Exploring the Potential Application of Machine Learning on NEN 2767 Bridge Data

An Assessment of the Netherlands' Readiness for Implementing Machine Learning on bridge Condition Data Maintained by Dutch Government Bodies

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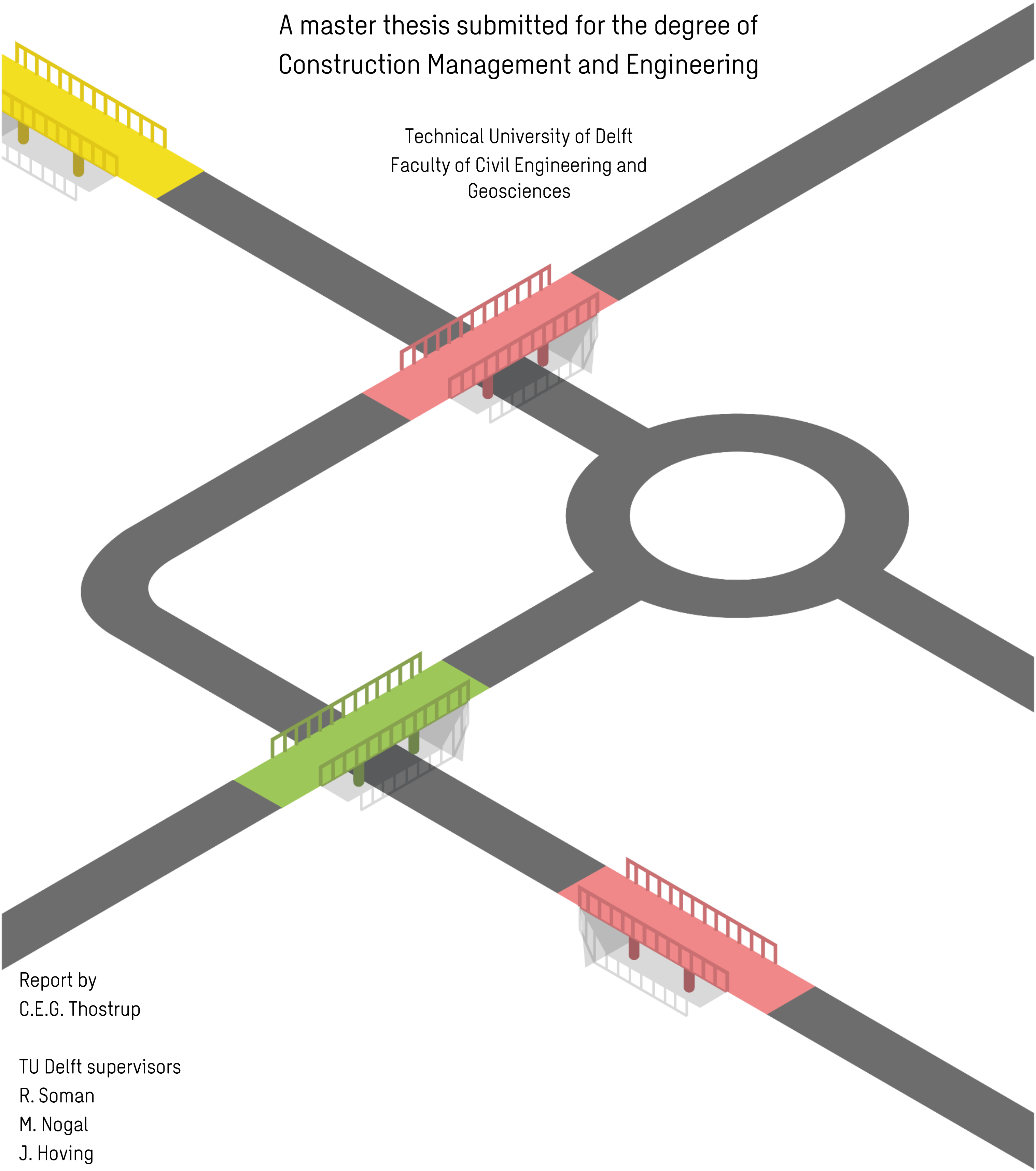

Report by
C.E.G. Thostrup

TU Delft supervisors
R. Soman
M. Nogal
J. Hoving

Sweco Supervisor:
L. Langhorst

TUDelft SWECO

Abstract

The Netherlands faces a significant challenge in maintaining its estimated 85,000 bridges, most of which were constructed between the 1950s and 1970s. Addressing this "Replacement and Repair Challenge" requires prioritizing bridges at high risk of deterioration to optimize maintenance efforts. Internationally, predictive maintenance studies have successfully utilized Bridge Deterioration Models (BDMs) that leverage inspection and supplementary data to train machine learning models for predicting bridge deterioration. This study investigates whether Dutch bridge inspection data, collected under the NEN 2767 standard, could similarly support BDMs for predictive maintenance. The aim is to evaluate the suitability of NEN 2767 data for this purpose and identify necessary modifications to enhance its predictive capabilities. Data from five provinces and seven municipalities were analyzed using the "4 Vs" framework: Volume, Variety, Velocity, and Veracity. Results indicate that, due to data inconsistencies, limited feature diversity, and insufficient volume, the Netherlands is not yet prepared to apply machine learning to NEN 2767 data. To explore these challenges further, semi-structured interviews were conducted with five government agencies and four inspectors. Findings suggest that while there is confidence in the NEN 2767 standard, significant variation exists in data collection and storage methods. Furthermore, maintenance decisions rely on additional information that is not consistently recorded in government databases alongside NEN 2767 data. A literature review on BDMs identified 25 critical features that could improve the predictive accuracy of NEN 2767 data for Dutch bridge deterioration. Based on these insights, four key recommendations are proposed. Firstly, preliminary recommendations were presented to stakeholders, after which some adaptations were maded to improve their quality. These for recommendations are as follows: (1) Extend the CUR 117 standard to enhance data collection, storage, and sharing protocols; (2) Develop a standardized Inspection Procedure, which would involve certification through the CUR 117 commitee; (3) Incorporate the 25 additional features identified as relevant for predictive maintenance; and (4) Utilize the Schouw, an annual inspection process, as a means to capture more maintenance data on bridges. These steps would collectively strengthen the predictive capabilities of NEN 2767 for proactive bridge maintenance in the Netherlands.

Keywords: Bridge Deterioration Model, Machine Learning, Predictive Maintenance, NEN 2767, Bridges

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1. Introduction

Since the liberation of the Netherlands on the 8th of May 1945 the country has gone through a large expansion in terms of housing, population and subsequently also infrastructure, to keep up with rising demand. To modernise the country a large amount of the countries' bridges were built between 1950 and 1970 (Kompeer & Schellevis, 2021). These connections were part of what allowed the country to flourish and become the strong economy it is today. These bridges, are, however reaching the end of their life cycle (Rasker et al., 2023). In conjunction with this travel demand has risen strongly and more is expected of this infrastructure than was ever estimated when they were built (NOS, 2016). There are an estimated 347 billion euros worth of infrastructure in the Netherlands (TNO, 2023), with an estimated 85.000 bridges and viaducts (De Verschil Makers, 2024; Rasker et al., 2023). We stand at a crossroads where replacement and repair must be performed. A large challenge is that the state of many of the bridges is unknown. TNO investigated municipalities and provinces to see which has a prognosis of the state of their infrastructure and found that only 12 out of the 342 municipalities and 4 out of 12 provinces had insights into the state of their assets (Rasker et al., 2023). This has made understanding when and where maintenance or replacement must take place very challenging.

"In recent years, a dozen objects in the Netherlands have failed partly or completely due to limited insight into the situation. After all, on the outside, you can't see what a bridge or road has been through. I know an example of two identical, equally old viaducts, one of which collapses immediately at the first impact of the wrecking ball, while the other shows barely a crack." - Lindy Molenkamp, the director of Management and Implementation (B&U) in North Holland (TNO, 2023).

An extensive body of research exists on how the state of infrastructure can be predicted using models which utilise various types of data called features; these models are called Bridge Deterioration Models (BDMs). BDMs typically rely on data from visual inspections, bridge geometry, environmental factors, loading conditions, and specific bridge characteristics. Various models, such as neural networks and Markov Chains, have been applied in studies across regions like the U.S., Australia, China, and Japan, showcasing their flexibility in predicting bridge deterioration and informing maintenance planning. Machine Learning effectiveness is highly dependent on the data which is available as well as what algorithm is chosen for the given data set (Domingos, 2012). The effectiveness of BDMs, utilizing ML, is thus strongly related to what data is available and whether algorithms are available that can work with the data and its characteristics.

