them as longitudinal cracks and the spider's web. These cracks were found to be influenced by the increase in traffic intensity and higher traffic weight over the past years. The exact location of these cracks within the deck and the number of cracks were not specified.

In Figure 32, the longitudinal cracks are illustrated within the central part of the road, following a parallel path of the troughs of the OSD. After deep investigation and conclusive analysis, it was determined that the primary issue was originated from the steel pylons and associated cables experiencing high stiffness due to overloading (Den Blanken et al., 2012). These stresses were then generating a cascade effect on the main girders, which were suffering from high bending as a result of insufficient bending capacity. This overstress further propagated into OSD crossbeams and deck plate. Finally, the concentrated stress ended up as fatigue cracks on the deck plate (Figure 33), manifesting as longitudinal cracks and the spider's web.

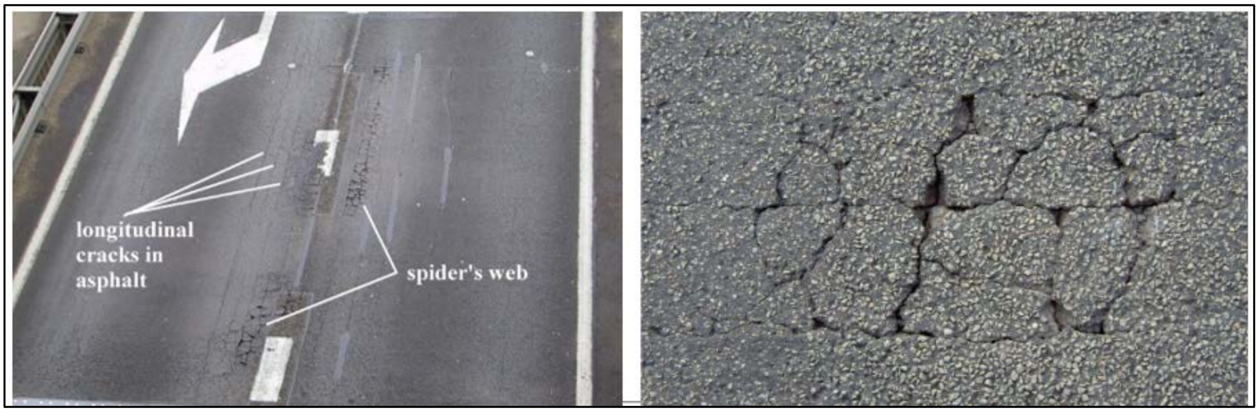

FIGURE 32: LONGITUDINAL AND SPIDER WEB CRACKS OF THE GALECOPPER BRIDGE (DEN BLANKEN ET AL., 2012).

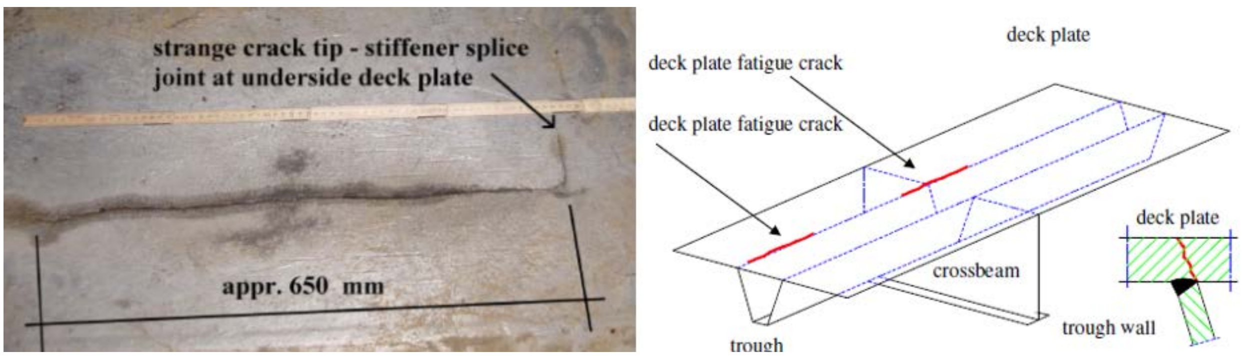

FIGURE 33: FATIGUE CRACKS IN THE DECK PLATE (DEN BLANKEN ET AL., 2012).

Research findings:

During the first intervention between 2013-2015, inspections found corrosion damage at the anchorages of the stay-cables at the south bridge (Abspoel‐Bukman et al., 2023). The detailed corrosion fatigue analysis concluded that the cables required structural intervention due to low and noncompliance safety performance levels.

Summary and remarks:

- The main influences that were detected within the case study were the high increase and intensity of the Traffic Loads, and the Environmental Factors that led to the corrosion of the cables. Besides these two factors, the research of Den Blanken et al. (2012) indicates that the cables carried more than 60% of the dead load and 40% of the live loads.
- The cascade effect was generated by the elements of the superstructure that ended with cracks on the deck plate. Based on the two studies, a potential cause-effect originating from the overload of the cables could be the corrosion damage found within the first intervention.
- High Strength Concrete (HSC) was used to repair the deck plate cracks. Although installing this extra layer strengthens the deck, the increased deadload may become a concern in the short term, as seen in the case of the overloaded cables.

Case study conclusions

With the findings in the case study and the literature review of the damages of interest, potential TEoL criteria are described based on the Galecopper bridge case:

TABLE 11: GALECOPPER CASE - TEOL CRITERIA CANDIDATES FOR STEEL BRIDGES.

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
1	Cable-stayed bridge	Superstructure	Cables	-	Corrosion	Medium and High
2	Cable-stayed bridge	Deck	Deck (OSD)	Deck plate	Fatigue cracks	High

For the TEoL criterion No. 1:

- The risk of failure was defined as medium only if there is a high visible presence of corrosion within an aging cable, due to localized condensation of moisture and failures of the external protective sleeve. It is recommended to inspect the anchorage where the lower part of the cable is connected. The threshold of these criteria lies solely in the expert judgment of the inspector. Further information will be provided within the expert interview section.
- The risk of failure was defined as high only when the corrosion damage diminished the cross-section area to less than 40% of its original size (Gao et al., 2023). The study concluded that with a 40% of cross-section loss due to corrosion, a nonlinear decrease of the ultimate strain is observed.

For the TEoL criterion No. 2:

- The risk of failure was defined as high when the deck plate shows a longitudinal crack of 500 mm or longer between the stiffener and the deck plate (Romeijn, 2006). This is true for a deck plate crack that originated near the crossbeam area. In the case of the Galecopper bridge, a deck plate crack of 650 mm was registered, the location is based on Figure 33.

Case study remarks:

- Damages within the superstructure can lead to cascade damages to elements within the Deck and the substructure. Inspection revealing damage within a specific element can potentially be caused by functional failure of other load-bearing structures.
- The HSC requires further investigation due to its brittleness, which is correlated to low ductility. If the traffic loads increase, the lower ductility of the element makes it more susceptible to cracking.
- The complete information of the preliminary framework for this case study is within the Appendix section A).

4.1.2. Ewijk Bridge

The Ewijk Bridge, also known as the Tacitus Bridge (object named by RWS), is a 1,055-metre-long fixed structure built in 1976, consisting of five traffic lanes, and located within the highway A50 within the Dutch network. The bride structure consists of ten spans, with a 480m long cable-stayed section that is over the Waal River (Figure 34). The cable-stayed bridge consists of a superstructure composed of high-strength steel wires, two pylons, and a trapezoidal box girder with OSD composition on the top and bottom flanges that extends over the ten spans (Figure 35) (Argentini et al., 2015) (Flint et al., 2013)(Lavery et al., 2013).

FIGURE 34: THE EWIJK BRIDGE. NEW BRIDGE (2014) LEFT, AND OLD BRIDGE (1976) RIGHT BY JEROEN STROES PHOTOGRAPHY, AND GOOGLE MAPS.

A consortium of contractors supervised by JV Managing Contractor (Arup, Royal Haskoning, and Greisch) completed the renovation work between 2012 and 2014. The intervention's scope included supplying HSC to the old structure to solve fatigue fractures in the steel deck as well as steel reinforcement for the box girder. The intervention's construction cost was €68.7 million (Flint et al., 2013). Additional research also revealed that the bridge’s stay cables had fractured wires. According to visual inspections carried out between 1990 and 2012, the research concluded that the defects were caused by manufacturing processes (Maljaars & Vrouwenvelder, 2014).

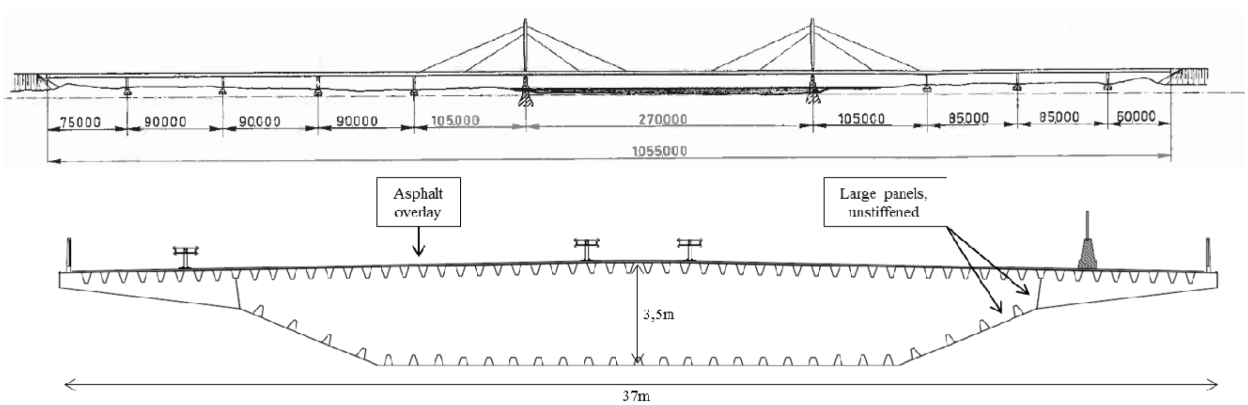

FIGURE 35: ELEVATION AND DECK STRUCTURE OF THE EWIJK BRIDGE (FLINT ET AL., 2013).

During the 90s, an initiative was carried out to review the condition of the steel bridges in the Netherlands. For the Ewijk bridge, fatigue damage was detected within the deck plate due to increased traffic overload and magnitude (Flint et al., 2013). The renovation included:

- Deck plate repairs and strengthened the 37m wide and 3.5m deep box girder to meet increasing load demands.
- Replacement of the fractured cables.

In the following paragraphs, each of the two renovations was explored.

Deck plate repair and box girder strengthened

The deck plate located in the upper part of the box girder showed local fatigue cracks due to overload caused by traffic. Other relevant traffic effects can be high density (number of vehicles passing), conditions (e.g. traffic jams), and road signs. In the proceedings of Flint et al. (2013), a numerical model was developed to highlight the localized stress within the deck. The results are illustrated in Figure 36:

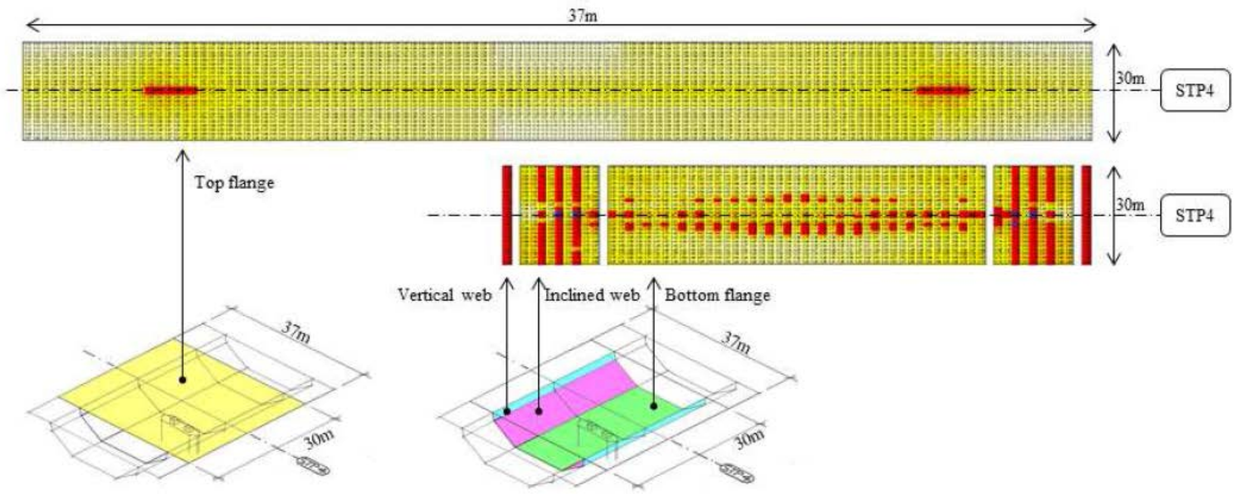

FIGURE 36: SUMMARY OF THE NUMERICAL MODEL ASSESSMENT OF THE GOVERNING SECTION IN THE SOUTHERN APPRACH SPAN (FLINT ET AL., 2013).

The red and purple areas indicate areas of higher stress compared with the original design capacity, the unity check ratio was used to determine these sections (red > 1, and purple > 2). Based on these findings, the solution was proposed by installing steel bearings to reinforce the upper and lower flanges of the deck (Figure 37). It was concluded that the bracings were strictly required to maintain the structure's integrity of the load-bearing element (box girder).

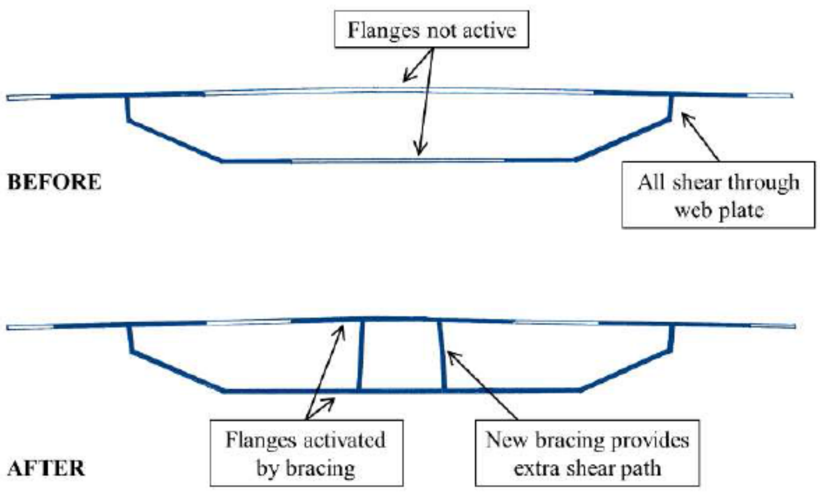

FIGURE 37: BRACING SOLUTION (FLINT ET AL., 2013).

In this specific case, the direction and localization of the high traffic was irrelevant due to the fact that the structure suffered from overload due to lack of support.

Replacement of the fractured cables

Ewijk bridge's cable-stay system consists of two steel pylons 270 meters apart over the river crossing. Each of the pylons secures an upper and lower set of cables, each one with a diameter of 101mm. The upper cables consist of 5 sets of strands with a length of 204m and the lower set has a length of 120m with a bundle of 3 strands. Each strand is composed of 235 wires arranged in 9 layers (Maljaars & Vrouwenvelder, 2014) (Lavery et al., 2013). Figure 38, illustrates the bridge elements:

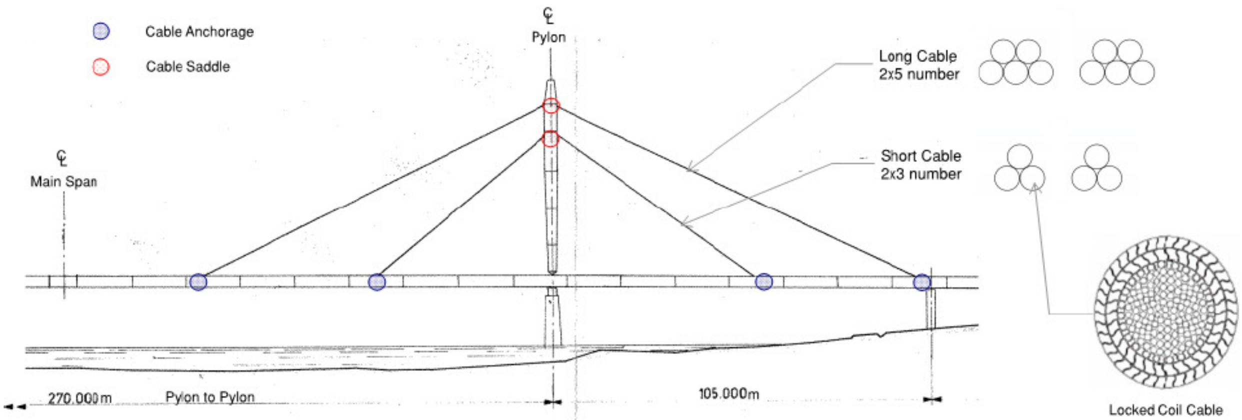

FIGURE 38: HALF ELEVATION OF MAIN SPAN AT EWIJK AND CABLE DETAILS (LAVERY ET AL., 2013).

To address local fatigue in the upper flange of the box girder, HSC reinforcement solution was proposed. As a result, the cables underwent inspection procedures to assess and recalculate their capacity to withstand the new load. The inspection revealed the presence of micro-fissures in the cables, leading to wire fractures along their lengths. Based on these findings, probabilistic assessments determined that the remaining life of cables could not be guaranteed (Lavery et al., 2013). In the research of Maljaars and Vrouwenvelder (2014) the inspections of 1990 and 2012 regarding the state of the cables were further discussed.

In the inspection of 1990, 11 fractured wires were found within the upper set of cables within the external layer, section A-A of Figure 40. The inspected length of the cable was 97.25m, almost half of the total length. Before the intervention, the inspections in 2012 revealed 29 fractured wires within the same strand. Laboratory examinations concluded that the initial defects in the cables were attributable to manufacturing problems. Initial cracks began to grow within the defected wire despite the moderate loading, ultimately leading to a fracture. The defects exhibited depths ranging from 0.1 to over 0.5 millimetres, with fractures spaced between 0.5 and 5 millimetres apart (Figure 39). Finally, the reason behind the fractures were laminations which was developed during the rolling process of the full lock wires (Maljaars & Vrouwenvelder, 2014).

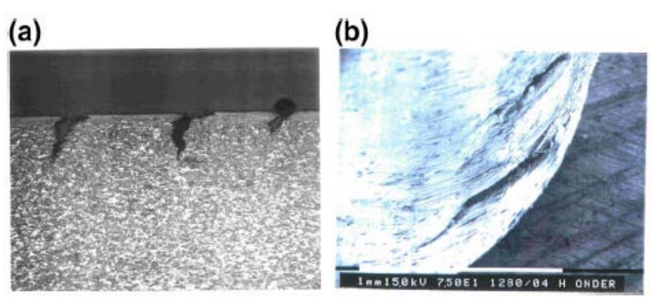

FIGURE 39: EXAMPLES OF INITIAL DEFECTS (LAMINATIONS) DETECTED IN THE FULL-LOCK WIRES (DEPTH APPR. 0.5 MM) (A) SECTION OF THE WIRE IN THE LENGTH DIRECTION. (B) SURFACE OF THE WIRE) (MALJAARS & VROUWENVELDER, 2014).

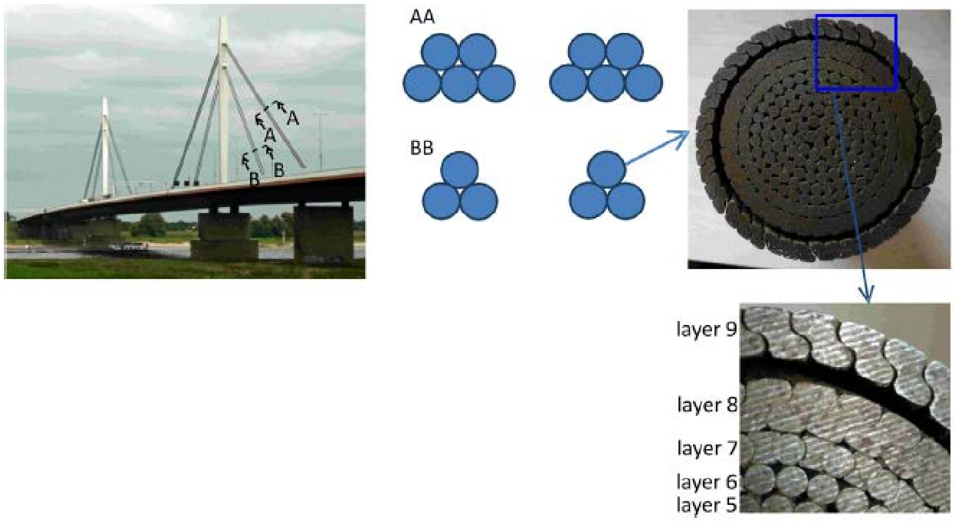

FIGURE 40: OVERVIEW OF THE EWIJK BRIDGE WITH ITS STAY CABLES (MALJAARS & VROUWENVELDER, 2014).