Despite the advancement in BDMs literature for Civil Engineering and Internet of Things (IoT) devices such as vibration-based sensors, image processing, concrete curing and crack detection (Mishra et al., 2022); most of the Netherlands's bridges are inspected through a visual inspection which utilise a documentation standard called the NEN 2767. This standard defines defects found on bridge components through three parameters: Severity, Extent Intensity. Although the NEN 2767 has been applied across the Netherlands for gaining insights into the state of bridges of Municipalities and Provinces; it remains unclear whether the data generated from the standard is suitable for BDM purposes. The purpose of this study is to assess the applicability of Machine Learning algorithms for BDMs using NEN 2767 bridge data, generated by government bodies, and how this data could be improved to increase predictive capabilities.

In section 1.1 the theoretical background is presented, followed by section 1.2 where the research gap is defined, the chapter continues with the research questions in section 1.3 and the research methodology and scope in 1.4, and the chapter concludes with a reader guide in 1.5.

1.1 Theoretical Background

This section provides an overview of the theoretical foundations and concepts that underpin this research. The purpose of this section is to provide an overview of the relevant concepts and research related to the research aim. There are four sub-sections. The first sub-section discusses Predictive Maintenance, the second sub-section Artificial Intelligence, the third deliberate Bridge Deterioration models and the last sub-section Asset Management within the Netherlands.

1.1.1 Predictive Maintenance for bridges

This sub-section discusses the theoretical background of Predictive Maintenance (PdM). Firstly, an overview of differing maintenance strategies is briefly discussed; this is to give some insights into other approaches which exist. This is followed by a discussion on the definition of PdM. Next, an overview is provided of different monitoring methods which have been applied to bridges to give an overview of the types of data collected. Lastly, various papers on bridge deterioration models, which enable PdM, are discussed; this provides an overview of what predictive deterioration work has already been conducted on bridges.

There exist different maintenance strategies besides Predictive Maintenance (PdM) which have developed overtime; three common maintenance strategies are Reactive Maintenance (RM), Preventative Maintenance (PM) and Reliability-Centred Maintenance (RCM). (Poór et al., 2019). RM, sometimes called Unplanned or Breakdown Maintenance is a strategy where maintenance is performed once an asset breakdown (Pintelon et al., 2006; Poór et al., 2019). PM or scheduled maintenance is a strategy where maintenance on assets is performed at a set scheduled time (Endrenyi et al., 2001; Pintelon et al., 2006; Poór et al., 2019). RCM or total productive maintenance is a strategy which compares various maintenance policies and chooses the most cost-effective one, these are, however heuristic and require expert knowledge (Endrenyi et al., 2001; Pintelon et al., 2006). Predictive Maintenance (PdM) distinguishes itself by being a technology based on historical data, mechanisms models and domain knowledge to predict equipment trends, behaviour patterns and correlations through statistical and AI models (Poór et al., 2019; Zhong et al., 2023).

Various definitions of PdM exist that align paradigms of the Internet of Things and Cyber-Physical Systems with knowledge within the field of automation, engineering information technology and data analytics to predict failures and the residual useful life of industrial assets and schedule maintenance actions consequently (Nunes et al., 2023). Carvalho et al. (2019) propose that PdM employs predictive tools to identify the optimal timing for maintenance actions. This approach relies on ongoing monitoring of machine or process integrity, enabling maintenance activities to be carried out precisely when necessary. Additionally, PdM facilitates early detection of potential failures through the utilization of predictive tools, which leverage historical data (such as Machine Learning techniques), integrity factors (including visual aspects, wear, and deviations from the original, among other indicators), statistical inference methods, and engineering approaches. The definition of Carvalho et al. (2019) will be applied within this proposed study due to its focus on historical data, rather than Internet of things principles and information. In addition, this definition suggests the application of machine learning techniques, which are a subcomponent of AI. This makes this term the most applicable for this proposed research.

As becomes apparent from the chosen definition that PdM relies on the monitoring of assets or processes to enable its predictive capabilities. The field of study which specialises in this examining is Structural Health Monitoring (SHM), which is now a common practice within the civil field (Mishra et al., 2022). It concerns the monitoring of structures over time and analysis of the characteristics of these structures, often through Artificial intelligence systems. Its main goal is to identify damage, and its characteristics and assess the current state, thus placing more focus on health assessment (Sun et al., 2020; Tinga & Loendersloot, 2014). SHM is often described as consisting of 5 different levels (Farrar & Worden, 2007; Rytter, 1993; Tinga & Loendersloot, 2014):

1. Damage detection,
2. Damage localization,
3. Damage characterisation,
4. Damage quantification,
5. Prognostics.

The application of SHM has a long history and has at least been implemented for 40 years in aerospace, civil, chemical, electrical and mechanical engineering infrastructure (Chen et al., 2023; Sun et al., 2020). Typically, when thinking of SHM monitoring is performed through sensors which generate time series data, which is then fed through model-based or data-driven methods (Bloemheuvel et al., 2021; Chen, 2018; Jia & Li, 2023; Sun et al., 2020). SHM has been studied extensively on bridge infrastructure and many differing types of sensors have been applied to monitor the behaviour of bridges. Through the use of vibration, temperature and strain sensors Bloemheuvel et al. (2021) were able to estimate the strain on the Hollandse Brug through the application of Graph Neural Networks. Chen et al. (2023) conducted a condition assessment on the thermal effects of suspension bridge data through Bayesian Neural Networks. Through the application of images and Fully Convolutional Networks, the detection of delamination and rebar exposure on bridge decks was made possible (Rubio et al., 2019). A Bayesian Network has been applied to rail bridges in the United Kingdom to predict their failure (Zhang & Marsh, 2018). Many more studies exist with often a lot of success in measuring the health of infrastructure (Fan et al., 2021; Jeon et al., 2024; Jia & Li, 2023; Niyirora et al., 2022).

Distinct, though nog mutually exclusive from SHM, are visual inspections which can also be considered a form of monitoring (Agdas et al., 2016). Various standards for visual inspections exist in the world, with each with its scoring system (Srikanth & Arockiasamy, 2020). In the United States of America, the National Bridge Inspection Standard (NBIS) applies. The NBI's purpose is to fulfil legislative reporting mandates and bridge owners, the Federal Highway Administration (FHWA), and the public with comprehensive data concerning the quantity and state of the nation's bridges (U.S. Department of Transportation, 2023). The standard requires visual inspections where a condition rating must be given between 0-9 for the deck, superstructure, substructure, and culvert (Federal Highway Administration, 1995). The data is stored in the National Bridge Inventory (NBI). Their database contains data on more than 615000 bridges in the USA (Bureau of Transportation Statistics, 2024), thus representing a large bulk of data. A body of research exists on the NBI and NBIS. Such as how often inspections should occur (Nasrollahi & Washer, 2015), historical lessons of the standard (Dekelbab et al., 2008) and prediction of bridge component condition (Bektaş, 2017; Bektas et al., 2013; Bolukbasi et al., 2004; Sun et al., 2004). In the Netherlands, another standard applies. The Royal Dutch Standardization Institute Foundation (NEN), together with various organisations; has since 2008 developed a standard for assessing the condition of infrastructure (NEN, 2019). The standard, called NEN 2767 has gone through various iterations, with the latest edition being published in 2019. The NEN 2767-1 expansion of the standard entails a method for measuring the condition of building components which are parts of an asset, such as a bridge (NEN, 2019). This is done by scoring the building components on a score from 1-6, 1 being perfect and 6 being terrible condition. This score is derived by inspecting defects on their severity, intensity, and extent (NEN, 2019). NEN2767-4 expands the standard by providing a codified list of elements, components and defects with associated material properties for specific assets; being the first steps into the creation of a standardised decomposition (NEN, 2024). These two standards have been widely adopted by Provinces, Municipalities. The researcher was unable to find any literature on this standard which critiques it or suggests improvements for PdM purposes. The NEN 2767 standard has also never been tested on its predictive capabilities.

1.1.2 Artificial Intelligence and Machine Learning

AI in its broadest sense, refers to the intelligence displayed by machines, especially computer systems. AI research focuses on creating and examining methods and software that allow machines to perceive their surroundings and utilize learning and intelligence to take actions that increase their likelihood of reaching specified objectives (Russell & Norvig, 2021). Artificial intelligence (AI) is having a large impact on the civil engineering sector (Rustell, 2022). Currently, the AIs which have been created can be described as narrow, they can solve a specific problem very effectively. Super AI, also known as general artificial intelligence, is a more general intelligence which can solve diverse tasks (IBM, 2024). Within AI exists Machine Learning (ML), which can be described as the study of programmes which can improve their performance on a given task automatically (Russell & Norvig, 2021). This sub-section provides an overview of Machine Learning and its implementation within the Civil Engineering field. Firstly, the relation between AI and ML is described, this is followed by an overview of the various types of algorithms which exist within Machine Learning. Third, the importance of data quality for ML is discussed, along with the challenges posed by class imbalance in datasets like the NBI. The NBI is comparable to the NEN 2767 standard. Potential solutions to address these challenges are also explored.

ML and AI are often used interchangeably; this is due to the two fields being strongly related. AI is the field which focuses on making computers which can behave in ways that both imitate and go beyond human abilities (Google, 2024; Microsoft, 2024; Russell & Norvig, 2021). ML is the application of AI using algorithms, trained on data to help a computer learn by itself (Google, 2024; Microsoft, 2024).
Within ML many algorithms exist but can be sub-divided into three distinct categories. The first are supervised learning algorithms, which utilise training data which contains both input vectors and the corresponding target vector (Bishop & Nasrabadi, 2006), an example is having a data set of pictures of both cats and dogs with known labels for those images. Second are unsupervised learning algorithms, these utilise training data with an input vector but without a given target vector (Bishop & Nasrabadi, 2006), an example is for example anomaly detection in data sets. Lastly is reinforcement learning algorithms, these attempt to find the most suitable action in a given situation to maximise the reward; this is done by providing a sequence of states and actions in which the algorithm can learn in its environment (Bishop & Nasrabadi, 2006). Many different Machine Learning algorithms exist but an overview of some common algorithms is provided in Table 1.

Table 1 Common Machine Learning Algorithms (Mahesh, 2019; Singh et al., 2016; Szepesvári, 2010)

Name Algorithm	Description algorithm
Supervised learning algorithms	
Naïve Bayes or Bayesian Network	Naïve Bayes' (NBs) are algorithms which apply the Bayes' probability theorem.
Logistic Regression	Logistic Regression is a statistical model used for binary classification that estimates the probability of a class by fitting data to a logistic function.
Decision Trees and Random forests	Uses a tree-like model of decisions and their possible consequences, while Random Forests are an ensemble method that builds multiple decision trees to improve accuracy and reduce overfitting by averaging their predictions.
Support Vector Machine	An algorithm used for classification and regression tasks that finds the optimal hyperplane to separate data points of different classes with the maximum margin, often employing kernel functions to handle non-linear boundaries.
K Nearest Neighbour	There are non-parametric classification algorithms that assign to an unlabelled sample point the class of the nearest previously labelled points.

Neural Networks	These are algorithms that are loosely based on the neuronal structure, processing method, and learning ability of the human brain but on a much smaller scale.
Unsupervised learning algorithms	
K-Means Clustering	K-means is a simple unsupervised learning algorithm for solving the clustering problem by classifying a dataset into a specified number of clusters, where the key is to strategically place k cluster centres far from each other to achieve better results.
Principal Component Analysis	is a statistical method that uses an orthogonal transformation to convert correlated variables into a set of linearly uncorrelated principal components, reducing dimensionality to simplify computations and explain the variance-covariance structure of the data.
Reinforcement learning algorithms	
Q-Learning	Q-learning is a model-free algorithm that learns the value of state-action pairs by updating estimates based on observed rewards and the maximum expected future rewards, guiding the agent to choose actions that maximize cumulative rewards.
Sarsa	SARSA updates the value of state-action pairs based on the action taken and the subsequent state and action, guiding the agent's policy through a combination of current and future rewards.

A very important part of the success of an ML Algorithm application is related to the data on which it is trained (Budach et al., 2022; Jain et al., 2020). There are many different factors which can influence the quality of data.

Dimensionality plays a large role in ML success. Dimensional data refers to data which is stored like a fact table, where each row is an event and the columns, referred to in this paper as features, represent the facts, where dimensionality increases the more columns there are (IBM, 2021). Dimensionality can be a challenge when both too large and too small. The curse of dimensionality refers to a problem where there are so many features that generalization becomes incredibly hard; in essence, the training set simply cannot cover all the possible events that could occur (Chen, 2009; Domingos, 2012). On the other hand, low dimensionality can also occur; this is where there are too few features to fully express a provided situation. Both can lead to problems with overfitting and underfitting. Overfitting refers to a situation where a model is too complex which causes it to capture noise or consider irrelevant patterns; in general, the model then performs well on training data but badly on test data (Aliferis & Simon, 2024; Domingos, 2012; Webb, 2010). Underfitting is where a model is too simplistic and thus does not capture the nuances or complexity of the data; in general, the model then performs badly on both training and testing data (Aliferis & Simon, 2024). A key part of solving such challenges is feature engineering; this is where the most important features are identified to enable prediction (Aliferis & Simon, 2024; Domingos, 2012). This is challenging as it is domain-specific and thus requires knowledge of the specific context (Domingos, 2012); and could lead to potential bias if done incorrectly (Aliferis & Simon, 2024).

The volume of data is also a highly important part of ML algorithms' capacity to learn. A rule of thumb by Domingos (2012) is: "A dumb algorithm with lots and lots of data beats a clever one with modest amounts of it." This is due to a few important factors. In the paper by Halevy et al. (2009), which is written about the importance of large data sets for translation; A particularly complex problem as language is such a diverse challenge. The paper discussed how simply having enough data, even when unlabelled could make an effective translation tool. This paper was revisited in Sun et al. (2017) where deep learning had taken centre stage; it indeed found that large data helps with representation learning and that performance increased logarithmically based on the volume of data. Although this paper focussed on images rather than translation. Jordan and Mitchell (2015) further state the importance of volumes of data in the success of machine learning: "... The sheer size of the data makes it essential to develop scalable procedures that blend computational and statistical considerations."

There are, however, also other factors which can play a role. Label noise is one of these; this refers to labelling errors in the data and can cause issues with accuracy (Jain et al., 2020). Data Class Imbalance, which involves an uneven ratio of classes, overlapping regions, dataset size, and sub-concepts that influence the classification of imbalanced input data; can result in algorithms receiving a high overall accuracy score but not detecting infrequently occurring anomalies (Jain et al., 2020; Treder-Tschechlov et al., 2023). Particularly Class Imbalance plays a big role in bridge PdM cases using data similar to the NBI as many bridges exist with different condition ratings, thus they are naturally imbalanced (Liu & El-Gohary, 2019; Mia & Kameshwar, 2023; Xia et al., 2022a). The data characteristics of the NEN 2767 are yet to be determined in literature; as NBI data is similar to that of the NEN 2767 Data Class-Imbalance may be characteristic this data also has.

The 4 V's described by Schroeck et al. (2012) are a way of determining the characteristics of the data one can work with. The first is Volume, how much data is available. Second, is variety, which refers to how many forms of data there are. Third is velocity, which is the speed at which data is generated, processed and analysed. Lastly, Veracity refers to how uncertain data is.

1.1.3 Bridge Deterioration Models

Data gathered from SHM systems and Visual inspections have been utilised for investigating various Bridge Deterioration Models (BDMs). These deterioration models may be deterministic or stochastic and could use physical models or AI (Srikanth & Arockiasamy, 2020) but they aim to determine the degradation of bridge elements (Bu et al., 2015; Srikanth & Arockiasamy, 2020); often to estimate funding needs in the future. These models enable PdM via detection of potential failures through the utilization of predictive tools which are taught using historical data. This sub-section first discusses the types of data which are utilized for these models, which is followed by an overview of case studies that have been performed. This provides an overview of data which has been utilised what various models have already been investigated and in which context.