Summary and remarks:

- The main influences that were distinguished within this case study were: Traffic Loads, due to the increase in traffic over the years, and Material Properties, in this specific case, manufactured defects.
- The moderate increase in traffic load was not solely the responsible the localized fatigue within the deck plate of the box girder, as concluded with the numerical model, the structure suffered from overload due to lack of support.
- During the renovation process of the Ewijk bridge, the implementation of the HSC resulted in increased loads in the cables by approximately 15%. With the increase in deadload, additionally to the fractures, the cables needed to undergo a major intervention.
- The cables underwent a like-for-like replacement. During the design process, alternative cable types were proposed; however, these proposals did not move forward because the commercial saddle systems available on the market were incapable of accommodating the necessary design cable system.
- The full lock wire system (the current cable system of the bridge) is more prone to fatigue failure than other alternative types.
- Lamination during the manufacturing rolling process was the main defect behind the discovered fractured wires that led to the cable replacements.
- Given that the defect resulted from a manufacturing process, further research on the topic of full lock wire manufacturers would be of great insight for other cable-stayed or suspension bridges within the Netherlands. The information of the manufacturer can be found within DISK, in the decomposition level 6, building component (IS part), under design properties (Table 32).

Case study conclusions

With the findings in the case study and the literature review of the defect of interest, potential TEoL criteria were described based on the Ewijk bridge case:

TABLE 12: EWIJK CASE - TEOL CRITERIA CANDIDATES FOR STEEL BRIDGES.

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
3	Cable-stayed bridge	Superstructure	Cables	Wires	Fractures (Lamination)	High
4	Cable-stayed bridge	Deck	Deck (Box Girder)	Deck plate	Local fatigue (cracks)	High

For the TEoL criterion No. 3:

- The risk was defined as high when lamination is detected within fractured wires. However, these microfractures are extremely challenging to detect during standard visual inspections, as they are invisible to the unaided eye. According to Adewole and Bull (2016), pre-service, crack-like laminations in wires remain undetectable even after performing wrap tests, which are commonly used to reveal surface defects. Therefore, microscopic examination techniques are essential for accurately identifying these imperfections.
- Another criterion would be to identify the manufacturer. If the information of the manufacturer is disclosed and can be traced to other cable-stay bridges, this could be a potential indicator for a major intervention.

For the TEoL criterion No. 4:

- The risk was defined as high based on the major intervention the deck underwent and the tone of the author. Based on the numerical model, the structure was not designed to meet the new traffic load demands. This criterion has specific characteristics since it only applies to box girder decks that lack load-bearing structures (bracings) due to localized fatigue.

Case study remarks:

- The case data lacked information on the characteristics of the fatigue crack and localization within the structure.
- Further study is needed to improve the detection of lamination and corrosion in steel wires during normal inspections for cable-stayed bridges for more precise maintenance strategies. Appendix section G illustrates a list of cable-stayed bridges within the Netherlands, therefore, highlighting the relevance of the topic.
- The complete information of the preliminary framework for this case study is within the Appendix section A)

4.1.3. VAN BRIENENOORD BRIDGE

The Van Brienenoord bridges are a set of movable steel bridges that are composed of an arch bridge section and a bascule bridge (Figure 41). Each bridge has a total length of 1320m; 300m is part of the arch bridge, and 60m for the bascule bridge. These infrastructure assets are located within the national highway A16 in the municipality of Rotterdam and over the new mass river. The Van Brienenoord bridges comprise 12 lanes that carry about 230,000 vehicles daily and 120,000 ships per year, making it one of the busiest bridges in the Netherlands (Acosta et al., 2023) (Structurae.net, 2023b).

The Van Brienenoord bridges were constructed between 1965 (I) and 1990 (II). In 1965, the western arch was first constructed, and in 1990, the eastern arch was incorporated. The arches have a high approximately of 40m and a width of 25m (old) and 27m (new) (Acosta et al., 2023).

FIGURE 41: THE VAN BRIENOORD BRIDGE BY MEGACONSTRUCCIONES.NET, AND GOOGLE MAPS.

During visual inspection in 1997, signs of fatigue cracks were detected within the OSD of the bascule bridge (Maljaars et al., 2012). Based on these defects and the noticeable increase in traffic intensity and load over the years, a major intervention is planned for 2025. This major intervention aims to strengthen the plate stiffeners to the main girders, and the arches, and add a new deck (Acosta et al., 2023).

Damages in the second Van Brienenoord bridge

Only 7 years after the completion of the eastern bridge in 1990, an inspection revealed that the OSD within the bascule bridge section suffered from fatigue cracks in the deck plate. Due to the serious risk to safety that the cracks imposed, the bridge underwent a renovation that replaced the ticker plates in order to provide stability and security (Romeijn, 2006). Figure 42, illustrates the OSD repair works.

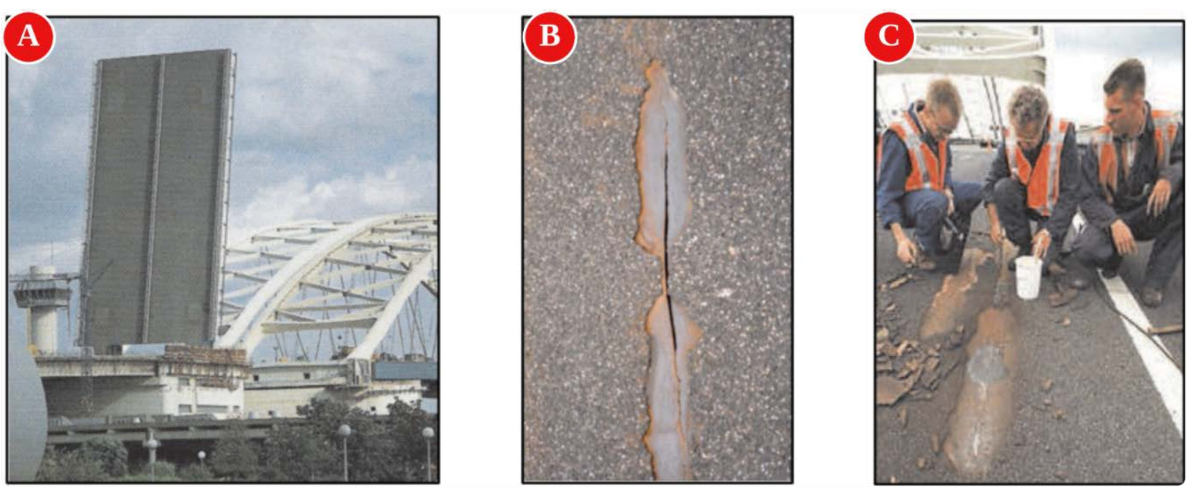

FIGURE 42: A) BASCULE BRIDGE OPEN 1990, B) CRACK IN DECK PLATE 1997, AND C) REPAIR WORKS 1997 (ROMEIJN, 2006).

The heavy traffic section of the bridge utilizes an orthotropic steel deck composed of a 12 mm thick deck plate. Reinforcement is provided by trough stiffeners with a wall thickness of 6 mm, spaced at intervals of 600 mm. Each trough stiffener is 300 mm wide at the top, narrows to 105 mm at the bottom, and has a depth of 325 mm. This configuration results in support for the deck every 300 mm through the trough walls.

The upper surface of the deck plate is coated with a thin epoxy layer, ensuring a minimum thickness of 6 mm (Maljaars et al., 2012).

The first crack was visualized on the surface of the 12 mm deck plate, located at the junction of the crossbeam web plate and the through wall. After a more detailed inspection, multiple cracks were located along the whole deck varying in length between 100-700 mm, and grew in longitudinal direction within the deck plate, mostly in the heavy truck lane (Figure 43). It was determined that the cracks could cause major traffic problems (Romeijn, 2006).

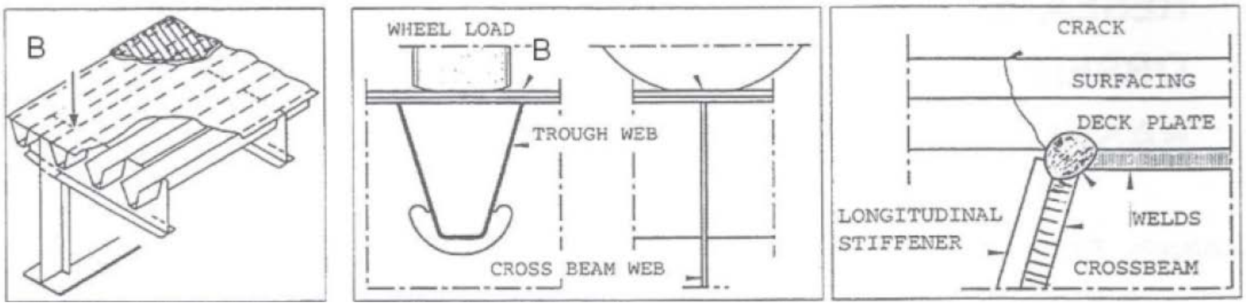

FIGURE 43: ORTHOTROPIC DECK STRUCTURE WITH FATIGUE BY WHEEL LOAD (B) (ROMEIJN, 2006)

In the research of Romeijn (2006) it is concluded that the deck plate type cracks are considered of high severity within steel structures. This type of crack is directly influenced by the fatigue caused by the passing vehicles on the material. The temporary solution for the fatigue cracks was to replace the whole bascule deck. The new deck changed from a 12mm deck plate to 24mm, and the trough thickness to 8mm (Figure **44** & Figure 45).

Based on the findings of Acosta et al. (2023), the bridge assessment indicated that the deck was suffering from fatigue due to the frequency of heavy traffic. The bridge was designed in the 80s according to the VOSB 1963 load class 60 (see Appendix section E) according to which, a bridge must be capable of supporting heavy vehicles up to 60 tons, along with associated traffic loads and dynamic effects. The Van Brienenoord bridge traffic monitoring during inspection time was composed of approximately 15% heavy vehicles and 85% regular traffic (see Appendix section H) (Romeijn, 2006).

After the severity of the cracks was determined, the movable bridge had to be replaced. The following figures illustrate the new deck composition with thicker plates:

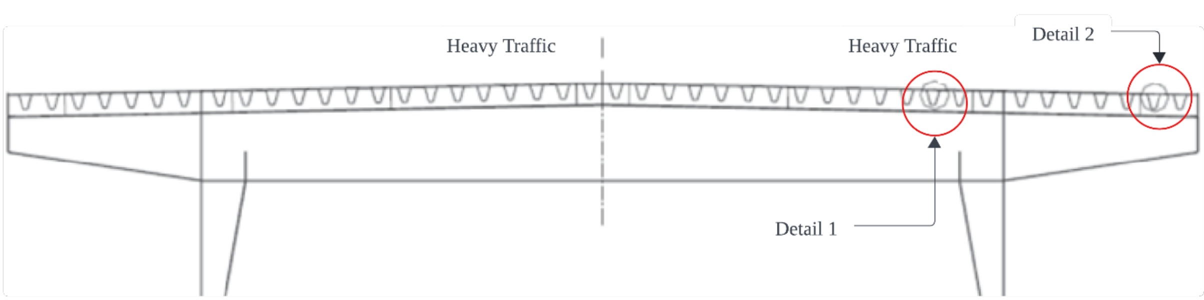

FIGURE 44: CROSS VIEW VAN BRIENENOORD BASCULE BRIDGE (ROMEIJN, 2006).

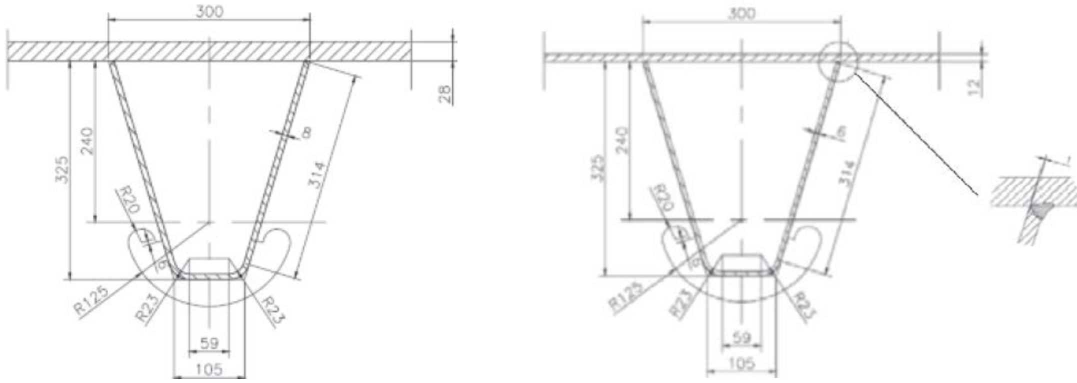

FIGURE 45: DETAIL 1 (LEFT), AND DETAIL 2 (RIGHT) (ROMEIJN, 2006).

Summary and remarks:

- According to the studies of Maljaars et al. (2012), the Van Brienenoord bridge, has continuous troughs (ribs/stiffeners) at the cross-beam web area, the space within the through is void, and is called a clown's-mouth.
- The study of Maljaars et al. (2012) mentioned the typical bridge dimensions of OSD for fixed and movable bridges in the Netherlands between the 1960s and the 1990s were:

TABLE 13: DIMENSIONS OF BRIDGE DECKS TYPICALLY USED IN THE NETHERLANDS (MALJAARS ET AL., 2012)

	Movable bridges	Fixed bridges
Deck plate thickness t	t = 12 mm	t = 10 mm
Surfacing finish of thickness t_s	epoxy, t_s = 6 mm	asphalt, t_s = 50 mm
Span of deck plate L[1)]	L = 300 mm – 6 mm	L = 300 mm – 6 mm
Cross-beam web thickness t_c	t_c = 10 mm or 12 mm	t_c = 10 mm or 12 mm
Cross-beam depth h_c	h_c = approx. 1000 mm	h_c = approx. 1000 mm

1) Span L = centre-to-centre distance of trough walls (300 mm) – 1 x trough wall thickness (6 mm)

By collecting the geometrical information of the bridges within the same construction period, within the national highways (load class 60), and with current information regarding an increase in traffic loads, potential TEoL criteria were suggested for both, fixed and movable bridges.

- The main influence that affected the OSD was the Traffic Loads in combination with the thickness of the deck plate. The bridge was not designed to withstand the new traffic demands.
- Within the major renovation planned for 2025, the additional welding and steel needed for the new deck will imply a renovation of the arch structure. The new replacement steel structures will be according to the Guidelines for Design of Civil Engineering Works (ROK2.0) and the Eurocode (prTS 1993-1-901) (Maljaars et al., 2012). Further research within the current norms could lead to the identification of current bridge elements that no longer provide the desired performance toward safety.
- It is valuable to emphasize that just 15% of the total traffic influencing the crack's propagation was heavy traffic.

Conclusions

With the findings in the case study and the literature review of the defect of interest, a potential TEoL criterion was described based on the Van Brienenoord bridge:

TABLE 14: VAN BRIENENOORD CASE - TEOL CRITERION CANDIDATE FOR STEEL BRIDGES.

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
5	Bascule bridge	Deck	Deck (OSD)	Deck plate	Fatigue cracks (Root-deck crack)	High

For the TEoL criterion No. 5:

- Based solely on the information provided by this case, fatigue cracks along the deck plate on the OSD are correctly posing a high risk of failure; however, additional information is necessary to fully determine this outcome. The high-risk classification was due to the properties of the crack and its location within the OSD. Therefore, root deck fatigue cracks occurring between the deck plate and the troughs close to the crossbeam, and with a minimum length of 500 mm on the top side of the deck plate, are considered to present a high risk of failure.

Case study remarks:

- In the research of Romeijn (2006), it was highlighted that the inspection time for a total structure assessment (asphalt surfacing, deck structure, crossbeams, main girders, bearings, etc.) was undertaken every five years. Within RWS, this is called maintenance inspection (see Appendix section C). Due to the difficulty to detect root-deck cracks with regular maintenance (Wang et al., 2021), potentially upgrading the maintenance techniques and timeframes, could lead to faster detection of crack initiations before they developed, preventing the cracks to reach the deck surface.
- High-stress concentrations at cutouts in the trough to crossbeam connections amplify peak stresses and increase the risk of fatigue cracks, leading to longer fatigue periods compared to continuous connections without cutouts. The geometry of cutouts significantly affects stress distribution; larger or excessively deep cutouts reduce resistance to out-of-plane displacements caused by trough rotations and heightening fatigue risks. (Qian & Abruzzese, 2009).
- Based on Romeijn (2006), the presence of small cracks on the bottom side suggests that larger cracks may exist on the top surface of the deck plate. Since the deck plate is covered by a wearing surface that obscures surface defects on the deck plate, inspections should focus on the underside of the deck, particularly aiming to detect small cracks near the crossbeam sections. It can be said, that a 500mm longitudinal crack in the surface deck plate can correspond to a crack length of approximately ≥ 125mm in the bottom side. As mentioned in the Galecopper case, 500mm longitudinal cracks in the surface deck may impose a risk of failure of the deck.
- According to the research of Pavlovic (2023), the recommendations based on the Eurocode 1993-2, rules for design OSD, the following design thresholds are recommended for vehicle traffic:
    - Deck plate thickness in carriageway:
        - $t \geq 14$mm for asphalt layer ≥ 70mm
        - $t \geq 16$mm for asphalt layer ≥ 40mm

- Spacing of the trough:
  - $e/t \leq 25$ (recommended $e \leq 300$mm)
- Thickness of the trough:
  - ≥ 6mm

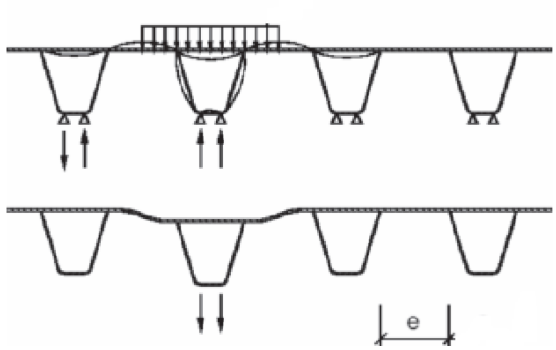

FIGURE 46: DIFFERENTIAL DEFLECTIONS OF THROUGH CAUSED BY LOCAL WHEEL LOAD (ROMEIJN, 2006)

Considering that this design information is derived from research conducted in 2006, further investigations into the adoption of these recommendations in new OSD designs were of relevant interest. If these design rules were implemented, it would be crucial to examine how the current structure behaves under existing traffic loads and how it might respond to future loading conditions.

- Another topic of interest is welding. Since the OSDs are prefabricated, and the cracks are within the welded connection between the trough and the deck plate, pertinent information can be derived from the manufacturing process. Such as the Ewijk case study of the defects within the cables, the welding process might reveal insightful information.
- The complete information of the preliminary framework for this case study is within the Appendix section A)

4.1.4. MOERDIJK BRIDGE

Standing as one of the major land connections in the country (>120,000 vehicles a day), the Moerdijk is a steel box girder bridge located at the crossing of the Hollands Diep within the municipality of Dordrecht and Moerdijk (Figure 47). Following the devastations of the Second World War and faced with escalating traffic demands, this infrastructure asset underwent multiple major interventions. The original structure became inadequate for increasing traffic needs, leading to the inauguration of a new, twice-as-wide bridge in 1976 to enhance the vehicle capacity. The bridge's deck is composed of ten spans of 100m each over a total length of 1,000m. The deck has a construction height of 3.5 meters and supports three lanes of traffic on each side (42.9 m wide in total) (Buitelaar & Braam, 2008).

After the replacement in 1976, the original piers and foundation were retained. The replacement strategy involved utilizing a lighter deck composition (OSD), which allowed the deck to be widened to meet new traffic demands while keeping the dead load on the piers and foundation approximately the same. Despite these efforts, the Moerdijk Bridge has suffered from fatigue cracks throughout most of its lifespan, resulting in repairs every four to six years (Buitelaar & Braam, 2008).

FIGURE 47: THE MOERDIJK BRIDGE BY RIJKSWATERSTAAT, AND GOOGLE MAPS.

<u>Reinforcement of the deck plate</u>

During 2005-2008, the bridge went through several interventions due to the appearance of fatigue cracks. To address this issue, Reinforced High-Performance Concrete (RHPC) was implemented on top of the deck plate (Buitelaar & Braam, 2008). Figure 48 illustrates the cross-section of the bridge before the RHPC layer was applied. The girder box bridge had a diverse deck plate thickness in different sections of the deck.