Varying data types are utilized for the training of BDMs; five data categories were identified through this literature review. Firstly, Visual inspection condition score data, such as those of the NBI have been utilized extensively (Bu et al., 2015; Huang, 2010; Setunge & Hasan, 2011; Srikanth & Arockiasamy, 2020; Wang et al., 2022), but also from Australia (Law, 2015; Ranjith et al., 2013) and China (Li et al., 2014). Secondly, often bridge geometry features, such as its length, width and area are included (Huang, 2010; Miao et al., 2023; Zhu & Wang, 2021) but also skew (Huang, 2010; Zhu & Wang, 2021). Thirdly, environmental factors such as temperatures (Miao et al., 2023), Carbon Dioxide concentrations (Miao et al., 2023), Airborne salt concentrations (Miao et al., 2023), Snowfall (Miao et al., 2023) and rainfall (Miao et al., 2023) are included in studies. Fourth, loading conditions, related to daily traffic volumes (Bu et al., 2015; Huang, 2010; Miao et al., 2023; Zhu & Wang, 2021), Designed load (Huang, 2010) and the number of large vehicles (Miao et al., 2023; Wang et al., 2022) are considered. Fifth other bridge characteristics such as age of the bridge (Bu et al., 2015; Huang, 2010; Miao et al., 2023; Zhu & Wang, 2021), or elements (Ranjith et al., 2013; Zhu & Wang, 2021), bridge maintenance history (Huang, 2010; Wang et al., 2022), location (Huang, 2010; Wang et al., 2022; Zhu & Wang, 2021) and material types (Bu et al., 2015; Wang et al., 2022; Zhu & Wang, 2021) have been taken into consideration.

Various studies have been conducted applying different models in differing contexts. Bu et al. (2015) investigated 40 bridges with 464 inspection reports from the New York network, their model applied Elman neural network (ENN) and compared it to a Markovian-based deterioration procedure. Miao et al. (2023) investigated 3368 bridges, with a wide range of data categories, from Japan; their model applied a Long Short-Term Memory (LSTM) recurrent neural network. Law (2015) investigated an unknown number of bridges in Australia between 1995 and 2012, their components deterioration was investigated by applying the Markov Chain Model. Setunge and Hasan (2011) investigated an unspecified number of bridges from 1995 to 2012 in Australia, they applied the Markov Chain model. Huang (2010) investigated 942 concrete decks of which they had 1241 records, in the study an Artificial Neural Network (ANN) with BP-MLP classifiers model was applied to determine the deterioration of these decks. Li et al. (2014) investigated 1801 bridges with records spanning 10 years in Shanghai by applying a Markov Chain model. Setunge and Hasan (2011) and Ranjith et al. (2013) investigated an unknown amount of timber bridges in Australia using the Markov Chain model. Wang et al. (2022) investigated 43320 bridges in Texas through their NBI condition data between 2001 and 2017 by using a Markov Chain model. Zhu and Wang (2021) also investigated bridges from Texas but applied data from 23104 bridges between 1992 and 2019; their study applies a ReliefF algorithm to select important data features with a degradation model consisting of a Recurrent Neural Network (RNN) and a Convolutional Neural Network (CNN).

1.1.4 Asset Management in the Netherlands

In essence, the technologies of Digital Twin, Predictive Maintenance, and Artificial Intelligence are enablers of Asset Management (AM). This section provides an overview of the context in which the NEN 2767 is applied. This sub-section begins with a discussion on the definition of the term Asset Management, this is followed by a discussion on recent developments in AM practices within the Netherlands civil sector as well as how the NEN 2767 slots in within these developments.

There is no consensus on how to define Asset Management due to the term being applied in many different sectors such as State treasuries and agencies, Government Bodies, Transport infrastructure, Water facilities, Power utilities, manufacturing, mining and the process industry (Frolov et al., 2010). A general definition provided by the International Organization for Standardization (ISO) in ISO 55000:2014 is "A Coordinated activity of an organization to realize value from assets" (ISO, 2014). Within the context of the Civil Engineering field various definitions exist. McElroy (1999) defined AM as "a systematic process of maintaining, upgrading and operating physical assets cost-effectively." This definition takes no consideration into societal or practical needs. Another definition provided by CROW is that AM is "the international term for the optimal management of capital goods (assets) that are of value to an organization. The meaning of 'optimal' is dictated by the goals that the organization pursues and the balance between performance, risks and costs" (CROW, 2024e). CROW is a Dutch knowledge platform dedicated to infrastructure, mobility and the living environment. One of their main themes is Asset Management (CROW, 2024d).

The Organisation for Economic Co-operation and Development (OECD) defines AM as "A systematic process of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organised and flexible approach to making the decisions necessary to achieve the public's expectations" (OECD, 2001). Due to the research's focus on the Dutch context, where CROW plays a large role in the AM sector, their definitions will be applied within this research.

Recent developments within the Dutch civil Asset Management sector have been the iAMPRO model and IMBOR, both initiatives by CROW. The iAMPRO model provides (government) organisations with the necessary activities, information and preconditions to implement Asset Management. In essence, it provides practical steps for implementing the ISO 55000 (Kuijper et al., 2021). In Figure 1 the iAMPro 'rose' is presented. There are three core features: Process steps, Data and information and Humans and organisation. There are 6 unique process steps (CROW, 2024a):

1. Policy and Strategy: The interests of the stakeholders are central in this process step.
1. Management and Programming: The drawing up of a multi-year program of measures of assets.
2. Planning and Preparing: The development of new construction plans, restructuring and maintenance measures into design solutions and specifications.
3. Construction and Maintenance: Carrying out measures (new construction, restructuring and maintenance activities) and operating new and existing assets.
4. Monitor and Analyse: monitoring the performance of the asset system and analysing the results.
5. Evaluate and Adjust: Evaluation of the asset management process and the functioning of the asset system.

The NEN 2767 is also discussed within the iAMPro model through the use of the NEN 2767-4 for defining terms of various assets, elements and components (Vuren, 2014).

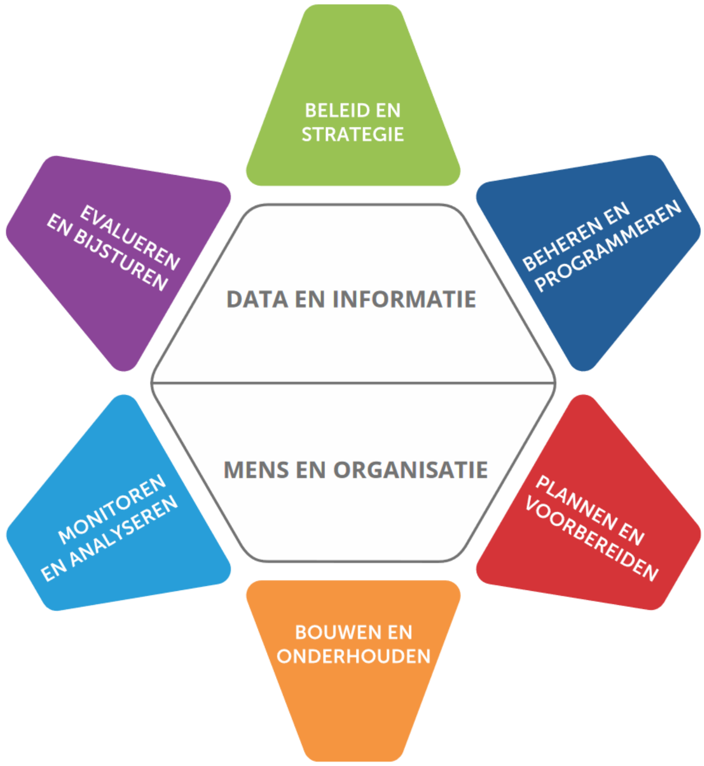


Figure 1 iAMPro 'rose' (CROW, 2024a)

The Information Model for Public Space Management (IMBOR) is an open data standard which provides a list of names for object types in the public space (CROW, 2024b). The standard holds a list of 300 objects with their definitions: intending to make the exchange of information between teams and government bodies simpler. In Figure 2 the information model of the IMBOR is presented. The Blue fields represent the information which is standardised within the IMBOR. The green fields represent the different types of disciplines which are involved within the IMBOR. The yellow fields represent the relation of the IMBOR to other standards, notably the NEN 2767 is mentioned (CROW, 2024c). In 2021 the two standards did not link with each other effectively. Particularly there are differences in how assets are defined which has led to Government Bodies having to choose which standard to go with; whether this has been solved is unclear (NEN, 2021). The Association for Dutch Municipalities (VNG) has recommended the standard (VNG, 2024), however, no literature exists on the IMBOR.