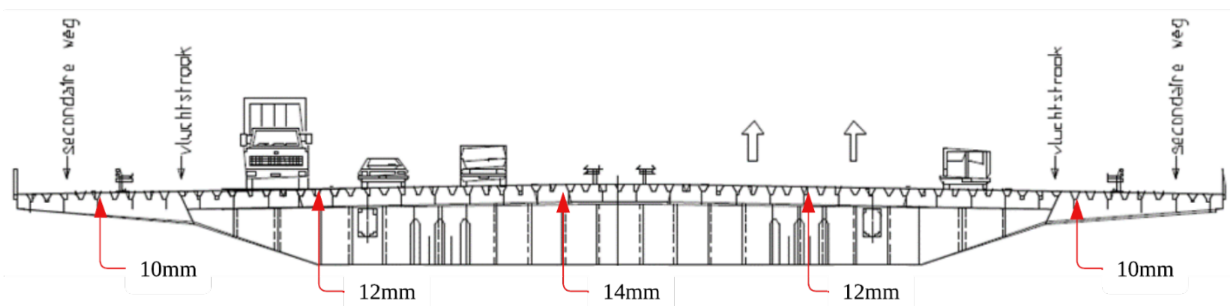

FIGURE 48: CROSS-SECTION OF THE MOERDIJK BRIDGE WITH DECK PLATE THICKNESS (DEN BESTEN, 2012) (BUITELAAR & BRAAM, 2008).

The Moerdijk bridge is considered the heaviest-loaded bridge within the Dutch highway network, with approximately 82,000 trucks per week (Van Dooren et al., 2010). According to the EN 1991-2:2003 (See appendix section D), the heavy traffic should be located within the external lanes of the deck as illustrated in Figure 49.

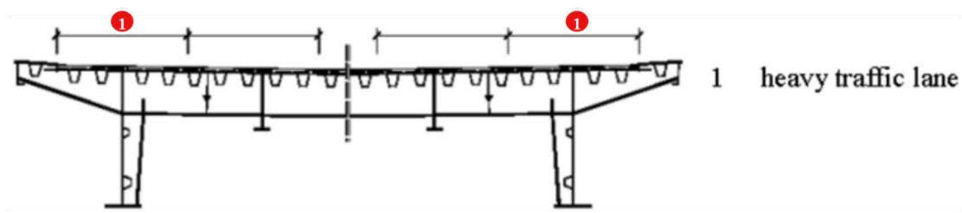

FIGURE 49: INDICATION OF THE HEAVY TRAFFIC LANE WITHIN AN OSD DESING (PAVLOVIC, 2023)

The bridge suffered from fatigue cracks that originated at the root of the welds, primarily due to poor weld geometry and inadequate fit-up between the stiffeners and the deck plate (Figure 13). These cracks propagate longitudinally, following paths parallel to the troughs (Figure 14). Prominently, this type of cracking does not directly affect the deck plate, and as a result, no immediate traffic safety issues are expected (Romeijn, 2006).

After the first and second interventions of 2005, the reinforced deck started to present cracks in 2 of the 20 newly renovated decks. The de-bonding defect was due to the poor interconnection between the new concrete and the interface creating gaps and voids up to 30mm (Buitelaar & Braam, 2008).

Summary and remarks:

- According to the illustration in Figure 48, the Moerdijk bridge has 12mm deck plates in the zone for heavy traffic. Due to the high intensity of traffic and the heavy traffic the bridge undergoes, fatigue cracks are expected to appear. Based on the recommendations of Pavlovic (2023), the deck plate should be 14mm.
- The correct placement of the RHPC is of high importance, this human-induced factor is not related to the theoretical correctness of the solution, but within the process of instalment. This external influence, if not detected or supervised could lead to a TEoL of the component.
- The longitudinal cracks within the deck plate of the Moerdijk bridge case were considered sufficient to make an intervention, even though theory suggests that the type of cracks presented in the deck do not endanger traffic safety based on the research of Romeijn (2006).

Case study conclusions

With the findings in the case study and the literature review of the defect of interest, potential TEoL criterion was described based on the Moerdijk bridge case:

TABLE 15: VAN BRIENENOORD CASE - TEOL CRITERION CANDIDATE FOR STEEL BRIDGES.

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
6	Girder bridge	Deck	Deck (Box Girder)	Trough	Fatigue cracks (Weld root crack)	Low

For the TEoL criterion No. 6:

- Based on the information from the case study, the Moerdijk bridge's damage on the deck plate originated from the increase in traffic load and poor welding between the trough and the deck plate. Since this crack was not registered near a crossbeam, the risk of failure was considered low, based on the findings of Romeij (2006).

Case study remarks:

- The lessons learned from the study of Buitelaar and Braam (2008) indicate that the configuration and the fixed positioning of the RHPC reinforcement to the deck is of high importance.
- The RHPC thickness was suggested by Buitelaar and Braam (2008) to be 50mm, but it also mentions that it can be reduced to 30mm if the reinforcement web is in a single welded mesh. Their research proposed a further investigation on this topic.

- The HPFRC was investigated since it was mentioned in correlation with the RHPC which was utilized in the case study of the Moerdijk bridge (see Appendix I). In the case study research, Buitelaar and Braam (2008) indicate in their definition of the RHPC the inclusion of fibres, but it is not mentioned any design process, material properties, or percentages utilized for the concrete mix utilized in the intervention. It was later concluded that the addition of 2% of steel fibres was optimal by Yoo and Yoon (2016), and Afroughsabe et al. (2016).
- The study of Chen et al. (2024) indicates that the fatigue-induced crack damages in the trough-to-deck welded joints can be mitigated by increasing the deck plate thickness and the weld penetration. By implementing these solutions, the fatigue performance of the deck increases.
- The complete information of the preliminary framework for this case study is within the Appendix section A).

4.1.5. ADDITIONAL TEOL CRITERIA

Derived from the multi-case study analysis, additional TEoL criteria were found. The following criteria included findings within different levels of decomposition, making paths to other elements and components of the bridge. To keep continuity in the data, the preliminary framework was utilized to summarize the findings.

Mechanical intervention: When implementing an HSC (or any extra layer of load) in the deck surface of a movable bridge, the additional extra weight must be smaller than the capacity of the hinges and the driving gear. If extra load is added to the deck, this extra load must be added to the counterweight without exceeding the final load capacity (Buitelaar & Braam, 2008). In the scenario that the extra load exceeds the load capacity, a major intervention must take place. Therefore, the critical component has reached its TEoL.

TABLE 16: MECHANICAL INTERVENTION - TEOL CRITERION CANDIDATE FOR STEEL BRIDGES

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
7	Movable bridge typologies	Deck	Deck (OSD)	Wearing surface (HSC)	Extra load exceeds the load capacity	High

Aging – Damage: When a bridge asset is close to reaching its design service life. Considering that the average lifespan of a bridge is 80-100 years, infrastructure assets reaching this age gap are prompt for a major intervention. This criterion is a higher-level criterion that considers the whole bridge as a single system. Therefore, this criterion should be further investigated by performing inspections. If the data is available, a deeper analysis utilizing the aging curve can be performed (Figure 26). Additional research must be carried out for the application of this tool on regards of this specific case. The aging curve is intended for components that do not have condition data, but due to the logic it follows, the ratio between aging and condition score can lead to a new approach that could give an indication of the TEoL of a whole system.

Ather potential criterion was defined by the age of the OSD. According to Table 36, the life expectancy of an OSD between the period of 1997 to 2004 was approximately 30 years. This criterion takes into consideration the deck plate as the component of interest, the type of cracks was not considered.

TABLE 17: AGING - TEOL CRITERIA CANDIDATES FOR STEEL BRIDGES

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
8	All typologies	-	-	-	Aging (Close to 80-100 years)	Unknown
9	All typologies	Deck	Deck (OSD)	Deck plate	Aging (30 years)	Unknown

Bulkheads: Looking at existing OSD troughs, if the trough has a closed geometry and the traffic load has increased significantly, high stress will focalize between the trough and the cut-out of the crossbeam. Therefore, if the trough does not have a bulkhead or any type of stiffeners, the high concentration of stress could lead to the early propagation of fatigue cracks to the deck plate. This criterion was dependent on various external and internal influences, such as increase in heavy traffic, geometry of the component, quality of material, and the location of the traffic within the deck.

TABLE 18: BULKHEAD - TEOL CRITERION CANDIDATE FOR STEEL BRIDGES

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
10	All typologies	Deck	Deck (OSD)	Trough	No bulkhead	Unknown

Deck plate thickness: According to the recommendations from Pavlovic (2023), the deck plate thickness of an OSD should be 14mm or thicker, depending on the wearing surface. In the Netherlands, between the 1960s and the 1990s (Table 13), the typical deck plate thickness of an OSD was 12mm. This discrepancy in the thickness of the deck plate was considered an indicator of potential TEoL of the element. Additionally to the thickness, if the component was subject to increased stress due to external influences (e.g., increase in load), this combination also serves as an indicator for determining TEoL criteria for OSDs.

Considering that the bridges between 1997-2004 (see Appendix section F), all suffered from fatigue cracks within the first 30 years of completion and theoretically had the same design composition (based on Table 13), the deck plate thickness was considered a high-risk of failure in combination with increased heavy traffic.

TABLE 19: DECK PLATE THICKNESS - TEOL CRITERION CANDIDATE FOR STEEL BRIDGES

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
11	All typologies	Deck	Deck (OSD)	Deck plate	Thickness of ≤12mm	High

Heavy traffic location and intensity: The preeminent external influence of the steel bridges, as literature and the case studies suggest, is the increase in heavy traffic load and intensity over the infrastructure asset. The heavy traffic has been in constant growth over the years, having an increase in traffic lorries over the national highways due to various economic reasons.

In the case study of the Van Brienenoord Bridge, the fatigue cracks were attributed to a combination of heavy traffic loads, specific stress locations within the deck, and the geometry of the deck plate. Between 1990 and 2010, heavy vehicles accounted for only 15% of the total traffic on the bridge (see Appendix section H). Despite this relatively low percentage, the substantial loads from these vehicles significantly contributed to high-stress accumulation, resulting in damages in the deck.

Figure 50, illustrates the Van Brienenoord and the Moerdijk steel bridges within the national highway A16. Both of these bridges had similar problems with fatigue cracks. Based on the analysis within previous chapters, it was concluded that both had a deck plate of 12mm and attributed the fatigue cracks due to heavy traffic. Therefore, an area data, system part criterion was proposed based on Table 5. By analysing the variable heavy traffic intensity within the highway, other bridges within the same network can be assessed.

FIGURE 50: BRIDGES IN THE MOTORWAY A16 (GEO.RIJKSWATERSTAAT.NL, 2024)

There are some limitations to this criterion:

- A highway is composed of multiple corridors that have a specific entrance and exit; the data gathered from one bridge might not be 100% accurate in long stretches due to the multiple entrances and exits of the highway, even though, it serves as a good indicator if data is not available.
- This had a potential use for rule-based criteria since it relies on data that is already collected from the infrastructure asset. The geometrical data of the bridge is within level 5 and level 6 of the decomposition, and the network data is gathered within level 3, all within DISK.

Further research is suggested for Level 3 - System part criteria. The connection of the current available datasets in a high-level (network) perspective could lead to better decision-making for network interventions and single management objects since the lessons learned from one infrastructure asset with similar decomposition data can be used to assess others with similar external influences.

TABLE 20: SYSTEM PART LEVEL - TEOL CRITERION CANDIDATE FOR STEEL BRIDGES

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
12	All typologies	Deck	Deck (OSD)	Deck plate	Fatigue cracks	-

Girders: The main girders, as illustrated in Figure 21, serve as the load-bearing components through which the OSD transfers the dynamic loads generated by the traffic. As a main load-bearing structural element of the deck, this element is susceptible to fatigue-induced cracks, corrosion, deformations, and other damage processes, as shown in Figure 11. Due to their critical role in the structural integrity of the bridge, maintaining the performance levels of the main girders is essential to ensure the safety and the reliability of the civil infrastructure. In the study conducted by So et al. (2012), an example of a replacement and rehabilitation strategy for steel girders was presented:

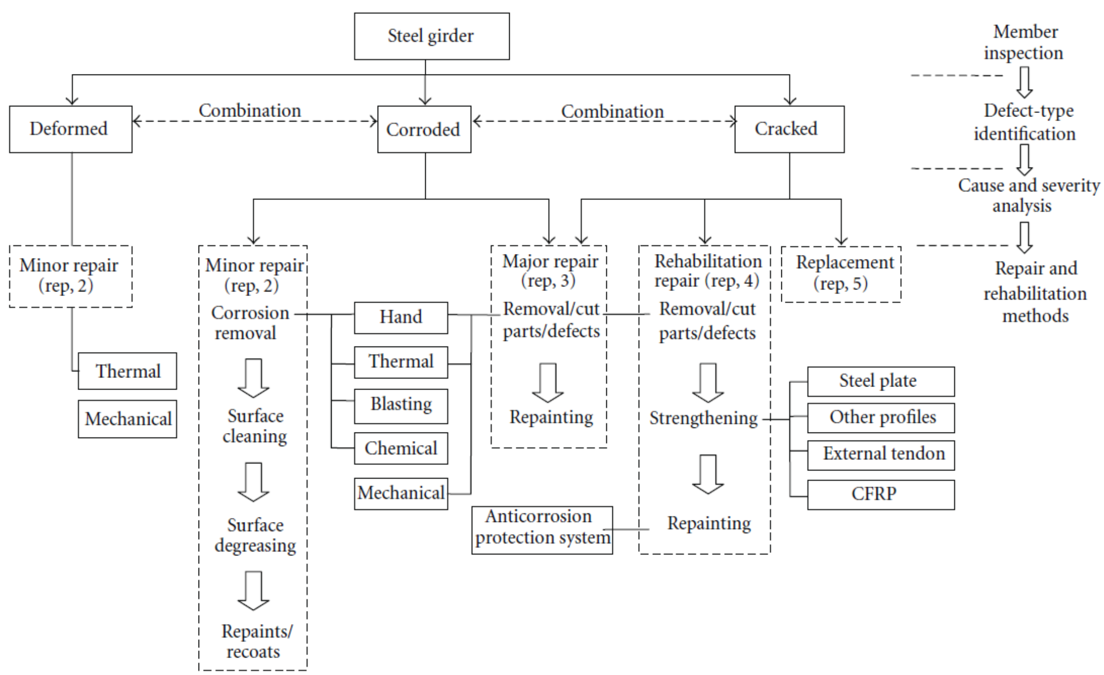

FIGURE 51: REPLACEMENT AND REHABILITATION METHODS FOR CONVENTIONAL STEEL GIRDER (SO ET AL., 2012).

According to Figure 51, the strategy outlines several repairs corresponding to three main defects (cracked corroded, and deformed):

- Minor repair: describes a repair strategy that slows deterioration without improving durability.
- Major repair: restores structure to its initial condition but doesn't enhance durability.
- Rehabilitation: restores and improves durability, reducing future damage.
- Replacement: replaces components, enhancing capacity and durability.

Based on these strategies, the defects “cracked” and “corroded” highlight a substantial threat to the structure’s integrity since these are the only defects that lead to a major intervention and/or replacement.

TABLE 21: STEEL GIRDER - TEOL CRITERIA CANDIDATES FOR STEEL BRIDGES

No.	Level 4 - Management Object	Bridge Section	Level 5 - Element	Level 6 - Building Component	Damages and Defects	Risk to Failure
13	All typologies	Deck	Steel Girder	-	Fatigue cracks	High
14	All typologies	Deck	Steel Girder	-	Corrosion	Medium

4.2. CONSOLIDATING THE TEOL CRITERIA CANDIDATES INTO CONCISE TEOL CRITERIA

Once the TEoL criteria candidates’ data were collected from the in-depth multi-case study chapter, it was then categorized into the different levels of decomposition, and subsequently compiled into a series of concise criteria. Given the nature of the data derived from the case studies, the primary objective of this section was to articulate the findings into structured and coherent sentences. Therefore, the first stage was to organize the criteria according to different levels of decomposition based on the NEN 2767-4 standard:

- **Level 3 – System part:** At the system part level, the TEoL criteria consider the broader highway network. This level addresses influences such as traffic patterns, norms, codes, and the distribution of bridges within a particular highway.
- **Level 4 – Management object:** Management objects include all bridges within a specific category, such as fixed or movable bridges, or by typology. This level addresses influences such as traffic patterns, norms, and codes.
- **Level 5 – Element:** At the element level, the criteria focus on specific load-bearing elements such as the deck, pylons, cables, etc. This level addresses influences such as damage processes and material properties.
- **Level 6 – Building Component :** The building component level examines the smallest components, such as deck plates, anchorages, crossbeams, wires, etc. This level addresses influences such as damage processes, and human-induced factors.

Once categorized, each of the consolidated criteria displayed:

- **Brief description:** A succinct contextualization of the damage within the specific object of analysis (e.g. bridge, load-bearing element, or building component). The brief descriptions were composed based on the overall data collection presented in Figure 28.
- **Perceived risk to failure:** According to Figure 28, a qualitative scale was assigned to state the level of perceived risk of failure based on the literature data found.
- **Threshold value:** Qualitative or semi-quantitative data according to the damage detected. Based on the data of the case studies.
- **Influences that govern the criterion:** Potential influences detected that had an effect on the damage initiation, and propagation..

- **Constraints and limitations:** This information displayed the limits of the criterion and highlighted relevant data based on the conclusions of the case studies of section 4.1.

The full set of concise criteria are listed in the Appendix section L.

<u>Example:</u>
Based on the conclusion of criterion #3 in Ewijk's case study and its complete framework in Appendix section K, C#9 was concluded:

TABLE 22: EXAMPLE OF THE CONSICE TEOL CRITERIA

C#9 (Criterion #3)	
If the high-strength steel wires (cables) of a steel cable-stayed bridge present fractures due to lamination by 10% or more of the total wire bundle, the cable has potentially reached its TEoL.	
Risk to failure:	High.
Threshold:	≥ 10% of the total wire bundle.
Influences:	Traffic loads (increase in heavy traffic over the years), and Material properties (manufactured defects).
Constraints and limitations:	o Fracture is defined when the fatigue crack lengthens to the point where it progressively lowers its cross-section area and its capacity to fulfil its function is compromised. o The 10% was determined by the case study of the Ewijk bridge, were 10% of the wires presented fractures and the cables needed to be replaced. o This criterion can consider the manufacturer as a threshold. The manufacturer data is gathered within the component level within DISK (Inspection Parts (IS parts)).

Table 22 exemplifies a concise criterion that analyses the cables of a cable-stayed bridge. Here, the defect detected was lamination that caused fracture damages, which had a threshold value of ≥ 10% of the total wire bundle. According to the case study data, the risk of failure is classified as high, based on the scientific data and the qualitative scale proposed within section 3.6.

With all the concise TEoL criteria consolidated and classified, an interview phase was initiated. The interview phase's purpose was to validate the perceived risk of failure and the threshold values of the TEoL criteria. The full interview phase is described in Appendix section N.

5

RESULTS – THE TEOL RULE-BASED ASSESSMENT

Once the interview process was completed (see appendix section N), the validated TEoL criteria for steel bridges were concluded. In order to utilize the criteria for an assessment approach, the criteria were clustered using a decision tree method. Furthermore, utilizing a scoring system, based on a qualitative scale derived from the feedback of the domain experts, a ranking classification was added to the assessment. Lastly, a step-by-step example illustrates the usefulness of the new TEoL rule-based criteria with an explanation of its possible outputs.

5.1. THE TEOL RULE-BASED ASSESSMENT PROCESS

The validated TEoL criteria were arranged according to a decision tree method (Song & Lu, 2015) and the NEN 2767-4. A total of twelve validated criteria are allocated within the decision tree, each of them located within their specific element or building component of assessment. Figure 52, illustrates a simplified model of the decision tree:

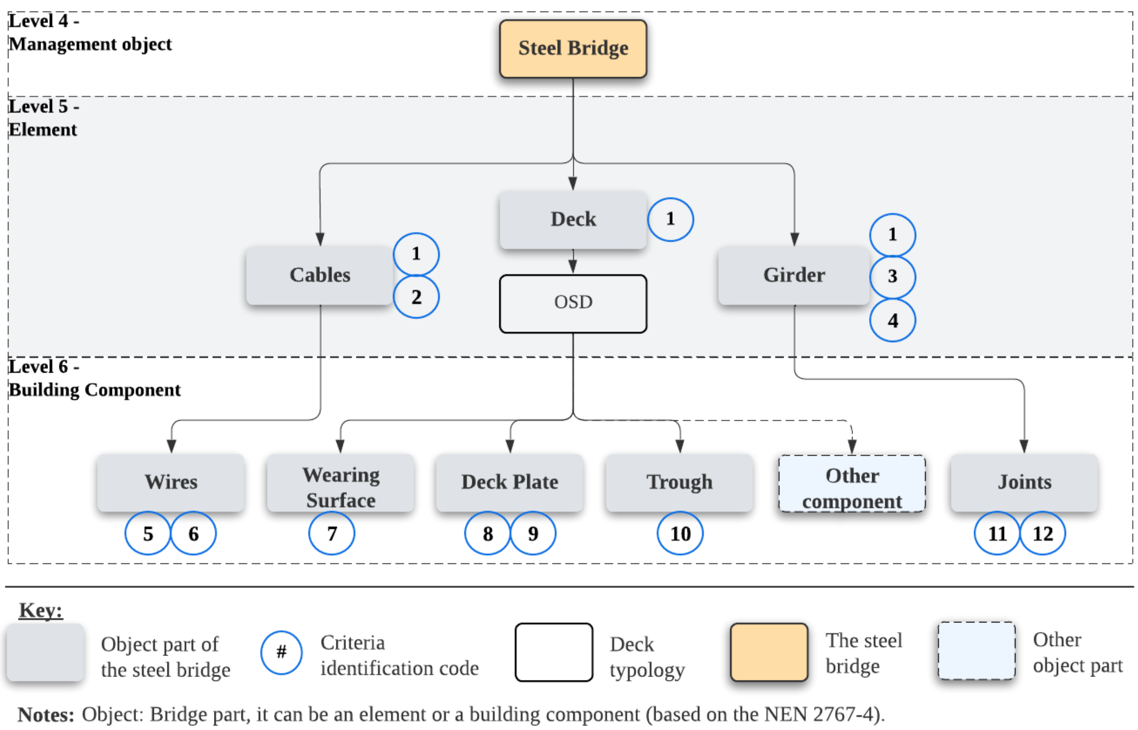

FIGURE 52: SIMPLIFIED MODEL OF THE TEOL DECISION TREE

The validated TEoL criteria were derived from the feedback and extra questions within the interview phase in appendix section N. Each of the criterion were composed of a short description, a perceived risk of failure and threshold values (which were validated on the interview phase), influences (assigned within the consolidated TEoL criteria based on the multi-case study analysis), and notes (relevant feedback of the interview phase).