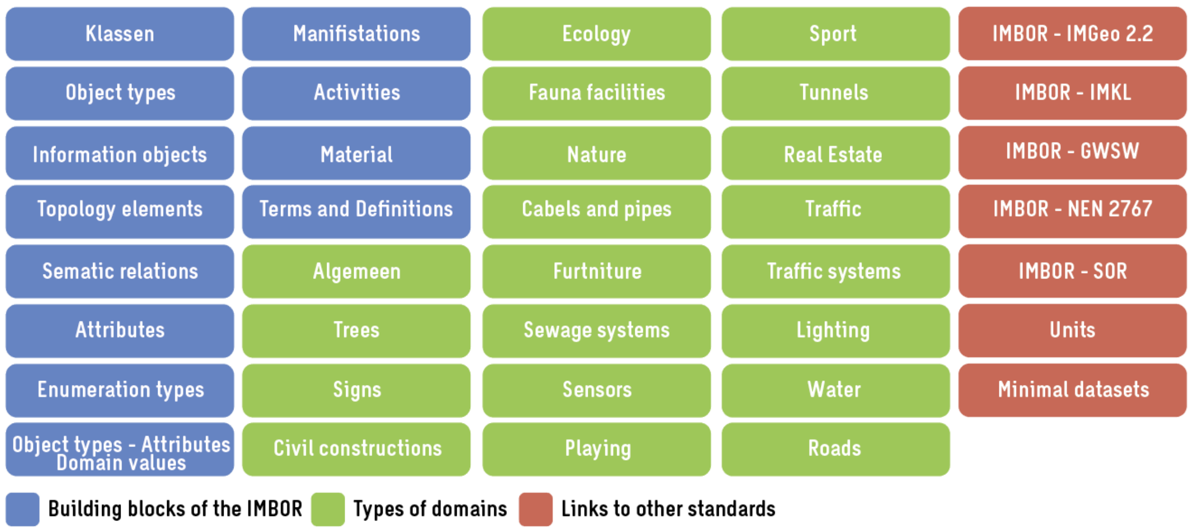


Figure 2 Translated IMBOR information model.

CROW, as part of the iAMPro model, have developed a standard, called the CUR 117, which provides a clear unambiguous procedure with rules and requirements for inspections, advice and further research for the management of assets (CROW, 2020); in essence, it aids Asset managers in setting up their requirements of inspectors. The standard provides a list of 4 main categories in which inspections, analysis, research and consulting are divided:

A) User safety of assets
   1. Schouw
B) The current state of assets
   1. Survey
   2. Condition inspection
   3. Contractual pre-requisite
   4. Contractual final assessment
   5. Restoration advice
C) The future state of assets
   1. Risk analysis
   2. Multi-year maintenance planning and budgeting
   3. Construction review
   4. Residual life analysis
D) Exceptional information requirements of assets
   1. Sampling and testing
   2. Refined financial reasoning
   3. Verification calculation
   4. Monitoring

The CUR 117 can be described as a 'menu' of different insights that can be requested by Asset Managers for an inspection. The standard has additional manuals which provide knowledge on materials, critical components and defects related to specific types of assets. Within the CUR 117, the NEN 2767 is suggested as a method for B1 survey and B2 condition inspections. The NEN's definitions are discussed as well as it being presented in templates and examples in the standard. It thus plays an integral role in the CUR 117, but it remains unclear what that exact role is in AM decision-making.

1.2 Research Gap

Despite the extensive development and application of Predictive Maintenance (PdM), Artificial Intelligence (AI), and Bridge Deterioration Models (BDMs) within the Civil Engineering field, there is a distinct gap in the literature and practical implementation regarding the use of NEN 2767 data specifically for predictive maintenance of Dutch bridges.

While the NEN 2767 standard has been widely adopted by various Dutch municipalities and provinces for assessing the condition of infrastructure, there is a lack of studies testing its predictive capabilities. The literature does not provide evidence on how effectively NEN 2767 data can be utilized in predictive maintenance applications. AI and ML models have been successfully applied to various datasets for Bridge Deterioration models in civil engineering. However, there is a gap in research specifically evaluating whether the NEN 2767 could be utilized by such models. The potential of leveraging NEN 2767 data for AI-driven predictions of bridge conditions remains unexplored.

The success of machine learning algorithms heavily depends on the quality and consistency of the data. The literature identifies issues related to data quality such as Volume of data, dimensionality of data, velocity of data creation, veracity off data, label noise and class imbalance. There is a lack of detailed investigation into challenges related to data quality, such as class imbalance and the unique data characteristics of NEN 2767, within the context of predictive maintenance for Dutch bridge infrastructure.

While the NEN 2767 is discussed within the broader context of asset management frameworks like iAMPRO, IMBOR and CUR 117, there is a gap in understanding how maintenance decisions are made within government bodies with NEN 2767 data. Research is needed to investigate what role NEN 2767 data plays in Asset Management decision making; and whether other data may play a role too. These insights could unveil how decisions are made and thus provide more guidance on what should be fed into a machine-learning algorithm.

Addressing these gaps can significantly advance the application of predictive maintenance for Dutch bridges, leveraging the NEN 2767 standard, and integrating it with ML algorithms. This would not only enhance the predictive capabilities but also ensure more efficient and effective maintenance strategies for bridge infrastructure management.

1.3 Research questions

Based on the theoretical background, in section 1.1, and the identified research gap, in section 1.2, an opportunity for expanding the knowledge base of the NEN 2767 for bridges in the Netherlands is revealed. This study aims to understand what capabilities the NEN 2767 data, gathered by government bodies, has for machine learning and how this could be improved. This section starts with the main research question which will be followed by the sub-questions which will give insights to enable the answering of the main research question. Each question's reasoning will be presented. The main research question is:

What potential does the NEN 2767 data hold for enabling Predictive Maintenance through Machine Learning, and what modifications or additions to this data could enable its predictive capabilities?

To answer this main research, question the following sub-questions will be posed with an explanation of their purpose.

a) What is the current state of implementation of the NEN 2767 in government bodies, and what impact does this have on the potential for applying machine learning to this data?

The Netherlands has many government bodies such as Municipalities and Provinces which have implemented the NEN 2767. However, it remains unclear how the implementation of the standard has been done and whether there are any differences. This research question aims at revealing the data which is stored by government bodies.

b) What are the causes of different data quality of government bodies in the NEN 2767 and what data is used to make maintenance decisions?

Differences were uncovered in sub-question a; however, their causes are not yet clear. In addition, it appeared that very little data was used to make maintenance decisions. This research question aims at revealing what causes differences in the data quality and what data is used to make maintenance decisions.

c) What additional features, used for bridge deterioration modelling, could enable the predictive potential of the NEN 2767?

To determine whether the additional data, of which some was revealed in sub-question b, is enough to enable predictive maintenance, an investigation into important factors must be performed. What features are used is one of the biggest factors in determining machine learning success (Domingos, 2012). Thus, this sub-question aims to reveal which features are most important for enabling the predictive maintenance of bridges. This can then be compared with what is captured already by inspectors and government bodies.

1.4 Research Methodology and Scope

This section presents the research methods and scope limitations. Firstly, the methodology is presented in subsection 1.4.1. The section concludes with the scope and limitations of the proposed research in subsection 1.4.2.

1.4.1 Methodology

The methodology of the research will be strongly linked to the proposed research aim: to understand what capabilities the NEN 2767 data, gathered by government bodies, has for machine learning and how this could be improved. Firstly, what data was gathered is discussed. Followed by the process for answering each sub-question.

Sub-question a

To understand how government bodies currently implement the NEN 2767 standard, sub-question (a) was developed to explore the limitations of the standard's data, additional information being stored, and data characteristics that could influence machine learning (ML) algorithm training. three secondary questions were posed to address this sub-question:

1. How do government bodies differ in storing decomposition and inspection data and what implications does this have on machine learning?
2. What additional data is recorded alongside NEN 2767 data in these documents?
3. What are the characteristics of NEN 2767 data, and how do these characteristics indicate data readiness for ML?