The input data for the rule-based assessment

The input data required for the complete assessment is the following:

- **Historic data:** Data regarding the year of construction of the steel bridge. This is collected within the management object level 4 within DISK (see Appendix section B).
- **Composition data:** Data describing the structural and geometrical composition of the bridge into load-bearing elements (level 5) and building components (level 6) within DISK (see Appendix section B).
- **Condition data:** Data regarding the current state of all the bridge parts. This information is collected within inspection reports.

If any of the input data is missing or it is not complete, the assessment can be performed with the consideration of "penalty" points. These points are based on the importance and quantity of the data missing. This is further explained below.

The rule-base assessment process

The decision tree starts with the level 4 of the decomposition from NEN 2767-4, which corresponds to the management object steel bridge. Subsequently, the assessment proceeds at the element level 5, evaluating three load-bearing elements: cables, deck (OSD), and girder. Finally, the assessment concludes at the building-component level 6, which includes the wearing surface, deck plate, trough, and joints. In the scenario that there is an additional building component within one of the load-bearing elements of the decision tree (cables, deck, or girder), this component would be considered within the rule-based assessment as "other component".

Each of the interconnections between nodes within the tree encompass a decision (e.g. "yes" or "no") or has an indication to proceed to other question (e.g. has). The assessment has two different types of branches; the decision branches with a single outcome route, and the parallel assessment branches, which require the assessor to review all interconnected nodes from which the parallel branch has originated. Figure 53 exemplifies the two branch types:

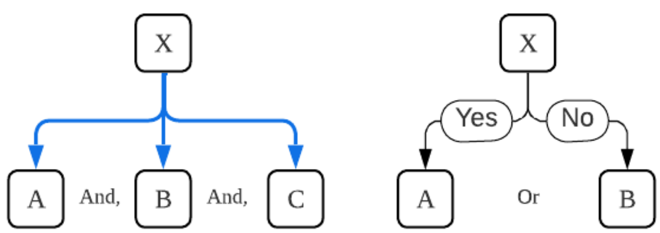

FIGURE 53: PARALLEL ASSESSMENT BRANCH (LEFT) AND SINGLE ASSESSMENT BRANCH (RIGHT)

Once the assessment path reaches a leaf node, the outcome is allocated into one of five possible scenarios:

- Termination of a branch assessment due to lack of damage within the available condition data (e.g. a wire has cracks, not corrosion. Therefore, the corrosion section within the decision tree is not assessed).
- Termination of a branch assessment where more information is needed. There are four reasons for this scenario:
    - No bridge composition data (e.g. steel bridge has no cable).

    - There is bridge composition data, but there is no condition data (e.g. steel bridge has a cable with no condition data).
    - There is condition data, but there is no bridge composition object within the assessment (e.g. there is a crossbeam with condition data. This building component is not within the scope of the assessment).
    - Redirects the assessment to other object parts within the decision tree (e.g. when welded cracks in the OSD reach a load-bearing element, the assessment suggests reviewing the girder based on expert judgment).
- Damaged has been detected and/or progressed within the object of analysis. In this scenario, a monitoring protocol is suggested to the asset manager based on the notes section within the validated TEoL criteria section below.
- Damaged has reached or surpass the threshold value assigned within the validated TEoL criteria, consequently compromising the performance of the object. Therefore, potentially reaching the TEoL of the object assessed. In order for this scenario to occur, the object has to have structural redundancy.
- Due to severe damages, a load-bearing element (e.g. girder) or a critical building component (e.g. wire, or joint) with no structural redundancy has reached its TEoL. Therefore, potentially reaching the TEoL of the bridge.

<u>The point allocation system and the validated TEoL Criteria</u>
The scoring methodology was integrated into the assessment to facilitate the systematic ranking of multiple steel bridges within a portfolio of similar assets, utilizing their current historical, composition, and condition data. The point-based system was based on a qualitative approach, relying on expert knowledge obtained during the interview process. Depending on the expert data and the TEoL criterion, a scoring ranging from 0.5 to 5 points were allocated to specific conditions, with a starting condition that a damaged component is equal to +1 point.

Given the inherent complexity of developing a scoring system that accounts for varying levels of importance across object hierarchies (e.g. load-bearing elements impose a higher risk than building components), object classifications (e.g. cable is more important than girder, and girder to deck), and damage types (e.g. cracks over corrosion), the point system was described within each validated TEoL criterion. The scoring system and the validated TEoL criteria were outlined as follows:

Validated criterion #1:
If a steel bridge, whether fixed or movable of any typology built in the Netherlands before the implementation of the Eurocode 3 (EN 1993), which takes into consideration fatigue:

Then:
- Perceived risk of failure: According to the answers of the TNO domain experts to the extra question #1 in Appendix section N, these two reasons are given:
    - If a bridge is assessed with the new code, it might not comply with the required performances, making the whole system more susceptible to fatigue crack initiation and propagation.
    - It also depends on the redundancy of the design: high redundancy meets code, while low redundancy typically fails the unity check above 1 in the new design code.

Therefore, this criterion was assigned with **+2** points to each of the elements in the lower level. This was decided since this criterion governs the whole design of the steel bridge and all of its parts.

- Threshold: The bridge was designed according to the VOSB 1963 or older than EN 1993 (2006 or younger (EN 1993-2, 2006)), or not.
- Influences: Design limitations (outdated design standards and regulations).
- TNO notes: Depending on the original VOSB 1963 load class design of the bridge, if the current use against the original functionality of the network changes, the perceived risk of failure would increase.

Validated criterion #2:
If cable, as part of a steel bridge, was built in the Netherlands between the 70's:

Then:

- Perceived risk of failure: Under the answer of TNO domain expert #1 within C#9 in Appendix section N, and the conclusions of Ewijk's bridge case study; it is important to consider the rolling process which probably the few manufacturers in the country used within that period. This criterion was assigned with **+2** points since it only covers the element level.
- Threshold: Yes or no.
- Influences: Material properties (lamination).
- Notes: Possible lamination defect during the manufacturing rolling process that could cause invisible micro cracks that could lead to fractures.

Validated criterion #3:
If a steel main girder, as part of a steel bridge presents any type of cracks or fractures:

Then:

- Perceived risk of failure: According to both TNO domain experts within C#6 in Appendix section N, cracks within the main girder can result in a high risk of collapse. The main girder with cracks does not have any initiation and propagation thresholds, the only threshold it was recorded and validated was the appearance of cracks. Therefore:
    - Final damage (over threshold): **+5**.
    - No structural redundancy: **additional +5**
- Threshold: Appearance of any type of cracks or fractures within the load-bearing element, or not.
- Influences: Traffic loads (increase in heavy traffic), and Damage processes (fatigue).
- RWS notes: In such cases where the main girder presents cracks, the asset manager must decide to take an immediate intervention. Since the failure of this element can lead to the collapse of the bridge.

Validated criterion #4:
If a steel main girder, as part of a steel bridge presents any type of corrosion in the main girder:

Then:

- Perceived risk of failure: According to both TNO domain experts within C#7 in Appendix section N, corrosion in cables is just an indicator of damage. Once fractures appear, or the threshold value is reached, the risk increases. Therefore:
    - Damage initiation: **+2**
    - Final damage (over threshold): **additional +3**
    - No structural redundancy: **additional +5**

- Threshold: Due to corrosion damage, the load-bearing element has a 5-10% loss of cross-section, or not.
- Influences: Traffic loads (increase in heavy traffic), Environmental factors (humidity and high-temperature ranges), and Damage processes (corrosion).
- RWS notes: The asset manager should conduct an assessment when any signs of corrosion are present; however, no urgent action is required unless fractures are detected. If fractures are detected due to corrosion damage, this scenario can lead to the collapse of the bridge.

Validated criterion #5:
If a cable, as part of a steel bridge, present cracks within any of the high-strength steel wires:

Then:

- Perceived risk of failure: According to the TNO domain expert #2 within C#9 in Appendix section N, the fractures are of high relevance for the bridge's structural integrity. Therefore:
    - Damage initiation: **+2**
    - Final damage (over threshold): **additional +3**
    - No structural redundancy: **additional +5**
- Threshold: Has fracture or breaking of the wires, or not.
- Influences: Traffic loads (increase in heavy traffic), and Damage processes (fatigue).
- RWS notes: If fractured wires are detected, the asset manager must take urgent action, such as limiting the traffic passage through the bridge. Depending on recalculations of load distribution and structural redundancy, further intervention strategies will follow.

Validated criterion #6:
If a cable, as part of a steel bridge, presents any type of corrosion damage within any of the high-strength steel wires:

Then:

- Perceived risk of failure: According to both TNO domain experts within C#8 in Appendix section N, corrosion by itself it's just an indicator that shows that the object has damage. The risk increases when by corrosion damage, the wires start to loos cross section which lead to broken wires. Therefore:
    - Damage initiation: **+1**
    - Damage propagation: **additional +1**
    - Final damage (over threshold): **additional +3**
    - No structural redundancy: **additional +5**
- Threshold: Has broken wires due to corrosion damage, or not.
- Influences: Traffic loads (increase in heavy traffic), Environmental factors (humidity and high-temperature ranges), and Damage processes (corrosion).
- RWS notes: If fractured wires due to corrosion are detected, the asset manager must take urgent action. While signs of corrosion within the cables are indicators of future fractures, immediate attention is required when fractures occur. Critical locations include the connections within the anchorage to the deck. If fractures occur, the redundancy in load distribution must be reassessed.

Validated criterion #7:
If the wearing surface, as part of an OSD, presents cracks:

Then:

- Perceived risk of failure: Based on the lessons learned from the Moerdijk bridge case study, If the wearing surface is made of HSC and presents cracks, the cracks can potentially be traced to a human-induced factor such as poor application of the wearing surface. On the other hand, if the cracks originate from a component of the OSD, the damaged component has to be assessed. Within thin-wearing surfaces (e.g. asphalt), based on the Galecopper case study, the wearing surface can experience longitudinal and/or spider's web cracks. Therefore:
  - Damage initiation: **+0.5**
  - Damage propagation (traced to another component): **additional +1**
- Threshold: has cracks, or not.
- Influences: Traffic loads (increase in heavy traffic), Damage processes (fatigue), Human-induced factors (poor welding, bad maintenance), and Design limitations (outdated design standards and regulations).
- RWS notes: These types of cracks can be the result of fatigue cracks originating from a damaged component of the OSD, or due to a poor application of the wearing surface.

Validated criterion #8:
If a deck plate, as part of an OSD, has a ≤ 12mm thickness in the heavy traffic lane:

Then:

Perceived risk of failure: According to the findings of Maljaars et al. (2012) (Table 13), steel bridges with an OSD and a ≤ 12mm deck plate geometry are susceptible to fatigue cracking. The allocated risk can be increased based on the design standards when the bridge was designed, the location of the thickness of the deck plate within the OSD (e.g. heavy traffic lane)(see Appendix section D), and the heavy traffic increase over the years. Therefore, this criterion was assigned with **+1** point since it covers a building component level.

- Threshold: has ≤ 12mm deck plate.
- Influences: Design limitations (outdated design standards and regulations) and Traffic loads (increase in heavy traffic).
- TNO notes: The location of the crack is important, such as the position of the heavy traffic within the deck (lane).

Validated criterion #9:
If a deck plate, as part of an OSD, has root-deck fatigue cracks (type II):

Then:

- Perceived risk of failure: According to both TNO domain experts and RWS domain experts (see Appendix section N), the root-deck crack is considered of high importance. While this damage is repairable as augmented by the domain expert of RWS, literature suggests that this type of crack can be considered a high threat to traffic safety (Romeijn, 2006). Therefore:
  - Damage initiation: **+1**
  - Final damage (over threshold): **additional +2**
- Threshold: Has ≥ 500 mm longitudinal crack in the deck plate originated by a root-deck fatigue crack, or not.
- Influences: Traffic loads (increase in heavy traffic) and Damage processes (fatigue).

- RWS notes: When multiple root-deck cracks are detected in the deck plate, the asset manager must implement an intervention strategy. The length of the crack provides an indication of the urgency for repair, the longer the crack, the more immediate the need for action. Depending on the number of cracks, the asset owner can decide to replace the whole deck, therefore, indicating a TEoL of the whole deck.

Validated criterion #10:
If a trough, as part of an OSD, has weld root cracks (type IV) between the deck plate and the trough:

Then:
- Perceived risk of failure: According to RWS domain expert within C#11 (revised) in Appendix section □N, welding cracks are not considered alarming and do not cause any inconvenience or threat to traffic safety. Therefore:
    - Damage initiation: **+0.5**
    - Damage propagation: **additional +1**
- Threshold: Has cracks within the welded joint, or not.
- Influences: Traffic loads (increase in heavy traffic), Damage processes (fatigue), and Human-induced factors (poor welding).
- RWS notes: Welding cracks are not considered urgent. Rapid action is required once propagation reaches a load-bearing element, such as the girder. This type of crack needs constant inspections to determine propagation. The potential risk of failure increases once the crack reaches a critical load-bearing element.

Validated criterion #11:
If a joint, as part of a main steel girder, has welded joint(s) built in the 60s:

Then:
- Perceived risk of failure: According to RWS domain expert within C#6 (revised) in Appendix section □N, that the welding process in the 60's was not as efficient as it is today, therefore, welding joints in the main girder are presenting early fractures due to the increase in heavy traffic over the years. This criterion was assigned with **+1** point since it only covers the building component level.
- Threshold: Yes or no.
- Influences: Human-induced factors (poor welding), and Traffic loads (increase in heavy traffic).
- Notes: None.

Validated criterion #12:
If a joint, as part of a main steel girder, presents any type of corrosion:

Then:
- Perceived risk of failure: According to RWS domain expert within C#7 (revised) in Appendix section □N, corrosion degradation within joints and bolts of the girder can be a serious problem due to the possible loss of mechanical strength. Therefore:
    - Damage initiation: **+1**
    - Final damage (over threshold): **additional +2**
    - No structural redundancy: **additional +3**
- Threshold: Due to corrosion damage, whether the joint has lost its mechanical strength, or not.

- Influences: Environmental factors (humidity and high-temperature ranges), and Damage processes (corrosion).
- Notes: The joint is attributed to the stability of the girder, if there is no structural redundancy in the joint, the potential TEoL of the joint can cause a cascade effect repercussing the structural integrity of the girder and finally the entire bridge.

In addition to the specific known damage and object, there were penalty points assigned based on the unavailability of data:

- Within the element level 5, when there is bridge composition data, but there is no condition data, the allocated points were:

    - **+1** point for the cable.
    - **+1.5** points for the deck.
    - **+2** points for the girder.

  The scoring was calculated by adding all of the lower scores of the possible damages of each of its components and dividing that number by two (e.g. cable = (+1 (wire-corrosion) + 1 (other component))/2). Since the assessment heavily relies on the availability of data to give insights into the current condition of the asset, with no data, only 50% of the damages are considered.

- When there is condition data, but there is no bridge composition building component within the assessment (out of scope), the allocated points were:

    - **+1** point for the other building component.

- When there is condition data and bridge composition data, but there is no allocated damage within the assessment, the allocated points were equal to the lowest damage within the known damages of the object. An example:

  The lowest registered damages within the girder are corrosion with +2 and cracks with +5, an additional possible damage will be allocated **+2**.

The maximum points a steel bridge can obtain are 76. This number contemplates the worst possible scenario with a complete historical, composition, and condition data set available. With only historical and composition data, the maximum points a steel bridge can obtain are 14.5. Therefore, the assessment results are highly dependent on the availability of condition data.

Figure **54**, illustrates the complete TEoL rule-based criteria assessment:

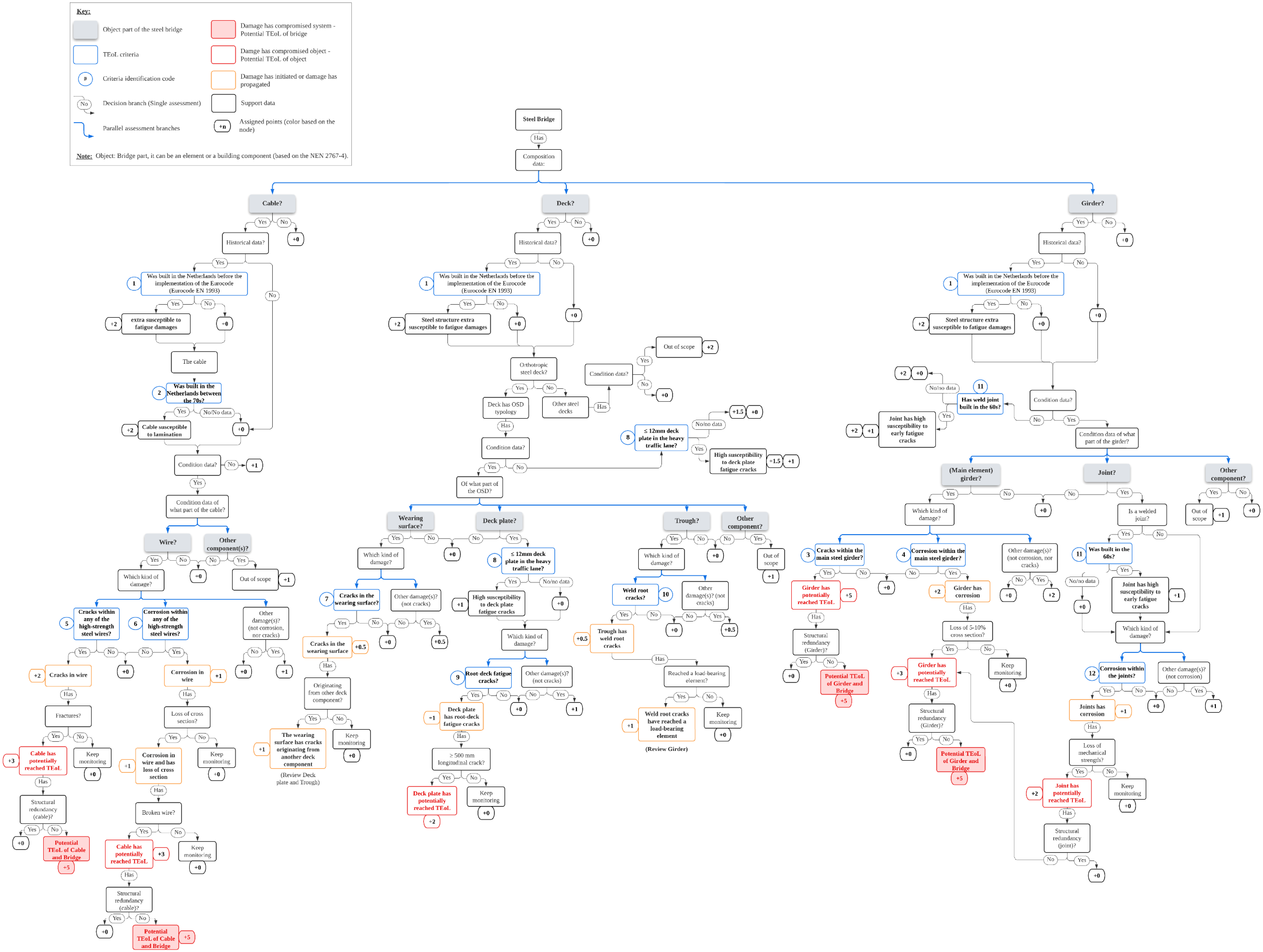

FIGURE 54: DECISION TREE OF THE TEOL ASSESSMENT FOR STEEL BRIDGE.

5.2. EXAMPLE OF THE TEOL RULE-BASED ASSESSMENT

The following examples illustrate the practical applications of the TEoL rule-based assessment. A detailed analysis of an individual steel bridge illustrates the step-by-step assessment, while a multi-case analysis highlights its potential utility in portfolio-level evaluations.

The first step to utilizing the rule-based criteria is to identify the available data:

- **Historical data:** Year of construction of the cable, the deck, and the girder. The date can vary if there were interventions already done. If there is no data regarding any interventions the year of construction of the bridge will rule the rest.
- **Composition data:** Load-bearing elements and building components that compose the steel bridge. The possible known objects for the assessment are illustrated in Figure **52**.
- **Condition data:** Recorded damages and associated properties of each of the object parts of the steel bridge.

Table 23 summarizes the input data collection that can be used for the assessment into a framework. A total of 21 data entries are required for a complete assessment.

TABLE 23: DATA COLLECTION FRAMEWORK FOR THE TEOL RULE-BASED CRITERIA ASSESSMENT

No.	**Year of construction:**	**Cable**	**Deck**	**Girder**
1, 4, 9				
No.	**Load-bearing Elements:**	**Building Components:**	**Detected damage(s) or defect(s):**	**Damage properties:**
2	Cables	Wires		
3	Cables	Other component		
5	Deck (OSD)	Wearing surface		
6	Deck (OSD)	Deck plate		
7	Deck (OSD)	Trough		
8	Deck (OSD)	Other component		
10	Girder	-		
11	Girder	Joints		
12	Girder	Other component		

Example #1 – Individual bridge assessment

For this example, the data from the Galecopper case study was utilized (see Appendix section K). Table 24 illustrates the first step of the assessment, the data gathering into the framework:

TABLE 24: SUMMARY OF THE TEOL RULE-BASED ASSESSMENT OF THE GALECOPPER BRIDGE

No.	**Year of construction:**	**Cable**	**Deck**	**Girder**
1, 4, 9		1973	1973	1973

No.	Load-bearing Elements:	Building Components:	Detected damage(s) or defect(s):	Damage properties:
2	Cables	Wires	High stiffness	High static overload
3	Cables	Other component	No data	No data
5	Deck (OSD)	Wearing surface	Cracks	Spider web crack + Longitudinal cracks on asphalt
6	Deck (OSD)	Deck plate	Root-deck fatigue crack	Longitudinal crack in deck plate of 650mm
7	Deck (OSD)	Trough	No data	No data
8	Deck (OSD)	Other component **(Crossbeam)**	Deformation	Low torsion resistance
10	Girder	-	Deformation	Low torsion resistance
11	Girder	Joints	No data	No data
12	Girder	Other component	No data	No data

Once the data was collected within the framework, the assessment was executed starting at the top of the decision tree with a parallel assessment branch as illustrated in Figure 55:

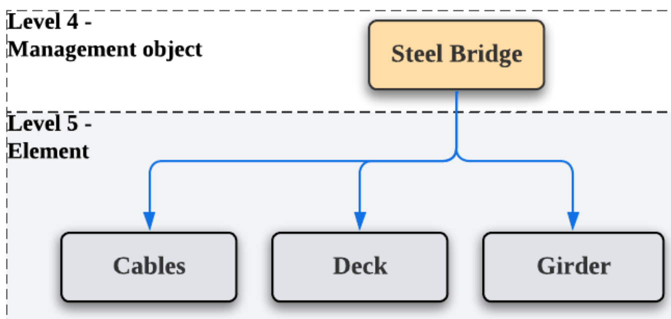

FIGURE 55: EXAMPLE OF THE GALECOPPER ASSESSMENT - STEP 2

According to the data collected in the framework, the assessment continues with the cable, next the deck, and finally with the girder. Figure 56 illustrates the path.

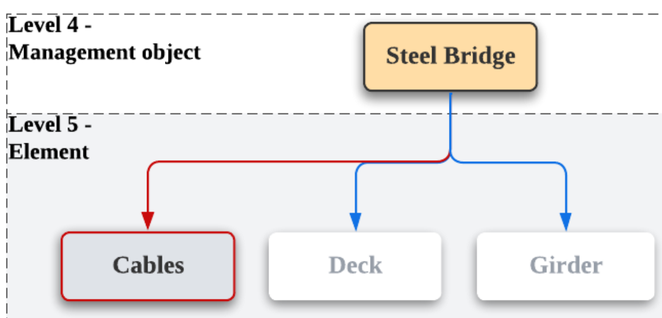

FIGURE 56: EXAMPLE OF THE GALECOPPER ASSESSMENT - STEP 3A

TABLE 25: EXAMPLE OF THE GALECOPPER ASSESSMENT - STEP 3B

No.	Year of construction:	Cable	Assigned points:	Notes:
1		1973	+4	Criteria #1 and #2
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
2	Cables	Wires	+1	
3	Cables	Other component	0	

According to Table 25, the cable had a total of 5 points. The deck was assessed consequently (Figure 57).

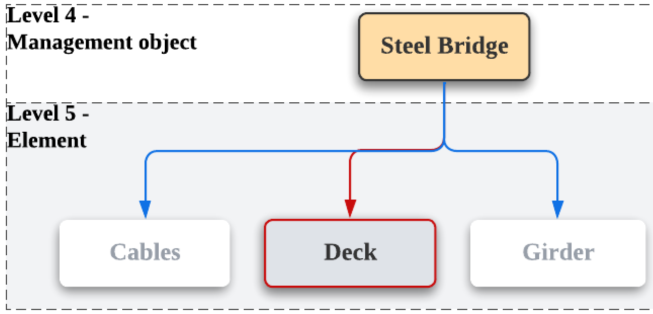

FIGURE 57: EXAMPLE OF THE GALECOPPER ASSESSMENT - STEP 4A

TABLE 26: EXAMPLE OF THE GALECOPPER ASSESSMENT - STEP 4B

No.	**Year of construction:**	**Deck**	**Assigned points:**	**Notes:**
4		1973	+2	Criterion #1
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
5	Deck (OSD)	Wearing surface	+1.5	Cracks originating from deck plate
6	Deck (OSD)	Deck plate	+3	Deck plate has potentially reached TEoL
7	Deck (OSD)	Trough	0	
8	Deck (OSD)	Other component **(Crossbeam)**	+1	

Based on the points allocated to each object in Table 26, the deck scored 7.5 points. Additionally, it was indicated that the building component had potentially reached its TEoL. The assessment continued following this systematic approach reviewing the girder.

TABLE 27: EXAMPLE OF THE GALECOPPER ASSESSMENT - STEP 5B

No.	**Year of construction:**	**Girder**	**Assigned points:**	**Notes:**
9		1973	+2	Criterion #1
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
10	Girder	-	+2	
11	Girder	Joints	0	
12	Girder	Other component	0	

Table 27 illustrates a total of 4 points allocated to the girder. Table 28 summarizes the results within all of the load-bearing elements assessed and highlights important data.

TABLE 28: EXAMPLE OF THE GALECOPPER ASSESSMENT - SUMMARY OF RESULTS

Load-bearing Elements:	**Total points:**	**Notes:**
Cable	5	
Deck (OSD)	7.5	Deck plate has potentially reached TEoL
Girder	4	
	16.5	

Table 28 concludes that the component deck plate had potentially reached its TEoL based on its damage properties. According to the validated TEoL criterion #9, the number of root-deck cracks can dictate the decision to replace the whole deck based on the number of cracks within the deck plate. Therefore, by identifying the theoretically potential TEoL of this component, RWS can initiate an investigation to than decide whether to plan an intervention or not.

Example #2 - Multi-bridge assessment

In the context of a portfolio analysis, the TEoL rule-based criteria were utilized to assess the four steel bridges of the multi-case study section in Chapter 4.1. The four bridges have different typologies and share the same deck composition. Table **29** summarizes the results of the TEoL rule-based assessments:

TABLE 29: SUMMARY OF THE TEOL RULE-BASED ASSESSMENT FOR THE FOUR CASE STUDY BRIDGES

	Load-bearing Elements:	Total points:	Notes:
Galecopper bridge	Cable	5	
	Deck (OSD)	7.5	Deck plate has potentially reached TEoL
	Girder	4	
		16.5	

	Load-bearing Elements:	Total points:	Notes:
Ewijk bridge	Cable	14	Potential TEoL of Cable and Bridge
	Deck (OSD)	3	
	Girder	0	
		17	

	Load-bearing Elements:	Total points:	Notes:
Van Brienenoord bridge	Cable	0	
	Deck (OSD)	7.5	Deck plate has potentially reached TEoL
	Girder	0	
		7.5	

	Load-bearing Elements:	Total points:	Notes:
Moerdijk bridge	Cable	0	
	Deck (OSD)	4	
	Girder	0	
		4	

Note: In appendix section O, the full TEoL rule-based assessment of the bridges is illustrated.

From Table **29**, the following conclusions are drawn:

- Within the Ewijk bridge, a load-bearing element has reached its TEoL. Due to the design composition of the bridge not having structural redundancy within the cables system, this load-bearing element is considered of high importance for the bridge's overall structural integrity. Therefore, its failure could compromise the entire bridge.
- Within the Galecopper and the Van Brienenoord, a component has potentially reached its TEoL However, these results do not involve a direct threat to the whole bridge's integrity.
- Within the Moerdijk bridge, more or multiple damages have been initiated, but there is no current potential TEoL threat to any of its components or load-bearing elements.

- In regard to the point-based system, the Ewijk bridge scored the highest among the evaluated structures, designating it as the primary candidate for major intervention. Then, the Galecopper with 16.5 points, and the Van Brienenoord with 7.5. Lastly, the Moerdijk bridge scored a total of 4 points, ranking it last among the four and suggesting it as the lowest in priority.
- If the four bridges were to be compare only by a single load-bearing element to set the priority, the following can be said:
  - For cables, the Ewijk bridge has a higher priority with a total score of 14.
  - For the deck, the Galecopper and the Van Brienenoord, with a total score of 7.5.
  - For the girder, the Galecopper with a total score of 4.

With these examples, the TEoL rule-based criteria illustrate its usefulness in providing insights into the current condition of a series of steel bridges and prioritising according to its current condition, historical, and composition data.

6

DISCUSSION AND LIMITATIONS

The TEoL rule-based criteria for steel bridges is a qualitative assessment that evaluates the current technical condition of the load-bearing elements and building components of a steel bridge at a portfolio level. In the context of RWS, the TEoL rule-based criteria expands on their current TEoL approach, which has focused solely on aging.

Practical implications

- With the addition of this new assessment, RWS can identify potential steel bridge candidates from its asset portfolio for further, more detailed investigations. As a result, this additional layer of assessment can be integrated into the planning phase of their intervention protocols.
- The significance of understanding structural redundancy within steel bridge assets cannot be overstated. As demonstrated through the TEoL rule-based assessment, structural redundancy is a critical factor in theoretically determining the TEoL of the entire system. In the context of RWS, the identification of non-structural redundant load-bearing elements (e.g. cables) and non-structural redundant building components (e.g. joints), offers the opportunity to integrate them into datasets, thereby enabling continuous oversight within inspection inquiries.

Comparison with other existing models and tools

Within the current EoL models and tools in chapter 3.4:

- The existing EoL model offers insights into locks, not steel bridges. Consequently, the TEoL rule-based criteria assessment approach for steel bridges can be considered an addition to the EoL knowledge.
- The condition score and the aging curve tools only assign a qualitative "risk of failure" score depending on a single object of analysis. The TEoL rule-based criteria takes into consideration multiple damages and influences within various objects. As an example, the cables are assessed by four different criteria.
- The TEoL rule-based criteria is a holistic approach that requires minimal historical, composition, and condition data in comparison with the quick scan tool. The quick scan tool requires extensive data for the analysis but gives a more precise result. Therefore, both tools can be used in tandem. Utilizing the TEoL rule-based criteria's outcome as input for the quick scan tool, an exhaustive analysis can be performed.

TEoL rule-based assessment limitations:

- The input data for the TEoL assessment was derived from historical, composition, and condition data. However, the accuracy of the assessment is predominantly influenced by the availability of condition data. Therefore, to obtain more reliable outputs, it is imperative to ensure the completeness of the condition data.
- The assessment was limited by the findings within the multi-case study section. As a result, the evaluation was limited to cables, girders, deck plates, troughs, joints, wires, and wearing surfaces. Consequently, the output data primarily encompasses cable, girder, and deck insights.

- Concerning the scoring system, score allocation was based on expert knowledge aligned with the validated TEoL criteria. Each of the composition objects of the bridge was assessed by a different number of TEoL criteria, resulting in differing maximum scores for the cable, the girder, and the deck. Nevertheless, the point system was designed to be utilized holistically. The most effective approach involves analysing and comparing similar load-bearing elements across multiple bridge assessments.
- The only damages assessed within the TEoL criteria are cracks and corrosion. Other extensive forms of damage affecting steel structures are addressed collectively through the application of penalty points.

The TEoL rule-based assessment usefulness for other asset managers of steel bridges

- This assessment holds potential utility for other asset managers for assessing steel bridges within the territory of the Netherlands. However, given that the TEoL criteria were composed by data of specific influences, such as traffic loads, European design limitations, environmental factors, human-induced factors, and material properties, the exact assessment of this research cannot be utilized by other road authorities from abroad. Nevertheless, the methodological framework established in this research can serve as a foundation for developing a customized assessment tailored to the unique contextual influences of other regions.

Data limitations within the study:

- Access to the non-public database of DISK, as well as the inspection reports from RWS, was not granted despite formal requests. The limited information was previewed by other agents who had already been granted access to the data for other projects out of the scope of this research. Due to the inability to access the data of RWS and based on the data collected by the scientific literature and web pages, the TEoL rule-based assessment for steel bridges is a proof of concept. The identification of criteria was a success, but to truly analyse the portfolio of RWS, the data must be provided.

- The data utilized within the multi-case study was strictly obtained from scientific-published articles. Missing geometrical data of the bridge load-bearing elements and building components were not publicly available.

Time limitations within the study:

Due to the interest and time limitations of this research, only a few physical damage processes are considered. Analysing all of the possible damage processes in combination with all the influences of TEoL for steel bridges could be focalized within another long-term research.

7

7. CONCLUSION

This final section presents the key conclusions derived from the research, and answers to the research questions. Finally, future research related to this topic is proposed, thereby contributing to the advancement of knowledge within the field of TEoL.

Following the conclusions of the research:

- Conclusion 1: Based on the main objective of the research, the validated TEoL criteria deemed useful as a proof of concept for analysing a portfolio of steel bridges. The only boundaries to tailor the analysis depend on the moment when the asset manager decides to intervene in conjunction with the level of theoretical certainty, and specific influences, such as design limitations and traffic loads.

- Conclusion 2: Establishing quantitative threshold values for each validated rule that contributes to the potential TEoL of steel bridges was not fully possible to achieve. Although the target was not fully achieved, the detection of load-bearing elements and critical components remains crucial. Similarly, the types of damages observed serve as measurable indicators of urgency that can be closely monitored.

- Conclusion 3: The preliminary framework for identifying TEoL criteria was a success, even though there were data limitations. The framework data collection could be expanded to include more quantitative information, therefore, consolidating a more precise TEoL criteria.

7.1. RESEARCH QUESTIONS ANSWERED

This section answers the research questions based on the lessons learned from the study.

Question 1: What are the criteria that contribute to the TEoL of steel bridges?
According to sub-chapter 5.1, the criteria that contribute to the TEoL are severe damages within the steel structure in combination with a mix of external influences. Based on the reach of this study, the severe damages were corrosion and fatigue cracking. The major influences were heavy traffic loads (e.g. heavy lorries), environmental effects (e.g. rain), human-induce factors (e.g. poor maintenance), and design limitations (e.g. old design codes).

Based on the interview phase of validation, the TEoL criteria for steel bridges highlights the main load-bearing elements, such as cables and main girders as structural indicators of TEoL. If these elements fail, the whole bridge would be compromised. Finally, the TEoL criteria are directly related to the number of case studies analysed; the more case studies, the more criteria can be identified.

Question 2: How can the TEoL rule-based criteria be utilized to plan intervention strategies for steel bridges within RWS portfolio?

Building upon the examples of the TEoL rule-based criteria established in sub-chapter 5.2, the TEoL rule-based criteria assessment can identify potential steel bridge candidates for a more in-depth inspection analysis. Based on the number of steel bridges in RWS's portfolio, realizing maintenance inspections (see Appendix section C) to all of their assets, requires vast resources. Therefore, by implementing the TEoL rule-based assessment, RWS can identify which steel bridges require a more urgent maintenance inspection. Consequently, allocating their resources more efficiently.

Question 3: How do different bridge typologies affect the rule-based criteria?

According to the decomposition framework outlined in NEN 2767-4 and the definition of TEoL, each bridge was assessed based on its individual load-bearing elements and building components. The TEoL rule-based assessment combines the TEoL criteria of these elements and components into one single assessment. Relying on bridge typology as a reference for the TEoL assessment is inappropriate; since bridges can vary within their superstructure composition (e.g. some might have cables, some other bridges do not), adhering strictly to the point system for prioritization will lead to an incorrect result. Therefore, the rule-based assessment should instead compare bridge load-bearing elements (e.g. OSD with OSD, and cables with cables).

This study focuses on the evaluation of specific elements, such as cables, girders, and the OSD. Consequently, bridge typologies with other load-bearing elements fall outside the scope of this assessment model.

7.2. FUTURE WORK

- Research proposal 1: Expand the preliminary framework to incorporate additional relevant data that could facilitate the identification of additional EoL criteria. This expansion should encompass functional and economic EoL aspects, thereby establishing a more holistic approach for data collection.

- Research proposal 2: The subsequent phase of this research should prioritize the development of an extended set of TEoL criteria, incorporating a wider range of structural components and damage processes. Consequently, setting a define scale of points for each load-bearing element. Also, with an expanded dataset, a Multi-Criteria Decision Analysis (MCDA) model can be employed to rank bridge assets. This advancement would significantly enhance the reliability of assessment and classification processes.

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A. Damage Processes

The following table explains the correlation between the performance indicators (PIs) and the Damage processes (Dis).

Damage processes		Cracks	Crushing	Rupture	Delamination	Scaling	Spalling	Holes	Debonding	Obstruction/Impending	Displacement	Deformation	Wire break	Prestressing cable	Reinforcement bar failure/bending	Stirrup rupture	Tensioning force deficiency	Loss of section	Deteriorated mortar joints	Frequency	Vibrations/oscillations
Physical	Abrasion			●				●				●	●					●	●	●	●
Physical	Aggradation (alluviation)									●	●	●									
Physical	Erosion	●		●		●		●			●	●	●		●	●		●	●	●	●
Physical	Changing geotechnical properties	●	●	●				●			●	●	●	●	●	●	●			●	●
Physical	Aging of material	●							●		●	●					●	●	●	●	●
Physical	Fatigue	●		●				●				●	●	●	●	●			●	●	●
Physical	Impact due to an accident			●						●	●										
Physical	Overloading of an element	●	●	●							●	●	●	●	●	●	●		●		
Physical	Freeze thaw	●			●	●	●	●	●			●						●	●		
Physical	High temperature				●						●	●					●		●	●	●
Chemical	Alkali aggregate reaction	●			●						●	●			●	●	●			●	●
Chemical	Sulphate reaction	●			●	●	●	●			●	●			●	●	●			●	●
Chemical	Chemical attack				●	●						●	●	●	●	●		●	●		
Chemical	Corrosion	●				●							●	●	●	●		●		●	
Biological	Biological growth	●	●	●				●	●	●	●	●									
Design and construction issues	Design and construction issues	●				●							●		●	●		●		●	

FIGURE 58: DAMAGE PROCESS VS PIS (IM-SAFE KNOWLEDGE BASE, 2022)

B. DECOMPOSITION BASED ON THE NEN 2767-4 AND RWS DISK

The following table lists all the possible data collected within DISK for the characterization of the Level 4 – Management Object:

TABLE 30: MANAGEMENT OBJECT DATA IN DISK (VIANA DA ROCHA, 2013)

Categories of *Management Object* data	Data content
1. Nomination and references	*Management Object* description, including: - Name (if the object is *wet* it is defined according to National Waterways File); - Disk (automatic) codes; - Detailed *Management Object* description; - Object type and object part.
2. Management property	Description of the responsible parties, including: - Administrator responsible; - Name of the authority as the owner may be addressed; - Management area (eg. RWS/ RPC North East); - Province; - Municipality; - Debtor service (defined in accordance to Current Route Profile).
3. Physical Nature	Data regarding the nature object is located, including: - Physical nature: dry or wet,
4. Network	Data regarding the network where the object is located, including: - Highways network (dry), or - Water network (wet)
5. Special Objects (or Features)	Indication if the object is considered *unique* (a list of unique objects is available in DISK; they are assigned special budgets)
6. Geographic reference (link to *KERNGIS*)	The Complex is described with reference to *KERNGIS (coordinates X and Y)*. Geographic data is also in line with the *Rijksdriehoekscoördinaten* (National Triangulation System).
7. Geographic properties	This includes details regarding location, such as: - For dry objects: 4. Number of highway the object is located (defined according to Current Route Profile); 5. Route of highway (defined according to Current Route Profile); 6. Traject (defined according to Current Route Profile); 7. Hectometrering (defined according to Current Route Profile); 8. Relation to road (eg. in RW, over RW or niet RW). - For wet objects: 9. Fairway number (defined according to National Waterway File); 10. Hectometrering.
8. Design properties	Design details, including: - For dry objects: 11. Material and size *(three (3) categories available in DISK: beton klein, beton groot, staal)*. - For wet objects: 12. Discharge capacity; 13. Shipping class (CEMT).
9. Historical data	Historical data, including: - Designer name; - Year of construction; - Year of demolition (if object is not being used).
10. Object use status	Use status of the object, including: *In use* or *not in use*.
11. Data control	*Data accuracy.* If a box is checked, it means that object data is verified and approved by the Administrator. If errors are detected, the checkmark must be removed. The box serves as an indicator for the user to know that data are checked and fixed.
12. Name of inspection families	Description of existent *on-site* permanent facilities used for inspection *(eleven (11) categories available in DISK: eg. borders, deksel, deur, wagen, voetpad,...).*
13. Hazardous substances	Data related to hazardous substances, including: - Substance name; - Description; - Status of the hazardous substance *(five (5) categories available in DISK: asbestos, safe non-destructive, safe non-destructive type A, safe non-destructive type B), and asbestos unsafe)*; - Document uploaded in DISK (optional).
14. Culture history	Data related to culture history, including: - Photos; - Status (valuation to CIWW). - Status color (related to object cultural value) – red, orange, yellow or green[5]; - Remarks (optional).