Data was collected by reaching out to all provinces in the Netherlands and select large municipalities. Additionally, data was gathered through the Obsurv system. Document analysis was conducted, focusing on NEN 2767 data provided by these government bodies. To address the first secondary question, the NEN 2767 standard was outlined, and relevant data fields were identified and compared across entities. Where government bodies used similar data fields, storage methods were analysed for consistency. For the third secondary question, any extra data included in the NEN 2767 documents was categorized and described. The gathered NEN 2767 data was then assessed using the 4 Vs of data: Volume, Variety, Velocity, and Veracity. This assessment provided insights into data characteristics relevant to ML applications. Specifically:

- Volume: A global analysis was conducted to evaluate data availability, including data points and features from each government body. The number of assets, defects, and components was quantified.
- Variety: The variety of data was examined by assessing the number of defects per inspection and component, as well as the diversity of unique components and defects.
- Velocity: The time span of data and average time intervals between inspections were analysed.
- Veracity: The reliability of data was evaluated, with a focus on identifying factors that could impact ML training.

Sub-question b

Sub-question (b) aim was to understand what data is generated during inspections, what data government bodies retain, and how this data informs maintenance decision-making. This inquiry provided insights into the roles of the NEN 2767 standard and other data types in maintenance strategies. To address this sub-question, four secondary questions were posed:

1. What causes the differences in the data quality of the NEN 2767 in government bodies?
2. What additional data is collected for maintenance decision-making?
3. How does data play a role in the maintenance decision-making process, and how do these compare in terms of importance?
4. What challenges are experienced when working with the data?

Interviews with Asset Managers of government bodies and NEN 2767 inspectors were conducted in Dutch. Asset Managers of government bodies were interviewed as they are typically the ones who make requests for data collection and decisions on the maintenance of bridges within municipalities and provinces. Inspectors were interviewed due to their experience with a broad range of clients and being the gatherers of inspection data. Asset Managers were chosen based on whether they worked as Asset Managers in a government body. Inspectors were interviewed based on experience with NEN 2767 inspections as well as if they did inspections on bridges. Interviewees were excluded if they were not Asset Managers or inspectors, had no experience with the NEN 2767 and did not work with bridges. The sample size was determined through saturation, the aim was to interview 5 government bodies and 5 inspectors. Interviews were performed either in person or through teams and transcription was performed by automated tools such as Word Online and Teams, later being verified by comparing the results of the recording with the resultant transcript. Interview questions were formulated through the insights gained in the secondary questions posed for sub-question A, these can be found in Appendix A: Interview questions, were conducted semi-structured to allow for flexibility, probing questions and in-depth exploration of the topic; given the lack of existing information on how government bodies in the Netherlands make decisions with the NEN 2767, this flexible approach was essential for uncovering new insights and understanding the nuances of the decision-making processes. The first interviews were considered exploratory, after which some questions were changed. These exploratory questions are also present in Appendix A. All interviewees were first explained of what would be done with their interview information. After this, they were provided with a consent form for their interviews to be either anonymously presented or with name and organisation. Results were anonymized with the possibility of quotes being used anonymously if the participant provided permission.

Data analysis was performed through thematic content analysis. Firstly, the transcripts were coded through open coding, these codes were then grouped into specific themes, which are presented in Table 2. Analysis was conducted using an inductive approach. As the interviews were conducted in Dutch Relevant Excerpts were extracted and translated. These excerpts were interpreted after which the authors' gained insights were documented.

Table 2 Codes and Themes for analysing interviews

Related themes	Codes
Potential causes of differences in NEN 2767 data	• Purpose of the NEN 2767 • NEN 2767 data storage • Interval of inspection • Inspection performer • Choosing inspector bid • Requirements for an inspector • Generation and delivery of data
Additional collected data	• Other types of inspections • RISK assessment • Intervention suggestions • Pictures • Recalculations • Other information collected • Longevity assessment
Decision making with data	• NEN 2767 • Risk assessment • Contextual Information • Changes in situation
Challenges experienced with data	• Subjectivity of extent score • Decomposition and real life • Data storage • Limitations of insights

Sub-question c

Sub-question c aims to investigate which bridge features are most important for predictive maintenance and which should be implemented to enable the predictive capabilities of the NEN 2767. To answer this sub-question 2 secondary questions were posed:

1. What features are used in bridge deterioration models?
2. Which of these features should be gathered to enable bridge deterioration modelling in the Netherlands?

To answer these questions a literature review was conducted. The investigation was performed through Scopus and Google Scholar as these are some of the largest libraries available. The search query used was "Bridge Deterioration model". The papers that were included were taken between 2020-2024. Papers had to be published in journals with a Cite score greater than 5 or an Impact Factor greater than 3 if a Cite Score was not available. This ensured that the papers were published in high-impact journals, giving the results more credence. The paper had to apply some form of machine learning with a case study. This resulted in the following inclusion and exclusion criteria.

Inclusion criteria:

1. Papers published between 2000 and 2024
2. Papers with a cite score → 5 else an Impact Factor → 3

Exclusion criteria:

1. Review articles
2. Papers that aren't about bridge deterioration models
3. Papers which do not apply any form of Machine Learning

In Figure 3 the PRISMA literature screening process is presented.

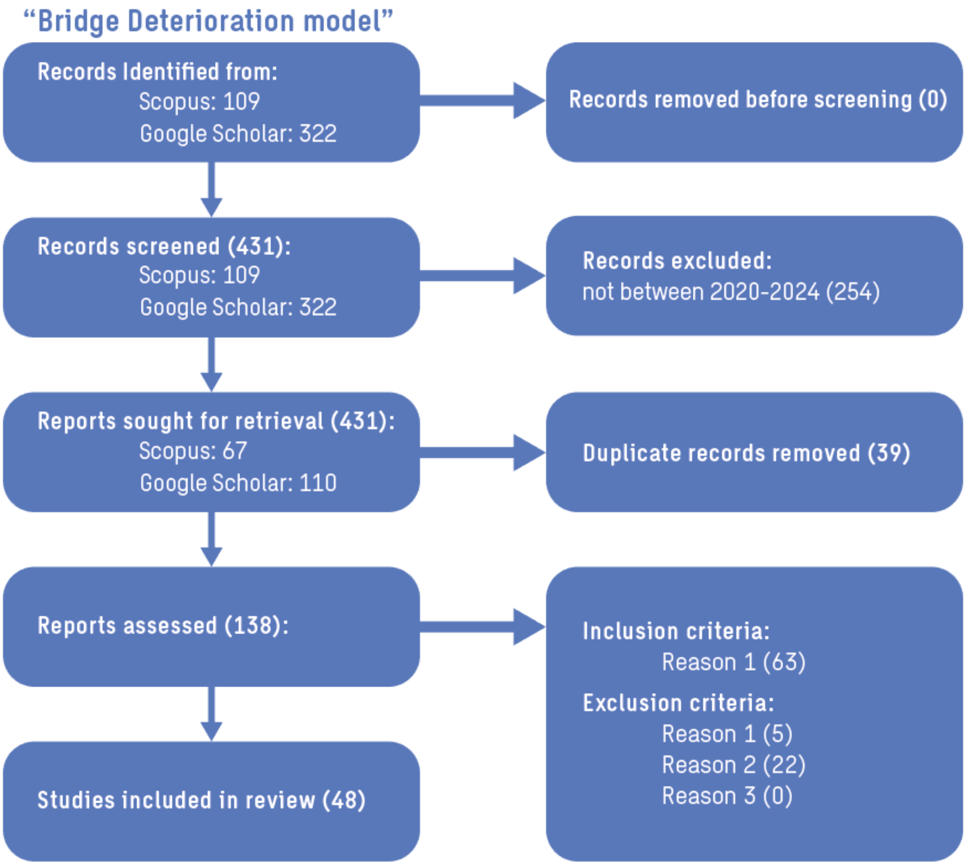


Figure 3 PRISMA literature review method

177 papers were retrieved after reading the executive summary and titles whilst considering the exclusion criteria through EndNote, 48 papers were read. Firstly, information regarding what standard was applied, the location of the case study of each paper and what component the study aimed at predicting was extracted. This was followed by a retrieval of the individual features which were applied in each paper. Features which were not applicable in the context of the Netherlands or the NEN 2767. Such as earthquake features, were removed. Similar features were combined to simplify analysis. A further 6 key points of information were extracted from each paper which applied a feature:

- Reason for inclusion: Each paper's reasoning for including the specific feature was extracted to see if a pattern could be observed in why authors believed the feature was significant.
- Significance ranking of features: Some papers provided a ranking in terms of the impact each feature had in their paper. If this was provided, it was extracted from the paper.
    - The component/element the paper aims at predicting: A component may have specific features that are more impactful on its deterioration than for other components; if a difference is impact is observed would be revealed by collecting this information.
    - Geographical context of the study: Some features' impact is linked to its geographic location.
    - Further insights shared: Authors sometimes provided additional insights about their impact findings, these can provide further reasoning for why a feature should or shouldn't be used.
- Velocity and volume: How a feature is recorded typically was also documented so that it is known how the data is collected, at which rate and how much information this is.