The following table lists all the possible data collected within DISK for the characterization of the Level 5 – Element, corresponding to Maintenance Parts (IH parts):

TABLE 31: MANAGEMENT PART DATA IN DISK (VIANA DA ROCHA, 2013)

Categories of *management part* data	Data content
1. Nomination and references	This includes data related to: - Description and name; - Disk (automatic) codes.
2. Design properties	Design properties, include: - Material of object part; - Technical description of object; - Deviating of addictive duty; - Length.
3. Geographic properties	This includes: - Highway number; - Hectometrering; - Track number; - Highway designation (four (4) categories available in DISK: HR, VB, VW and OJ); - Position of the element (three (3) categories are available in DISK: L, M and R); - Letter (in case of an *exit*).

The following table lists all the possible data collected within DISK for the characterization of the Level 6 – Building component, corresponding to Inspection Parts (IS parts):

TABLE 32: INSPECTION PART DATA IN DISK (VIANA DA ROCHA, 2013)

Categories of *Inspection Part* data	Data content
1. Nomination and references	This includes data related to: - Name; - Disk (automatic) codes.
2. Design properties	Design properties, include: - Material; - Form; - Place the display on the drawing role; - Name of the manufacturer; - Letter of material; - Technical description; - Characteristics; - Value.

Hierarchical Decomposition from the NEN 2767-4-1

The example from the NEN 2767-4 2011, condition assessment – Part 4: Infrastructure – Part 1: Methods.

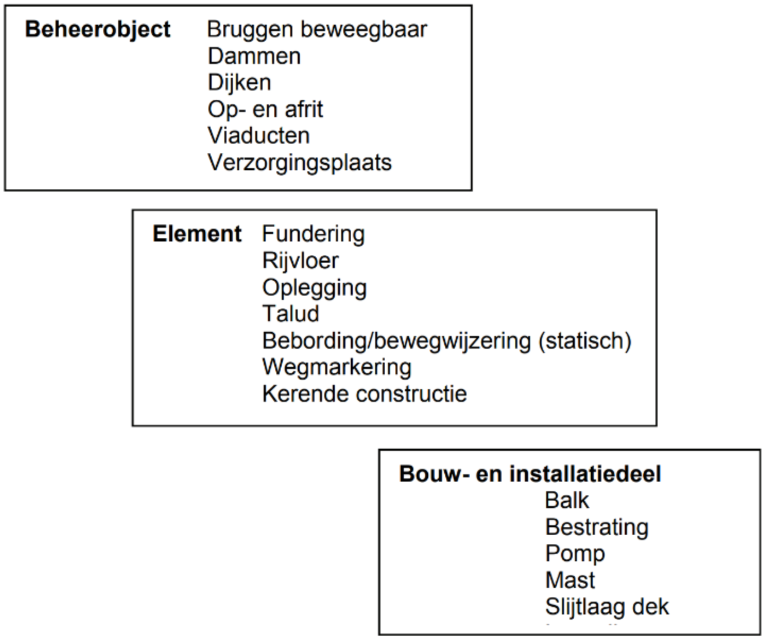


FIGURE 59: NEN 2767-4 HERARCHICAL DIVISION (NEN 2767-4-1, 2011).

C. RWS INSPECTION TIMEFRAMES

The table explains the timeframe of RWS intervention types and scope.

TABLE 33: INSPECTION CATEGORIES. GOALS AND RESULTS (VIANA DA ROCHA, 2013)

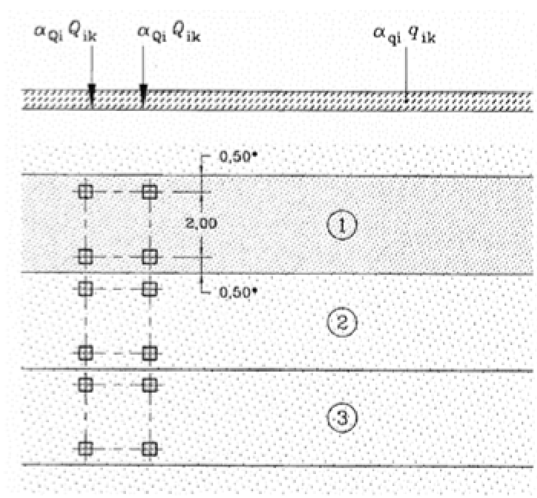
Inspection type	Interval *(indicative)*	Goal	Main results
Regular Inspection	Daily basis	Detecting emergencies, faults or other weaknesses that are relevant for the context of liability. Take advice to initiate condition inspections.	• Registration of potential liability incidents. • Direct control measures to be taken. • Fixed maintenance. • Condition inspection.
Condition Inspection	½ - 2 years	Detecting defects that can affect negatively the object, directly in the short term for its proper and safe operation.	• Capture current state. • Final judgement of parts function, safety and condition (also testing and checking parts of which at normal litigation are not in use). • Propose actions with maintenance.
Maintenance Inspection[1]	5 or 6 years	Update/ validate file details of objects or parts of objects. Deliver an opinion and technical preconditions for updating the IHP.	*(see chapter 3)* • Current status data. • Technical bandwidth for future action in the Maintenance Plan (economic optimum and technical extreme moment of intervention). • Advice on adjusting the IHP.

D. NEN EN 1991-2:2003

Within the Eurocode 1: Actions on structures—Part 2: Traffic loads on bridges, under section 4.3.2 Load Model 1. It is textually stated that "*LM 1 is intended to cover flowing, congested or traffic jam situations with a high percentage of heavy lorries. In general, when used with the basic values, it covers the effects of a special vehicle of 600 kN.*"

TABLE 34: LOAD MODEL 1: CHARACTERISTIC VALUES (EN 1991-2, 2003),

Location	Tandem system *TS*	*UDL* system
	Axle loads Q_{ik} (kN)	AC1 q_{ik} **(or** q_{rk}) (kN/m^2) AC1
Lane Number 1	300	9
Lane Number 2	200	2,5
Lane Number 3	100	2,5
Other lanes	0	2,5
Remaining area (q_{rk})	0	2,5



Key
(1) Lane Nr. 1 : Q_{1k} = 300 kN ; q_{1k} = 9 kN/m^2
(2) Lane Nr. 2 : Q_{2k} = 200 kN ; q_{2k} = 2,5 kN/m^2
(3) Lane Nr. 3 : Q_{3k} = 100 kN ; q_{3k} = 2,5 kN/m^2
AC1 Tandem axle spacing = 1,2 m AC1
* For w_l = 3,00 m

FIGURE 60: APPLICATION OF THE LOAD MODEL 1 (EN 1991-2, 2003).

E. LOAD CLASS

Information pertinent to the load classification utilized in the Netherlands for bridges.

TABLE 35: FORMER TRAFFIC LOAD CLASSES, WITH THE CORRESPONDING CLASSIFICATION FOR VOSB1933 AND VOSB1963, WHERE A LOWER LOAD CLASS THAN 30 IS OMITTED (HARREWIJN ET AL., 2020).

VOSB1933 [Load class]	VOSB1963 [Load class]	Bridges:
A	60	in the national road network;
B	45	in the main network with accidental heavy traffic;
C	30	not intended for heavy traffic;
D	-	intended for light traffic (pedestrians).

(1) In the design of bridges the carriageway should be divided in the same number of lanes as the connecting roads, or, when not applicable, in the maximum number of notional lanes with a width of 3 meters that fit in the total width of the carriageway.

(2) The design load consists of a uniformly distributed load over the total width of the carriageway and an axle system of concentrated loads in the lanes.

(3) When more than 1 lane can be loaded by an axle system a maximum of 2 axle systems may be considered together with the uniformly distributed load. In this case the total load combination may be reduced to 80 %.

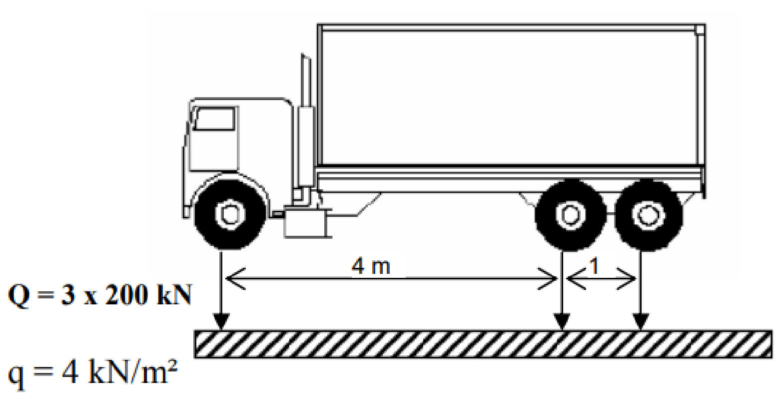


FIGURE 61: TRAFFIC LOAD MODEL 1963 (VOSB 1963 LOAD CLASS 60) (SCHAAFSMA, 2019)

F. OSD Bridges Between 1997-2004

List of Dutch bridges that had deck plate cracks observed between 1997-2004.

TABLE 36: OVERVIEW OF DECK PLATE CRACKS OBSERVED IN A NUMBER OF DUTCH HIGHWAY (DE JONG, 2006).

Bridge	Type	Year of completion	First visible crack detected in...	Age [years]
Ketelbrug	movable	1968	1998	30
Scharsterrijn	movable	1972	2002	30
2nd Van Brienenoordbrug	movable	1990	1997	7
Calandbrug	movable	1969	1998	29
Brug Zijkanaal C	movable	1969	2003	34
Julianabrug	movable	1966	2001	35
Calandbrug	fixed	1969	2002	33
Brug Hagestein	fixed	1980	2002	22
Galecopperbrug	fixed	1971	2002	31
Moerdijkbrug	fixed	1976	2001	25
Boogbrug Beek	fixed	1968	2004	36

G. Cable-stayed Bridges in the Netherlands

TABLE 37: CABLE-STAYED BRIDGES IN THE NETHERLANDS (WEGENWIKI.NL, 2024)

brug	hoofdoverspanning	route	openstelling
Erasmusbrug	278 m	s122	04-09-1996
Tacitusbrug (Waalbrug Ewijk)	270 m	A50	30-06-1976
Willemsbrug	270 m	s123	01-07-1981
Prins Willem-Alexanderbrug	270 m	N323	01-06-1974
Martinus Nijhoffbrug	256 m	A2	18-01-1996
Molenbrug	194 m	N764	04-10-1983
Galecopperbrug	180 m	A12	05-07-1971
Muiderbrug	162 m	A1	15-12-1970*
Eilandbrug	150 m	N50	21-01-2003
Prins Clausbrug	150 m	Bevrijdingslaan (Utrecht)	17-05-2003
Heusdensebrug	115 m	N267	00-00-1989
Harmsenbrug	109 m	N57	00-00-1968
Calatravabruggen	143 m	Hoofdvaart Haarlemmermeer	01-07-2004

H. TRAFFIC INTENSITY OF THE VAN BRIENENOORD BRIDGE (1990-2010)

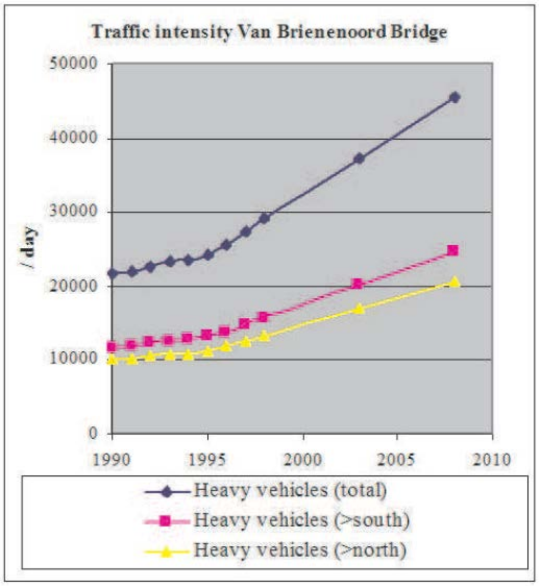


FIGURE 62: MEASUREMENT OF TRAFFIC INTENSITY, MEASURE POINTS NEAR ROTTERDAM (LEFT) AND INTENSITY (RIGHT) (ROMEIJN, 2006).

I. HPC AND UHPC FOR RHPC

This table illustrates the property differences between the High Strength Concrete and the Ultra High-Performance Concrete based on the findings of Buitelaar et al. (2006).

TABLE 38: PROPERTIES OF THE RHPC OVERLAY BASED ON BUITELAAR ET AL. (2006).

Description	RHPC overlay with HPC	RHPC overlay with UHPC
Compressive strength concrete in MPa: 24 h / 2 d / 3 d / 7 d / 28 d	50/ 70/ 80/ 90/ 120	75/ 100/ 120/ 150/ 180
Flexural strength concrete in MPa: 24 h / 7 d / 28 d	7/ 9/ 11	9/ 12/ 15
Flexural strength RHPC overlay in MPa: 24 h / 2 d / 3 d / 7d / 28 d	60/ 70/ 74/ 77/ 80	70/ 80/ 84/ 87/ 90
Density concrete in kg/m³	2,600	2,700
E- modulus concrete	48,000	55,000
Wear resistance DIN 52108 Böhme - value in cm³/50 cm²	< 6	< 4
Impact resistance	Very high	Extremely high
Frost/thaw resistance SS 13 72 44A-IV	Very good	Very good
Frost/thaw resistance CDF	Average 4 g./m² 100 times less than reference 58 MPa concrete	Average 4 g./m² 100 times less than reference 58 MPa concrete
Chemical resistance compared to high quality concrete (45MPa)	Very good	Very good
Water penetration according DIN/ISO 7031	< 1.5 mm	< 1.5 mm
Chloride penetration after 24 months according Nordtest	Not to measure (< 1.5 mm in concrete skin)	Not to measure (< 1.5 mm in concrete skin)
Typical amount of steelfibers in% by volume	1 – 2%	1 – 2%
Typical amount of steelfibers per m²	2 – 4 kg	2 – 4 kg
Typical amount of reinforcement in % by volume	4 – 10%	4 – 10%
Typical amount of reinforcement per m²	8 – 80 kg	8 – 80 kg
Typical thickness of RHPC overlay	30 – 100 mm	30 – 100 mm

J. Selection of the Case Studies

The selection of the four case studies was based on the amount of scientific data found in the academic search engine Google Scholar. Searching in apostrophes the name of the bridge, plus the word "bridge" and counting the number of results, e.g. "Ewijk bridge."

The list of bridges was given by a cooperation of TNO and RWS, Den Besten (2012) gathered additional data (geometrical, damages, notes) that was also used in the assessment.

TABLE 39: AMOUNT OF SCIENTIFIC RESEARCH REGARDING EACH CASE STUDY WITHIN GOOGLE SCHOLAR

Bridge	Results of scientific articles within Google Scholar
Moerdijk	127
Van Brienenoord	113
Ewijk	69
Galecopper	12
Suurhoff	12
Scharsterrijn	9
Scharsterrijn	9
Harmsen	7
Hagestein	6
Kampen	4
Muider	3
Kreekrak	3
Ketel	3
Wantij	3
Kruiswater	1
Schiphol	1
Euvelgunnerbrug	1
Boog (bridge) Beek	0
Scharberg	0

K. Case Study Analysis: Frameworks

This section of the appendix will include all the complete framework data for each independent case study analysed. The colour code of the spreadsheet is as follows: **Gold**, suggested defect based on literature and external influences. **Green**, data found within literature, not part of the case study related data, and **Blue**, indicates the values from the case-study articles.

1. Galecopper Bridge

Level 4 - Management Object Data (NEN 2676)								None-NEN		
1. Nomination and references			2. Management property		4. Network	9. Historical data		Interventions	Bridge Section	
Name	Disk code	Description	Province	Municipality	Highway network (dry)	Designer name	Year of construction	Number and Year	Data number	Superstructure, Deck, Substructure, Foundation, Mechanical
Galecopper bridge	31H-005	Cable-stayed bridge	Utrecht	Utrecht	A12		1971	1st (2013-2015)	1	Superstructure
Galecopper bridge	31H-005	Cable-stayed bridge	Utrecht	Utrecht	A12		1971	1st (2013-2015)	2	Superstructure
Galecopper bridge	31H-005	Cable-stayed bridge	Utrecht	Utrecht	A12		1971	1st (2013-2015)	3.1	Deck
Galecopper bridge	31H-005	Cable-stayed bridge	Utrecht	Utrecht	A12		1971	1st (2013-2015)	3.2	Deck
Galecopper bridge	31H-005	Cable-stayed bridge	Utrecht	Utrecht	A12		1971	1st (2013-2015)	4	Deck
Galecopper bridge	31H-005	Cable-stayed bridge	Utrecht	Utrecht	A12		1971	2nd (2015)	1	Superstructure

Level 5 - Element Data (NEN 2676)					Level 6 - Building Component Data (NEN 2676)			
1. Nomination and references	2. Design properties			3. Geographic properties	1. Nomination and reference	2. Design properties		
Description and name	Material of object	Tech description	Length	Position of element (L,M and R)	Name	Material	Name of manufacturer	Tech description
Cables	Steel	High-strength steel wires + wrap						
Pylon	Steel							
Deck	Steel	Orthotropic steel deck			Deck plate	Steel		
Deck	Steel	Orthotropic steel deck			Crossbeams	Steel		
Mian girder	Steel	High-performance structural steel plate						
Cables	Steel	High-strength steel wires + wrap						

None-NEN					Reference
Damages and Defects				Risk of Failure	
Detected damage or defect	Properties	Potential causes (Influences)	Threshold	Perceived risk (High, Medium, Low)	
Fatigue stress (High static overload)	High stiffness	Overload			(Den Blanken et al., 2012)
Fatigue stress (High static overload)	High stiffness	Overload			(Den Blanken et al., 2012)
Fatigue cracking	Spider web crack + Longitudinal cracks on asphalt	Deck plate thickness + Increase traffic load	Longitudinal crack in deck plate of 650mm	High - Structural integrity at risk	(Den Blanken et al., 2012)
Deformation (High bending)	Low torsion resistance	Insufficient bending capacity + Cascade effect due to cables provide insufficient support			(Den Blanken et al., 2012)
Deformation (High bending)	Low torsion resistance	Insufficient bending capacity + Cascade effect due to cables provide insufficient support			(Den Blanken et al., 2012)
Corrosion	Damage near the anchorage	Degradation + Humidity and temperature	Cross-sectional area diminishes to less than 40% of its original size	Medium - Recommended intervention (case study) and High (Threshold)	(Abspoel-Bukman et al., 2023), (Gao et al., 2023).