Once this data was collected and presented an interpretation was provided on whether the feature could be useful in the Dutch bridge context. Features were grouped into three categories: should be included in a deterioration model, could be included, shouldn't be included or inconclusive based on the findings. This was based on the following points:

- Reasoning of authors for including the feature
- The feature's impact on deterioration in comparison with other features
- On what components does the feature have an impact
- If the geographic location of the case study impacted the feature and whether this location had similar characteristics to the Dutch context
- Whether the data could be collected within the Dutch context

After grouping the features into four categories, a discussion is held on which of the features in the 'could' group just prioritised for inclusion. This is presented in the final discussion of the paper.

Recommendation validation

This research concludes with various recommendations on modifications or additions to NEN 2767 data which could enable its predictive capabilities. How these are percieved by stakeholders could indicate whether these recommendations are realistic to implement. Due to this it was important to do a round of feedback on a set of preliminary recommendations which could then be modified. Two questions were posed for each recommendation:

1. What challenges are observed by interviewees with the proposed recommendations?
2. How could these be mitigated or minimized?

To answer these questions semi-structured interviews were organized. Firstly, a brief overview of the findings were provided to interviewees after which the recommendations were presented one by one. After each recommendation 4 questions were posed; each recommendation had the same structure, only with stlighly different wording. The questions can all be found in appendix G. Data analysis was performed through thematic content analysis. Firstly, the transcripts were coded through open coding, these codes were then grouped into specific themes; these themes corresponded to the 4 recommendations. Analysis was conducted using an inductive approach. As the interviews were conducted in Dutch Relevant Excerpts were extracted and translated. These excerpts, which can be found in appendix H, were interpreted after which the authors' gained insights were documented.

Recommendations where then altered based on the mitigation strategies proposed.

1.4.2 Scope and limitations

This sub-section presents the scope and limitations of the research. Firstly, the scope is defined and why this is the case. Secondly any limitations related to the methodology used will be discussed.

Scope

There are 4 points which are made regarding the scope of this research.

Firstly, this research is limited to municipalities and provinces and thus the data gathered may not fully represent NEN 2767 implementations across all Dutch organizations. Specifically, organisations such as Rijkswaterstaat or real estate managers may apply the NEN 2767 also. Rijkswaterstaat was not included as their asset management strategies vary quiet a bit from municipalities and provinces, but also because Obsurv does not have them as a client. Comparing the data of Rijkswaterstaat too other government bodies could, however, in future be interesting.

Secondly, only bridges and viaducts are considered in this research. The NEN 2767 covers a much wider range of assets and the findings, in terms of data used and how maintenance decisions are made may be very different. Therefore, these were not included.

Third, this research is context-specific, focusing on government bodies in the Netherlands and their use of the NEN 2767 standard. Findings may not be generalizable to other contexts where inspection data standards and ML applications might differ. Thus, the conclusions drawn about data characteristics for ML may only be relevant within this context.

Fourth, no machine learning is applied. This means there is no direct evidence of how these data characteristics might affect ML outcomes, such as model accuracy or bias. Without technical validation, it remains unclear whether the data is genuinely ML-ready, despite the assessment. This was done as the believe is that there is currently not enough data. Due to time limitations this was considered out of the scope and that it was better to focus on improving the data quality.

Limitations

A further 14 limitations were identified through. The first 4 were related to sub-question a, points 5 to 9 focussed on limitations related to sub-question b and points 10 to 14 placed an emphasis on limitations related to sub-question c.

Firstly, the study relies on data from provincial and municipal government bodies that were willing to share their documents. If some provinces or municipalities declined to provide data, this could lead to gaps or biases.

Secondly, without observational data or actual testing of the data within ML models, the study may not capture practical issues that arise when using this data in ML algorithms. Document analysis provides a static view, whereas ML model development is iterative and may reveal challenges that the initial data characteristics do not immediately indicate.

Third, While the 4 Vs framework is helpful for an initial assessment of data quality, it might not fully capture the complexities of ML readiness. In addition, the interpretation of the 4 Vs may vary based on the researcher's perspective, which could affect the conclusions about the data's suitability for ML. Different researchers might assess the same data differently, leading to variability in findings.

Fourth, the process of categorizing additional data fields and assessing their characteristics may involve subjective decisions. This could lead to bias, especially if the categorization was done without standardized criteria or oversight.

Fifth, the interviews have limited generalizability. Although saturation is a goal, the limited number of interviews may not capture all variations across different regions, municipalities, or organizational practices within the Netherlands.

Sixth, there may be a bias towards maintenance decision makers using the NEN 2767. It may overlook insights from those who handle similar tasks but use alternative methods or who may have opted not to use NEN 2767. This could, for example, be a particular problem for smaller government bodies.

Seventh, the semi-structured nature of the interviews, though flexible, might still bias responses toward specific themes anticipated by the researchers. This could lead to confirmation bias, where the responses reflect expected themes more than organically arising insights. These semi-structured interviews may also inadvertently lead interviewees to focus on certain issues or challenges that align with the researchers' expectations, limiting the discovery of unexpected insights. Given the wide range of themes covered (data quality, additional data, decision-making, and challenges), there may be limited depth in any single theme. This could result in a less thorough understanding of each theme, especially if certain themes (e.g., challenges with data) require more extensive exploration to capture nuances. In addition, while interviews provide insights into how data influences decision-making, there's no analysis of actual decisions made. As a result, the findings may not accurately reflect the practical impact of data quality or additional data on real-world maintenance decisions. Observing inspectors and asset managers in action or reviewing specific maintenance decisions could provide context that interviews alone may not capture.

Eight, Thematic content analysis relies on the researchers' judgment to categorize and interpret responses. This can lead to varying interpretations, especially for complex or ambiguous responses. Coding choices, particularly in an inductive approach, might reflect the researchers' biases and affect theme development.

Nine, focusing on asset managers and inspectors overlooks perspectives from other relevant stakeholders, such as maintenance contractors, software developers for data systems, or policymakers involved in setting standards. These additional perspectives might provide important insights into broader challenges and practicalities of implementing NEN 2767 data in decision-making.

Ten, the search was limited to Scopus and Google Scholar, which, while extensive, may omit relevant studies or sources published in specialized or regional journals. Important insights specific to bridge deterioration in similar geographical or environmental contexts might be missed.

Eleventh, Restricting papers to those with a Cite Score over 5 or an Impact Factor over 3 can ensure high-quality studies, but it may also exclude practical or niche research that, although less cited, might offer valuable findings relevant to bridge deterioration in the Netherlands.

Twelfth, by selecting papers from 2020-2024, older studies with potentially foundational insights are excluded, even though they may offer valuable, long-term findings on bridge deterioration. This could limit the comprehensiveness of the literature review, as older studies might address fundamental features and methodologies still relevant for predictive models. Since deterioration models evolve over time, using only recent studies could reduce the diversity of approaches and overlook well-established features that remain relevant. Broader time frames might reveal a more holistic view of important features across various deterioration models.

Thirteenth, Although the study attempts to identify features that apply to the Netherlands, translating findings from other regions with distinct climates, bridge types, and inspection practices can be challenging. The differences in environmental or structural contexts between countries might lead to misinterpretation of feature importance.

Fourteenth, grouping features into "should," "could," or "shouldn't be included" categories involve subjective judgment. Different researchers might categorize features differently based on their interpretation of the literature. This subjective grouping might affect the consistency and replicability of the findings. In addition, grouping features can obscure the complexity of interactions between features. For example, a feature that appears insignificant alone might play an important role in combination with others. This oversimplification might limit the applicability of the findings in comprehensive predictive models.