2. EWIJK BRIDGE

Level 4 - Management Object Data (NEN 2676)								None-NEN		
1. Nomination and references			2. Management property		4. Network	9. Historical data		Interventions	Bridge Section	
Name	Disk code	Description	Province	Municipality	Highway network (dry)	Designer name	Year of construction	Number and Year	Data number	Superstructure, Deck, Substructure, Foundation, Mechanical
Tacitus bridge (Old Ewijk bridge)	39H-100-01	Cable-stayed bridge	Gelderland	Overbetuwe	A50		1976	1st	1	Superstructure
Tacitus bridge (Old Ewijk bridge)	39H-100-01	Cable-stayed bridge	Gelderland	Overbetuwe	A50		1976	1st	2	Deck

Level 5 - Element Data (NEN 2676)					Level 6 - Building Component Data (NEN 2676)			
1. Nomination and references	2. Design properties			3. Geographic properties	1. Nomination and reference	2. Design properties		
Description and name	Material of object	Tech description	Length	Position of element (L,M and R)	Name	Material	Name of manufacturer	Tech description
Cables	Steel		240m upper set & 120m lower set	M	Wires	Steel		High-strength steel wires, 5 (upper) and 3 (lower) strands composed by 235 wires within 9 layers + wrap (steel sleeves)
Deck	Steel	Steel box girder (OSD)	1,055 m	M	Deck plate	Steel		

None-NEN					Reference
Damages and Defects				Risk of Failure	
Detected damage or defect	Properties	Potential causes (Influences)	Threshold	Perceived risk (High, Medium, Low)	
Fracture cracks - 11 wires (1990) & 23 wires (2012)	Lamination	Manufacturing problem (1970s) + increase traffic load	Wire fractures ≥ 10% of the total wire bundle.	High - Structural safety at risk (The calculated reliability of the stay cables was lower than the target value, so that measures need to be taken.)	(Lavery et al., 2013), (Maljaars & Vrouwenvelder, 2014).
Local fatigue	Insufficient static shear capacity	Increase load traffic + insufficient support	Does have or not bracings	High - Safety at risk	(Flint et al., 2013)

3. VAN BRIENENOORD BRIDGE

Level 4 - Management Object Data (NEN 2676)								None-NEN		
1. Nomination and references			2. Management property		4. Network	9. Historical data		Interventions	Bridge Section	
Name	Disk code	Description	Province	Municipality	Highway network (dry)	Designer name	Year of construction	Number and Year	Data number	Superstructure, Deck, Substructure, Foundation, Mechanical
Van Brienenoord bridge	37H-006-02	Arch bridge + Bascule bridge	Rotterdam	Zuid-Holland	A16	WJ van der Eb	1990	1st	1	Deck

Level 5 - Element Data (NEN 2676)					Level 6 - Building Component Data (NEN 2676)			
1. Nomination and references	2. Design properties			3. Geographic properties	1. Nomination and reference	2. Design properties		
Description and name	Material of object	Tech description	Length	Position of element (L,M and R)	Name	Material	Name of manufacturer	Tech description
Deck	Steel	Orthotropic steel deck	60 m	M	Deck plate	Steel		

None-NEN					Reference
Damages and Defects				Risk of Failure	
Detected damage or defect	Properties	Potential causes (Influences)	Threshold	Perceived risk (High, Medium, Low)	
gue cracking	Root-deck crack	High traffic load (stress) at the rib-to-deck joint	≤ 12 mm deck plate, ≤ 6 mm through, and one or multiple 500 mm long root deck fatigue crack.	High - Structural integrity at risk	(Wang et al., 2021), (Romeijn, 2006)

4. Moerdijk Bridge

Level 4 - Management Object Data (NEN 2676)								None-NEN		
1. Nomination and references			2. Management property		4. Network	9. Historical data		Interventions	Bridge Section	
Name	Disk code	Description	Province	Municipality	Highway network (dry)	Designer name	Year of construction	Number and Year	Data number	Superstructure, Deck, Substructure, Foundation, Mechanical
Moerdijk bridge	44A-101	Girder bridge	Dordrecht	Zuid-Holland	A16		1976	1st	1	Deck

Level 5 - Element Data (NEN 2676)					Level 6 - Building Component Data (NEN 2676)			
1. Nomination and references	2. Design properties			3. Geographic properties	1. Nomination and reference	2. Design properties		
Description and name	Material of object	Tech description	Length	Position of element (L,M and R)	Name	Material	Name of manufacturer	Tech description
Deck	Steel	Steel box girder (OSD)	100 m	M	Trough	Steel		

None-NEN					Reference
Damages and Defects				Risk of Failure	
Detected damage or defect	Properties	Potential causes (Influences)	Threshold	Perceived risk (High, Medium, Low)	
Fatigue cracking	Weld root crack	High traffic load (stress) + crack at the weld-to-trough	≤ 12 mm deck plate, and one or multiple weld root cracks	Low - No risk to traffic safety is expected	(Romeijn, 2006)

L. THE CONCISE TEOL CRITERIA

In this section of the appendix was described the concise criteria before validation. The criteria are a result of the compiled data gathered in the multi-case study section. The criteria are classified by their level of decomposition based on the NEN 2767-4, and they are not arranged by any hierarchical importance.

Level 3 – System part

C#1 (Criterion #12)	
If a steel bridge, either fixed or movable of any typology, with an OSD has reached TEoL due to fatigue cracks within the deck plate due to an increase in heavy traffic, and the traffic data of the damaged bridge is available, this data can be used to assess the potential TEoL of other steel bridges within the same highway network, with the same deck composition.	
Risk to failure:	None.
Threshold:	TEoL of an OSD bridge within the highway network of interest.
Influences:	Traffic loads (Heavy traffic intensity, load, and position in the deck), Desing limitations (Designed by the same code), Damage process (Similar damages and age), and Material properties (Same geometry and material properties in component level).
Constraints and limitations:	o The criterion can be utilized only if the influences and deck typology within the TEoL bridge are similar to the ones from the bridge in question. o This criterion does not indicate a level of risk, due to its higher hierarchical level, this criterion is intended as a reference dataset for other assessing other bridges.

Level 4 – Management object

C#2 (Criterion #8)	
If a steel bridge, either fixed or movable of any typology, has a service life between or close to 80-100 years, the infrastructure asset has potential reached its TEoL.	
Risk to failure:	Unknown.
Threshold:	80–100-year-old bridge asset.
Influences:	Damage processes (Aging), Human-induced factors (Correct maintenance), Environmental factors, and Traffic loads (increase in heavy traffic over the years).
Constraints and limitations:	o This criterion is a generalization of the status of the bridge. It is dependent on the TEoL of any of its elements and components. If one of the elements of the system reaches TEoL, the whole object system reaches TEoL. This criterion serves as a general indictor for a more rigorous inspection when data of the current status of the bridge is not available. o The 80-100 years is derived from RWS (2022) determination of the service life.

Level 5 – Element

C#3 (Criterion #7)	
When an existing movable steel bridge featuring a bascule section composed of an OSD undergoes an upgrade with a new wearing surface, such as a RHPC overlay, it is crucial to inspect and assess the hinges and the driving gear responsible for actuating its opening and closing mechanism. If the additional load introduced by the new overlay exceeds the design capacity of the mechanical system, potentially diminishing its performance or functionality of the mechanism, it indicates that the mechanical gear has reached its TEoL.	
Risk to failure:	High.
Threshold:	Mechanism performance is compromised.

Influences:	Component obsolescence (element is unrepairable).
Constraints and limitations:	o Based on the performance thresholds of the current norms and standards that rule the movable steel bridges and their mechanical systems. This threshold information has to be further researched.

C#4 (Criterion #9)	
If a steel bridge, either fixed or movable of any typology, has an OSD with a service life close to 30 years, the OSD has potential reached its TEoL.	
Risk to failure:	Unknown.
Threshold:	30 years since it was constructed.
Influences:	Traffic loads (increase in heavy traffic over the years and position within the deck), Damage processes (Aging, fatigue cracks), Material properties (geometry of the OSD), Design limitations (based on the same construction code).
Constraints and limitations:	o This criterion has been derived from Table 36, were the average service life of OSD's was 30 years. o The criterion is mainly triggered by the increase in heavy traffic loads. o The material properties are ruled in combination with the design limitations that were in place during the construction time of the bridge. According to the multi-case studies, the OSD with a deck plate of ≤ 12mm are prompt to fatigue cracks, therefore, this criterion analyses OSD with a deck plate with ≤ 12mm. o Further study on the type of crack will determine the perceived risk to failure.

C#5 (Criterion #4)	
When a steel bridge, of any typology, has a deck composed by a steel box girder, and the deck plate has suffered from fatigue cracks due to heavy traffic loads, the OSD has potentially reached its TEoL, if the OSD composition does not have bracings that support the new dynamic loads.	
Risk to failure:	High.
Threshold:	Does have or not bracings.
Influences:	Traffic loads (increase in heavy traffic over the years and position within the deck), and Damage processes (Aging, fatigue cracks).
Constraints and limitations:	o The type of fatigue cracks and localization within the deck plate is not relevant, the relevance for the potential risk of failure comes from the lack of load bearing structures (bracings) due to localized fatigue within the OSD.

C#6 (Criterion #13)	
If a steel bridge, either fixed or movable of any typology, has a main steel girder element within the deck composition, and it presents any type of fatigue cracks, the girder has potential reached its TEoL.	
Risk to failure:	High.
Threshold:	Unknown.
Influences:	Traffic loads (increase in heavy traffic over the years), and Damage processes (Aging, fatigue cracks).
Constraints and limitations:	o The main girder is part of the main load bearing components of the steel bridge. o The location and the quantity of cracks is not taken into account. o Further research on the localization of stress concentrations could lead to points of interest within the girder. o Type of connections and joint material compositions are not considered.

C#7 (Criterion #14)	
If a steel bridge, either fixed or movable of any typology, has a main steel girder element within the deck composition, and it presents any type of corrosion damage, the girder has potential reached its TEoL.	
Risk to failure:	Medium.
Threshold:	Unknown.
Influences:	Traffic loads (increase in heavy traffic over the years), Environmental factors (Humidity and temperature), and Damage processes (corrosion).
Constraints and limitations:	o Similarly to C#6, the main girder is part of the main load bearing components of the steel bridge. o The location of the corrosion is not taken into account. o Type of connections and joint material compositions are not considered.

Level 6 – Building Component

C#8 (Criterion #1)	
If the high-strength steel wires (cables) of a steel cable-stayed bridge have a cross-sectional area that is less than 40% of its original size due to corrosion degradation, the cable has potentially reached its TEoL.	
Risk to failure:	High.
Threshold:	Cross section < 40% of its original size.
Influences:	Environmental factors (Humidity and temperature), Damage processes (Corrosion, aging), Human-induced factors (Inspector's expertise), and Traffic loads (increase in heavy traffic over the years).
Constraints and limitations:	o Corrosion propagation can originate from damages within the protecting sleeve of the cable (wrap) or in the anchorages to the deck. o The cables are usually bundles of wires forming different layers. It is unknown the percentage of wires that have to be damaged to cause the TEoL of the element. o The risk level is dependent on the expertise of the inspector. Due to the nature of visual inspections, it is difficult to quantify the percentage of cross-sectional damage caused by corrosion within the cable. Therefore, if the perceived risk to failure is considerate high, the cable has potentially reached its TEoL. o The 40% is based on the findings of of Gao et al. (2023).

C#9 (Criterion #3)	
If the high-strength steel wires (cables) of a steel cable-stayed bridge present fractures due to lamination by 10% or more of the total wire bundle, the cable has potentially reached its TEoL.	
Risk to failure:	High.
Threshold:	≥ 10% of the total wire bundle.
Influences:	Traffic loads (increase in heavy traffic over the years), and Material properties (manufactured defects).
Constraints and limitations:	o Fracture is defined when the fatigue crack lengthens to the point where it progressively lowers its cross-section area and its capacity to fulfil its function is compromised. o The 10% was determined by the case study of the Ewijk bridge, were 10% of the wires presented fractures and the cables needed to be replaced. o This criterion can consider the manufacturer as a threshold. The manufacturer data is gathered within the component level within DISK (Inspection Parts (IS parts)).

C#10 (Criteria #2, #5, and #11)
If a steel bridge of any typology possesses an OSD with a deck plate thickness of 12 mm or less, that is also composed of closed troughs, and exhibits longitudinal fatigue cracks of 500 mm in length or more on

the top side of the deck plate, which are attributed to root deck fatigue cracks (Type II) occurring between the deck plate and the troughs near the crossbeam due to increased heavy traffic, then the OSD may have potentially reached its TEoL.	
Risk to failure:	High.
Threshold:	≤ 12 mm deck plate, and one or multiple 500 mm long root deck fatigue crack.
Influences:	Traffic loads (Heavy traffic intensity, load, and position in the deck), Damage processes (aging of material and fatigue), and Material properties (thickness of the deck plate).
Constraints and limitations:	o According to theory and the case studies, a deck plate of ≤ 12mm is susceptible to fatigue cracks. o The longitudinal cracks within the top side of the deck plate will be distinguished by longitudinal cracks and /or spider's web cracks within the wearing surface (pavement). o The ≥ 500 mm length of the crack is bases on the findings of Romeijn (2006). o The root deck fatigue crack is considered of high threat to traffic safety if it is near the crossbeam area, therefore of high potential risk. o The cases attributed a 6 mm of thickness of the trough, but the type of crack is attributed to the deck plate.

C#11 (Criterion #6)	
If a steel bridge of any typology possesses an OSD with a deck plate thickness of 12 mm or less, that is also composed of closed troughs, and exhibits longitudinal fatigue cracks in the trough, which are attributed to weld root crack (Type IV), then the OSD may have potentially reached its TEoL.	
Risk to failure:	Low.
Threshold:	≤ 12 mm deck plate, and one or multiple weld root cracks.
Influences:	Traffic loads (Heavy traffic intensity, load, and position in the deck), Damage processes (aging of material and fatigue), Material properties (thickness of the deck plate), and Human-induced factors (Poor welding).
Constraints and limitations:	o This criterion is categorized as a potentially low risk to failure, even though, based on the Moerdijk case study, the deck was renovated, therefore, considered as a major intervention. o This criterion is dependent on the quality of the welding (Figure 10).

C#12 (Criterion #10)	
When a steel bridge, of any typology, has an OSD, that has closed troughs, and suffers from high concentrations of stress due to the increase in heavy traffic, if the trough does not have bulkheads that reduce the localized stress, then the OSD may have potentially reached its TEoL.	
Risk to failure:	Unknown.
Threshold:	Does have or not bulkhead.
Influences:	Traffic loads (Heavy traffic intensity, load, and position in the deck), and Damage processes (aging of material and fatigue).
Constraints and limitations:	o The geometry of the cut-out and the trough are not considered in the criterion due to the lack of quantitative data. o According to theory, the velocity of crack propagation after the initiation phase is dependent on the ability to reduce stress concentrations.

M. CONSENT FORM FOR THE SEMI-STRUCTURED INTERVIEWS

The consent form, alongside an information sheet, was utilized for obtaining the writing consent from TNO domain experts to utilize their expert knowledge to validate the case study criteria.

Information Sheet for the Potential TEOL Rule-Based Criteria for Steel Bridges

(you will be given a copy of this informed consent form)

The purpose of the research:

Discussions revolving around the aging bridge structures in the Netherlands and the need for major interventions of these assets was an incentive to research the topic of technical end-of-life of bridges at a portfolio level. This research aims to highlight a series of criteria that trigger the potential technical end-of-life of bridges. By determining the technical end-of-life, a series of rule-based criteria can be extracted to analyse the portfolio of bridge assets of Rijkswaterstaat which subsequently will be utilized as a guideline to prioritize major intervention strategies. Therefore, broadening the scientific knowledge within asset management and fostering a new approach to tackle this urgent infrastructure issue.

Benefits and risks of participating:

This research project is under review and approval by the department of Civil Engineering and Management of the University of Twente and TNO.

Procedures for withdrawal from the study:

The participant can, at any-time, withdraw from the study. His/her information will be deleted.

Usage of the data during research:

- The data gathered will be used for academic purposes.
- The researcher and TNO will only hold the data.
- Confidentiality will be maintained.
- The data will be achieved within video recordings and notes, within TNO database.

Retention period for the research data:

The collected data will be held for the remainder of this research project.

Personal information about the participant:

Only the department name within TNO, and the domain of expertise will be gathered.

Contact details of the researcher:

Name: Alexis Demetrio Anguiano Ventura (Student)
Institution: University of Twente
Email address: a.d.anguianoventura@student.uwtente.nl
Phone: +31 617243527

Contact Information for Questions about Your Rights as a Research Participant:

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee/domain Humanities & Social Sciences of the Faculty of Behavioral, Management and Social Sciences at the University of Twente by ethicscommittee-hss@utwente.nl

Consent Form for the Potential TEOL Rule-Based Criteria for Steel Bridges

(you will be given a copy of this informed consent form)

Please tick the appropriate boxes	Yes	No
Taking part in the study:		
- I have read and understood the study information dated _____________, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	O	O
- I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason.	O	O
- I understand that taking part in the study involves an audio-recorded interview and the elaboration of written notes of the interview. The purpose of the audio recording is to support the field notes observations, this will be transcribed as text, and later on the recording will be destroyed/deleted.	O	O
Use of the information in the study:		
- I understand that information I provide will be used for academic reports, publications and online content, using the same terms as in the study information sheet.	O	O
- I understand that personal information collected about me that can identify me, such as (e.g. my name), will not be shared beyond the study team.	O	O
- I agree that my information can be quoted in research outputs as "TNO domain expert(s)".	O	O
- I agree to be audio/video recorded.	O	O
Future use and reuse of the information by others:		
- I understand that the anonymized information I will provide can be shared with, and potentially used by the partners of the TNO DBE project team.	O	O
- I give the researcher permission to keep my contact information and to contact me for future research projects.	O	O

Signatures:

______________________	______________________	______________
Name of participant	Signature	Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Alexis Demetrio Anguiano Ventura	______________________	______________
Researcher	Signature	Date

N. INTERVIEW PROCESS AND SUMMARIES

Here are the processes and summaries from the three interviews. The information is organized in two, first, based on the criterion number (Cn) and the research related questions to the domain experts at TNO, and lastly the revised TEoL criteria to the asset manager from RWS.

1. TNO DOMAIN EXPERT INTERVIEWS

Interview Process TNO:

- The information sheet and consent form were read and signed by the participants (See appendix section L).
- The questions, in the form of descriptive criterion were presented one-by-one to the participant in the form of presentation slides.
- Once the criterion was explained by the interviewer, the discussion initiated, and the threshold values reviewed.
- Extra questions were asked due to relevance for the study, such as:
  - Did the updates on the standards and regulations (such as NEN 6771 to NEN-EN 1993-1) had a noticeable impact on steel bridge design and thresholds of safety? This question was asked to give additional weight to C#1.
  - If one of the elements (or components) of the system (bridge) reaches TEoL, the whole object system reaches TEoL? (Based on C#2). This question was intended to seek for critical components that are key to the bridge in relation to the TEoL.
  - Are the load bearing elements of the steel bridge of higher importance than the components in the assessment of TEoL? (Based on C#6 & #7) This question had the purpose of ranking the criteria based on domain expert judgement.
  - Do the types of fatigue cracks have any hierarchy in terms of importance regarding the TEoL? (Based on C#10 & #11) This question gives insides on hierarchy of importance.

C#1	
TNO domain expert 1:	TNO domain expert 2:
- The criterion can be considered, for data purposes for assessing other bridges, if the geometry, material properties, and design standards of the element and components are the same in both bridges. - Difficult to estimate and know the traffic intensity within multiple corridors within the same highway network.	- You can use traffic data from comparison (similar locations). If the bridge that has the data does not suffer any TEoL, you can use the traffic data to assess the other bridge. In the other hand, the appearance of fatigue cracks could be originated from other bridge specific sources not necessary from traffic. This can be the geometry, maintenance (welding), etc. - Ideally, you should have the traffic data from the bridge to base on any assessments to that specific bridge, currently, one database is used for several bridges within different networks (not ideal), but using generic data from the same highway network can be taken into account as a step forward. Even if two bridges are in the same network, the behaviour and characteristics of traffic vary,

	example of the Van Brienenoord and the Moerdijk. - External and internal influences, in general, can be used to assess bridges in a management object level (e.g., design standards, and quality of materials).

C#2	
TNO domain expert 1:	TNO domain expert 2:
- Steel has no aging consequence; fatigue is the crucial damage mechanism, dependent on the number of heavy trucks. - The risk to failure definition needs to be assessed based on the change in threshold (number of heavy trucks).	- Age (construction date) does not reflect much into the status of the bridge; the influences are the ones that determine the status of the bridge. - Recommended to remove this criterion.

C#3	
TNO domain expert 1:	TNO domain expert 2:
- The risk to failure is correct, but it is quite unusual to add a layer of RHPC on top of a movable bridge, it is an excessive load to the mechanism. - If additional load is added, its preferable to replace the whole movable bridge.	- "*If your gears are designed for a deck that now is twice as heavy, there is no need to inspect the mechanism, its already a problem*." - The mechanism also has unity checks. If the mechanism was designed 40 years ago, the regulations have changed and the mechanical actuator could not be in accordance with the current norm (unity check < 1), or to the new traffic demands.

C#4	
TNO domain expert 1:	TNO domain expert 2:
- Same conclusion as in C#2, the TEoL of the OSD is dependent on the number of heavy trucks, not in the age. - The concentration of stress is relevant to consider, if the stress goes up, the fatigue has an exponential increase, therefore, a drastic reduction of the service life.	- Hard to determine only with the age. - The year of design is more important than the service time. The year of design is closed coupled with the regulations that were in place at that time. Same concept as C#1, the influences can determine status of the elements.

C#5	
TNO domain expert 1:	TNO domain expert 2:
- The criterion was concluded as ambiguous, hard to put into practice.	- The criterion makes sense, but the criterion is not feasible. Most of the bridges have it, and if they do not have it, a recalculation of stresses is needed to determine if it needs it or not. The fatigue cracks on the upper flange are not sufficient data to tell if the OSD needs reinforcements or not. - Another example of change in regulations. If the bridge was design for a lower load class, the change in function of the network led to

	an increase in traffic load that the deck was not originally designed for.

C#6	
TNO domain expert 1:	TNO domain expert 2:
- The risk to failure is correct, cracks within the main girder can result in a high risk of collapse. - The threshold value was not discussed.	- If there are any cracks within the main girder, action is needed. High sense of urgency. - *"If a main girder fails, the bridge fails."*

C#7	
TNO domain expert 1:	TNO domain expert 2:
- Change threshold to 5-10% loss of cross-section due to corrosion, and the risk of failure classified it as high.	- Corrosion is also alarming, but cracks are more urgent than corrosion.

C#8	
TNO domain expert 1:	TNO domain expert 2:
- *"Is not about cross section reduction, it's about stress concentration."* - The anchorage is a point of relevance due to the difficulty that it has to be inspected. - The risk to failure is correct. Further research on determining a correct percentage or number of damages wires due to corrosion should be considered.	- The number of damaged wires is unknown by the domain expert to determine a possible failure moment. - Corrosion is an important indicator to inspect. - The location of the corrosion within the lower connection is of relevance due to the runoff of the rainwater. - *"Fracture/breaking is the alarming thing."* Both corrosion and lamination lead to cracks which can grow and cause fractures. - *"If corrosion appears on the outer layer, you need to assume that inside the cable there is also corrosion."*

C#9	
TNO domain expert 1:	TNO domain expert 2:
- Instead of seeking the manufacturer as an indicator for TEoL of cables due to their process (causing lamination), use the process as the indicator. The period of this process can be relevant to research.	- The fractures are of high relevance. - The number of wires broken is also an alarming thing, they shouldn't be broken. - For the threshold value, an exact number of wires that would be alarming is unknown based on the knowledge of the expert.

C#10	
TNO domain expert 1:	TNO domain expert 2:
- The risk to failure, and the threshold sound reasonable. - If the component fails, the element fails. In this case, is the deck plate fails, the deck has to be replaced.	- There are maintenance strategies for the fatigue cracks, there is no need for a whole deck replacement. - The location of the crack is important, and the position of the heavy traffic within the deck (lane).

	- Focusing on the crack propagation, where the heavy traffic lane is, the cracks will propagate faster. - The urgency is due to the deck plate, the crack size, and crack location; the geometry can tell if its more alarming or not (< 12 mm deck plate).

C#11	
TNO domain expert 1:	TNO domain expert 2:
- The number of cracks is not an issue, they can be repaired quite easily form the bottom of the deck. - The length is important to take into account, this should be the threshold. - The damage (cracks) will be repeated within 2 crossbeam sections. If there is one weld crack within 2 crossbeams, usually, there will be along all sections of the deck within the total span of the bridge. - The TEoL based on the definition, will depend on the number of cracks to be repaired and the decision of the asset manager. If the asset manager sees fit to replace the whole deck, then just give regular maintenance, then, theoretically, the bridge has reached TEoL.	- This type of crack is less alarming than the root deck crack. The only issue is that the crack might propagate to other locations which are more critical (e.g., deck plate, cross girder). - This type of crack needs constant inspections. The first inspections can indicate that the crack is started within the weld. The second inspection will reveal if the crack propagated to a critical component or if it remains only on the weld.

C#12	
TNO domain expert 1:	TNO domain expert 2:
- This should not be considered as a criterion since most of the bridges in the Netherlands do not have it, and according to the criterion, all of the bridges in the Netherlands would be TEoL. - The bulkheads will only work if they align perfectly with the crossbeam web, if they are off by a centimetre, they will cause problems due to localized stress. - The addition of bulkheads to the OSD impose a challenge in terms of constructability, and also, they would result an increase in weight and cost. - Not considered as an effective criterion for the Netherlands.	- This type of reinforcements is unknown in practice by the domain expert. - The criterion data makes sense, but further research is needed.

Extra question #1: Did the updates on the standards and regulations (such as NEN 6771 to NEN-EN 1993-1) had a noticeable impact on steel bridge design and thresholds of safety?	
TNO domain expert 1:	TNO domain expert 2:
- Yes, there have been changes in various standards. As an example, the old way of	- Important one is that fatigue now is in the code. Example of the quick scan tool used to

bridge designs based on load class, and now, the design should comply with the Eurocode. If a bridge is assessed with the new code, it might not comply with the required performances. There are many changes that should be further studied.	review if the structure has a unity check number above 1. - It also depends on the redundancy of the design, if the redundancy is high, the bridge will most likely will comply. On the contrary, if the redundancy is low or null, the bridge will most certainly will not comply with the unity check above 1 in the new design code.

Extra question #2 - If one of the elements (or components) of the system (bridge) reaches TEoL, the whole object system reaches TEoL?	
TNO domain expert 1:	TNO domain expert 2:
- *"This is not true."*	- *"No, not necessarily."* - Load bearing elements are of higher importance then the components. Only critical load bearing elements can dictate the TEoL of a bridge. Example of the Galecopper bridge, which has five cable bundles; if one cable breaks the other ones redistribute the load, in comparison with the Van Brienenoord that only has one cable, if that cable breaks, the bridge is in direct danger to collapse.

Extra question #3 - Are the load bearing elements of the steel bridge of higher importance then the components in the assessment of TEoL?	
TNO domain expert 1:	TNO domain expert 2:
- It depends on the decision of the asset manager, whether they consider a damaged element of higher importance over another within the bridge. It is closely bonded with the economical EoL.	- "Yes."

Extra question #4 - Do the types of fatigue cracks have any hierarchy in terms of importance regarding the TEoL?	
TNO domain expert 1:	TNO domain expert 2:
- Yes. Deck plate cracks are more important, therefore, toe-deck crack (Type I), and root-deck cracks (Type II) are mor important than, toe-trough crack (Type III), and weld root crack (Type IV). Type I and II, the repair is more costly since the wearing surface has to be removed to repair the cracks, and type III and IV can be maintained without removing the wearing surface. Crack type II is considered the worst, or most important, due to the fact that it cannot be inspected until damages rise in the wearing surface.	- I and II are higher due to the cracks within the deck plate, than IV, lastly III.

Following the completion of the TNO interviews, a revised version of the criteria and their corresponding threshold values was attained. Based on their feedback, the following changes were made:

- **C#1:** Decided not to be utilized as a criterion. As discussed in the TNO interviews, this specific consolidated criterion covers only the influences that affect the bridge, considering the civil asset as a single object. This criterion does not convey an answer to weather the bridge is reaching a potential TEoL. This criterion is predominantly governed by functional performance indicators that can be useful to assess other bridges, but not directly their TEoL.
- **C#2:** According to TNO experts, only the age (construction date) does not reflect the status of the bridge. The influences on the other hand, are relevant to consider.
- **C#3:** The domain experts believed that this criterion was out of the ordinary, affirming that they have not seen such a case. Even though a clear example was not illustrated, the concept of the extra weight on a movable deck was suggested relevant.
- **C#4:** As with C#2, the age is not of relevance, but the design limitations over the years are of influence to consider.
- **C#5:** Criterion was unused due to its infeasibility and the ambiguity surrounding its practical application.
- **C#6:** A threshold value was added, establishing that once any type of cracks was detected in the load-bearing element the perceived risk to failure is considered high.
- **C#7:** A threshold value was added. A high perceived risk to failure is reached when the main girder has 5-10% loss of cross-section.
- **C#8:** The threshold value was modified. According to domain experts, the critical threshold factors are the location near the anchorage and the development of cracks or fractures due to degradation mechanisms.
- **C#9:** The threshold value was simplified, therefore, stating that once a wire is fractured or broken, a perceived high risk to failure of the load bearing element is reached.
- **C#10:** Remained the same.
- **C#11:** The perceived risk of failure was reevaluated to high, directly correlating with the new threshold that accounts that once the crack propagation reaches other critical or load-bearing elements, the component has potentially reached the TEoL.
- **C#12:** Eliminated. Based on insights from domain experts, it was determined that most bridges in the Netherlands do not incorporate this type of reinforcement, therefore, should not be considered in the assessment.

2. RWS ASSET MANAGER INTERVIEW

After processing the feedback from the interview phase with the TNO domain experts, the next step of the interview process was the interview with a RWS asset manager/domain expert. The purpose of this interview was to explore the asset manager's perspective of major and minor interventions depending on the severity of damages. Therefore, only criteria within the element and component level were assessed (C#6, #7, #8, #9, #10, and #11).

Interview Process RWS:

- The information sheet and consent form were read, acknowledge, and verbally agreed by the participant (See appendix section L).
- The revised criteria and validated threshold values were subsequently presented to the participant via presentation slides. These criteria employed a levelling approach, in which the participant, assuming the role of the asset manager, was tasked with indicating when a major intervention (replacement or

renovation) was necessary based on the provided information. Figure 63, depicts the methodology utilized for the six revised and validated criteria.

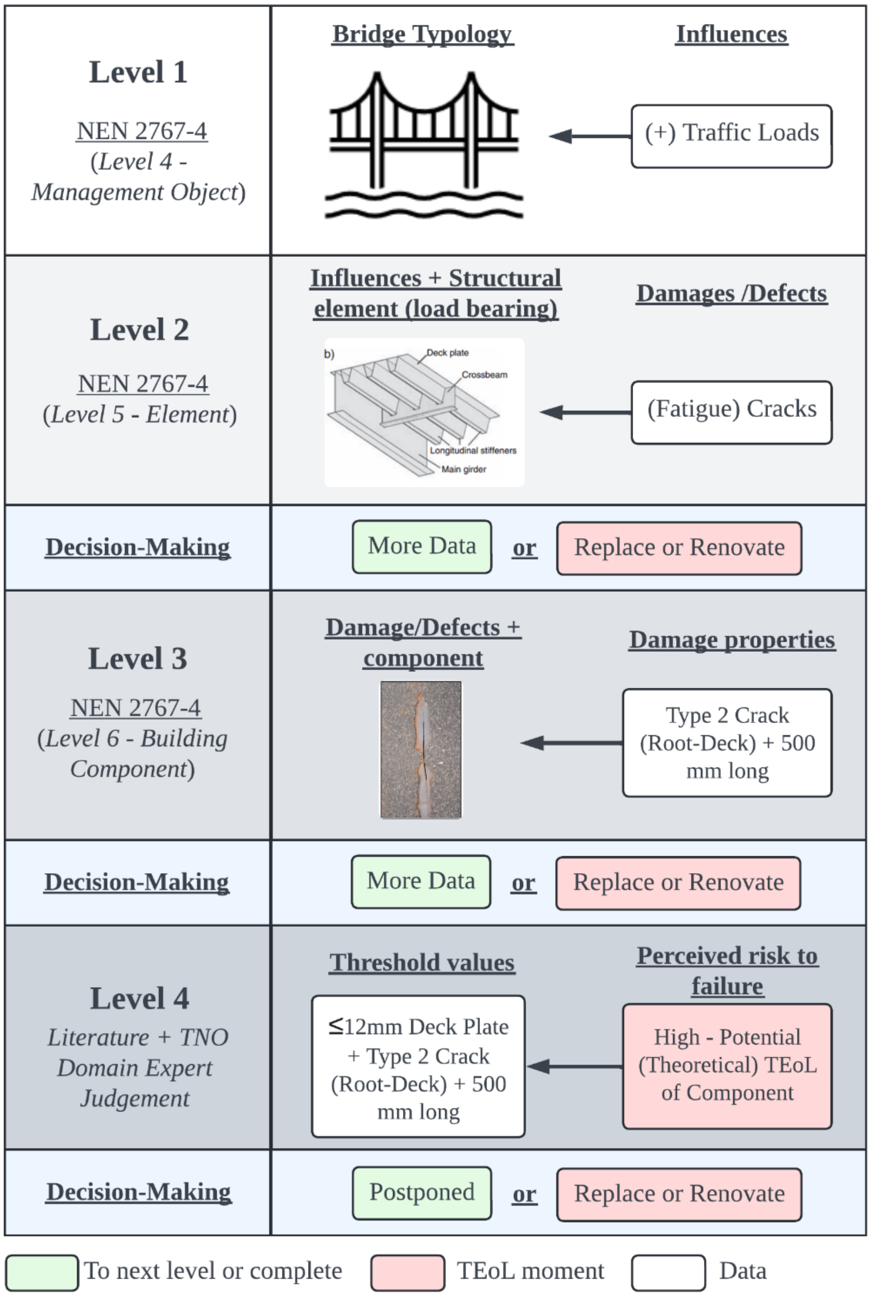


FIGURE 63: GRANULARITY LEVEL OF THE REVISED TEOL CRITERIA FOR STEEL BRIDGES WITH EXAMPLE

- Extra questions were asked due to relevance for the study, such as:
    - If one of the elements (or components) of the system (bridge) reaches TEoL, the whole object system reaches TEoL? (Based on C#2). This question had the purpose of exploring the asset manager's perspective.
    - Are the load bearing elements of the steel bridge of higher importance than the components in the assessment of TEoL? (Based on C#6 & #7) This question had the purpose of ranking the criteria based on RWS asset manager's judgement.

C#6 (Revised)
RWS asset manager (Bridge expert)
- Within the Level #2 (Figure 63 - Element level), action is required from the perspective of the asset manager. - If the girder presents any type of cracks, immediate action is needed, e.g., cold cracks. - Mentioned about the welding process. It is mentioned by the expert that the welding process in the 60's was not as efficient as it is today, therefore, welding joints in the main girder are presenting early fractures due to the increase in heavy traffic over the years. - Agreed thresholds and risk allocation.

C#7 (Revised)
RWS asset manager (Bridge expert)
- *"Corrosion is not necessarily the problem, it's the location"*. - Fractures are more relevant than corrosion. - Corrosion degradation in the bolts (joints) of the girder it's a serious problem due to the possible loss of mechanical strength.

C#8 (Revised)
RWS asset manager (Bridge expert)
- Remark on the location of the anchorage, corrosion on the anchorage is alarming. - "Braking" cables give a sense of urgency, corrosion is just a potential indicator of future wire breaking. - Agreed thresholds and risk allocation.

C#9 (Revised)
RWS asset manager (Bridge expert)
- Once a wire is broken and it is detected, immediate action is taken. These actions can be limiting traffic within the bridge. - Recalculation is needed to determine if the bridge asset requires a renovation and replacement strategy. - Agreed thresholds and risk allocation.

C#10 (Revised)
RWS asset manager (Bridge expert)
- By assessing a building component, a decision-making action after Level #2 (Element level) cannot be assigned, more information is always needed. - The longitudinal cracks and spider web cracks on the wearing surface (asphalt) are not necessarily from a deck plate crack. - The spider web cracks are considered of high risk to heavy traffic due to accumulation of stones within the damaged section. - Crack type #1 (toe-deck crack) is not detected in practice, it might be considered by RWS only in re-calculations, but only crack type #2 (root-deck crack) is normally detected in the field. - The length of the crack gives an indication of a timeframe to repair, the longer, more urgent. - Agreed thresholds and risk allocation.

C#11 (Revised)
RWS asset manager (Bridge expert)
- Welding cracks are not an alarming damage to take immediate action. No problem for the traffic. - Welding cracks are easy to repair. - Welding cracks and fatigue are closely related.

- The crack starts to become a problem once it extends to a load bearing element, as mentioned in the threshold.

Extra question #2 - If one of the elements (or components) of the system (bridge) reaches TEoL, the whole object system reaches TEoL?
RWS asset manager (Bridge expert)
- It is not dependant on the element or component itself, it depends on various factors, such as, cost of maintenance, frequency of maintenance, and the specific criticality of an element or component within the bridge. - The TEoL is not the indicator of a major intervention on a bridge, the major interventions are closely related to an economical concern or due to functional changes. Also mentioned, political decisions can be the reason to replace or renovate.

Extra question #3 - Are the load bearing elements of the steel bridge of higher importance then the components in the assessment of TEoL?
RWS asset manager (Bridge expert)
- Cables are considered for the expert as top importance, then girders, finally deck plate. - The location of the damage is more crucial than the element itself. If the damage is located or propagating towards a critical point or points of the bridge, then the element or component becomes of high importance.

After completing the interview on the six criteria, the following conclusions were obtained:

- C#6 (Revised): Crack within the main load-bearing element need immediate action.
- C#7 (Revised): Corrosion in the location of the joints of the load-bearing elements is of concern. Additional assessment should be included in the building component level.
- C#8 (Revised): There is a sense of urgency when a wire is broken, the detection of corrosion within the cables serves as an indicator of the remaining time of the cable before it needs an intervention.
- C#9 (Revised): A broken wire requires immediate action.
- C#10 (Revised): The length of the crack gives an indication of a timeframe to repair, the longer, more urgent.
- C#11 (Revised): This criterion does not indicate a potential TEoL of any component or the OSD as a whole. While welding cracks are not considered urgent initially and pose no direct risk to traffic (Based on the asset manager's experience), they require constant inspection to monitor crack propagation. A potential risk is detected if the crack reaches a critical component or load-bearing element.

With the inclusion of these feedback, and the previous TNO interviews, the validated TEoL criteria were concluded.

O. SUMMARY OF THE EXAMPLES OF THE TEoL RULE-BASED ASSESSMENT

This section of the appendix illustrates the summary of the TEoL rule-based criteria assessment of the Ewijk bridge, the Van Brienenoord bridge, and the Moerdijk bridge, based on the multi-case study data.

The Ewijk bridge:

No.	Year of construction:	Cable	Deck	Girder
1, 4, 9		1976	1976	-
No.	**Load-bearing Elements:**	**Building Components:**	**Detected damage(s) or defect(s):**	**Damage properties:**
2	Cables	Wires	Fractures	Lamination
3	Cables	Other component	No data	No data
5	Deck (OSD)	Wearing surface	No data	No data
6	Deck (OSD)	Deck plate	Local fatigue cracks	Insufficient static shear capacity
7	Deck (OSD)	Trough	No data	No data
8	Deck (OSD)	Other component	No data	No data
10	Girder	-	No data	No data
11	Girder	Joints	No data	No data
12	Girder	Other component	No data	No data

No.	Year of construction:	Cable	Assigned points:	Notes:
1		1976	4	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
2	Cables	Wires	10	Potential TEoL of Cable and Bridge
3	Cables	Other component	0	

No.	Year of construction:	Deck	Assigned points:	Notes:
4		1976	2	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
5	Deck (OSD)	Wearing surface	0	
6	Deck (OSD)	Deck plate	1	Assumed root-deck cracks
7	Deck (OSD)	Trough	0	
8	Deck (OSD)	Other component	0	

No.	Year of construction:	Girder	Assigned points:	Notes:
9		-	0	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
10	Girder	-	0	
11	Girder	Joints	0	
12	Girder	Other component	0	

Total of **17** points and potential TEoL of Cable and Bridge.

The Van Brienenoord bridge:

No.	Year of construction:	Cable	Deck	Girder
1, 4, 9		-	1990	-
No.	**Load-bearing Elements:**	**Building Components:**	**Detected damage(s) or defect(s):**	**Damage properties:**
2	Cables	Wires	No data	No data
3	Cables	Other component	No data	No data
5	Deck (OSD)	Wearing surface	Cracks	Longitudinal cracks originated from the deck plate
6	Deck (OSD)	Deck plate	Fatigue cracking	Root-deck fatigue crack within the 12mm deck plate of 100-700 mm
7	Deck (OSD)	Trough	No data	No data
8	Deck (OSD)	Other component	No data	No data
10	Girder	-	No data	No data
11	Girder	Joints	No data	No data
12	Girder	Other component	No data	No data

No.	Year of construction:	Cable	Assigned points:	Notes:
1		-	0	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
2	Cables	Wires	0	
3	Cables	Other component	0	

No.	Year of construction:	Deck	Assigned points:	Notes:
4		1990	2	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
5	Deck (OSD)	Wearing surface	1.5	
6	Deck (OSD)	Deck plate	4	Deck plate has potentially reached TEoL
7	Deck (OSD)	Trough	0	
8	Deck (OSD)	Other component	0	

No.	Year of construction:	Girder	Assigned points:	Notes:
9		-	0	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
10	Girder	-	0	
11	Girder	Joints	0	
12	Girder	Other component	0	

Total of **7.5** points and the deck plate has potentially reached TEoL.

The Moerdijk bridge:

No.	Year of construction:	Cable	Deck	Girder
1, 4, 9		-	1976	-
No.	**Load-bearing Elements:**	**Building Components:**	**Detected damage(s) or defect(s):**	**Damage properties:**
2	Cables	Wires	No data	No data
3	Cables	Other component	No data	No data
5	Deck (OSD)	Wearing surface	Cracks	De-bonding defect
6	Deck (OSD)	Deck plate	No data	No data (12mm deck plate)
7	Deck (OSD)	Trough	Fatigue fractures	Weld root crack within
8	Deck (OSD)	Other component	No data	No data
10	Girder	-	No data	No data
11	Girder	Joints	No data	No data
12	Girder	Other component	No data	No data

No.	Year of construction:	Cable	Assigned points:	Notes:
1		-	0	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
2	Cables	Wires	0	
3	Cables	Other component	0	

No.	Year of construction:	Deck	Assigned points:	Notes:
4		1976	2	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
5	Deck (OSD)	Wearing surface	0.5	
6	Deck (OSD)	Deck plate	1	
7	Deck (OSD)	Trough	0.5	
8	Deck (OSD)	Other component	No data	No data

No.	Year of construction:	Girder	Assigned points:	Notes:
9		-	0	
No.	**Load-bearing Elements:**	**Building Components:**	**Assigned points:**	**Notes:**
10	Girder	-	0	
11	Girder	Joints	0	
12	Girder	Other component	0	

Total of **4** points.