1.5 Reading Guide

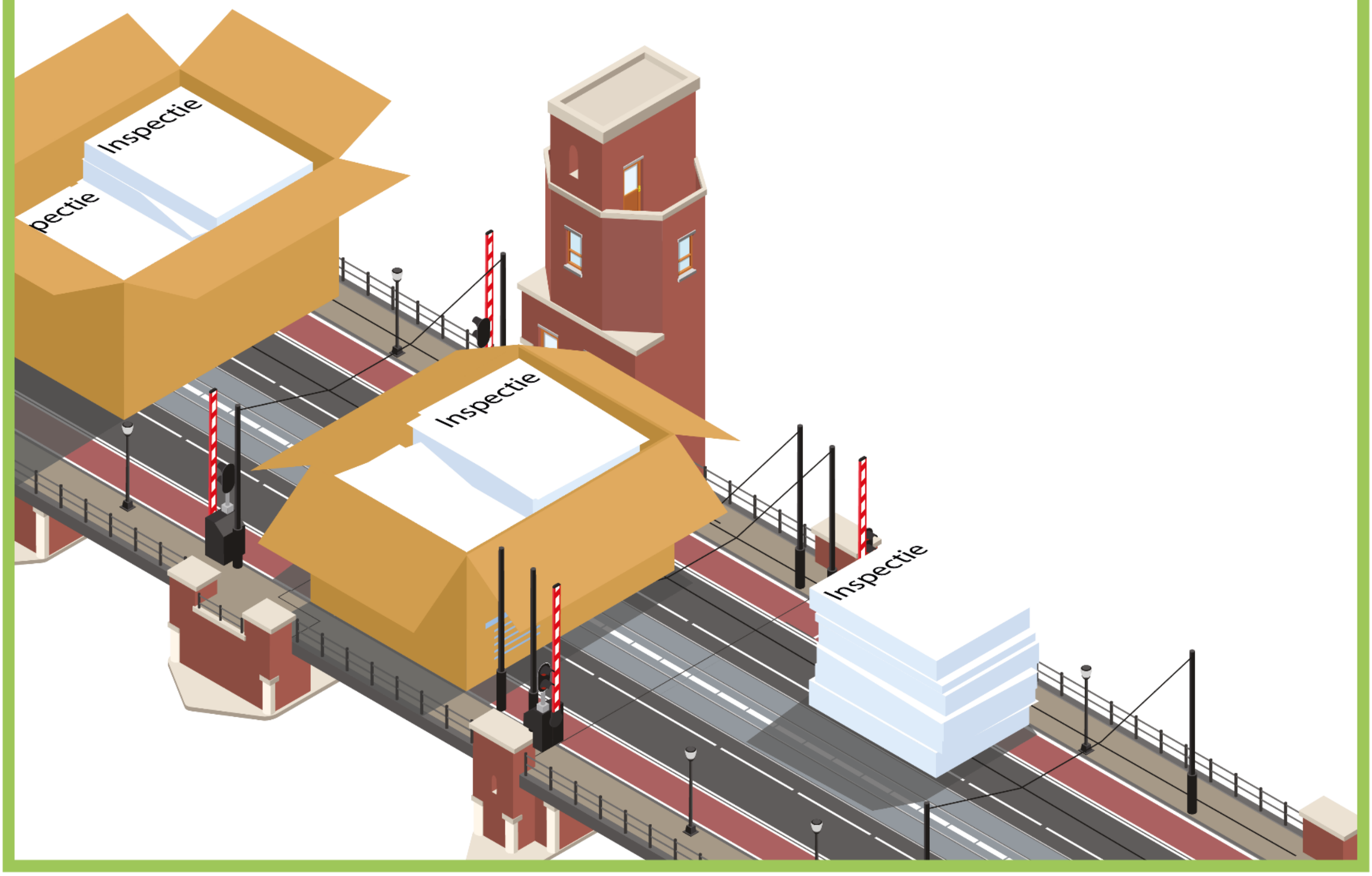
In this section what is to follow in this thesis is provided. In chapter 2 the current state of the NEN 2767 is described by analysing data from municipalities as well as provinces for their readiness of Machine Learning. In chapter 3 the insights gained from interviews with government bodies and inspectors are presented and interpreted to gain a further understanding on what data is important and what changes should be made. In chapter 4 the extensive literature study on features used in bridge deterioration models is presented to understand which other features should be captured to enable predictive maintenance of the NEN 2767 data. The report then continuous with a discussion of the findings, where key insights are shared. This is followed with recommendations on what changes government bodies could implement to improve their ability to perform predictive maintenance and what further research steps could be taken. The report ends with a conclusion and all used recommendations.

2. The Current state of the NEN 2767

In this chapter, the current state of the NEN 2767 implementation in government bodies is presented. The chapter consists of 4 sections. The first section represents the NEN 2767 methodology, where how the standard currently works is explained. The second section describes the NEN 2767 data in practice; here the data gathered from government bodies is presented in 3 different parts. Firstly, how the decomposition data is stored, secondly how defects are recorded and lastly what additional information is stored. The third section describes the data characteristics of the NEN 2767 through the 4 V's: Volume, Velocity, Variety and Veracity. This will provide insights into what attributes the data holds with a perspective on Machine Learning. The last section gives an overview of the findings of the study.

In this chapter the following secondary questions are answered:

1. How do government bodies differ in storing decomposition and inspection data and what implications does this have on machine learning?
2. What additional data is recorded alongside NEN 2767 data in these documents?
3. What are the characteristics of NEN 2767 data, and how do these characteristics indicate data readiness for ML?



2.1 The NEN 2767 methodology

Within this section, the NEN 2767 methodology is presented as described in the standard. The section is divided into two sub-sections. Decomposition and parameters. The decomposition refers to the breakdown of the assets, specifically bridges, within this research. The parameters refer to how defects are recorded.

2.1.1 Decomposition method

The standards breakdown structure consists of 6 levels but considered only 3 in its scope for condition assessment. As can be seen in Figure 4 these are the Asset, Element and Building or installation components. The following definitions are provided for these levels in NEN 2767 (NEN, 2019), with an overview provided in Figure 4.

1. Asset: Demarcated unit of an overlying network, a portfolio of properties, a complex or an area consisting of an integrated assembly of elements with one or more autonomous usage functions.
2. Element: Identifiable part of an asset that is distinguished exclusively based on the function required and that consists of one or more building or installation components.
3. Building or installation component: Independent and identifiable part of an element, distinguished by composition or design, consisting of one or more sub-components to which technical properties and maintenance history can be related.

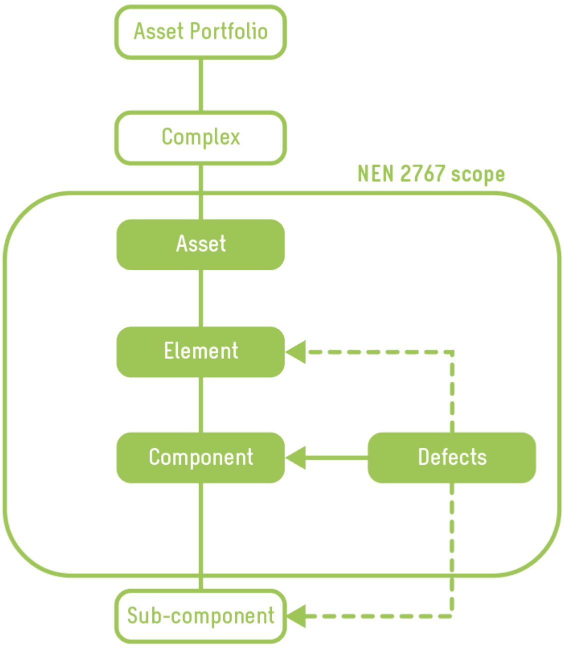


Figure 4 Breakdown structure of the NEN 2767 (NEN, 2019)

The level of abstraction increases as one goes up in the levels. It should be noted that a full decomposition of an asset is not required. Rather, if a defect is found it is directly linked to a Building or installation components, which will from now on be referred to as components. These components are then linked with specific elements and elements are linked with specific assets. A standardised list of assets, elements and building or installation components is provided for condition assessment of infrastructure in the form of the NEN 2767-4; this is a web application created by the NEN (NEN, 2024). The decomposition list consists of 64 Assets, 415 elements, 818 building or installation components and 63 material types. Each of these has a provided written definition. It should be noted that Assets may contain the same, or different elements. Elements may also contain the same or different building or installation components.

Within the scope of this research only 3 Assets are of relevance there are the Bridge (movable), Bridge (fixed) and Viaduct. Their descriptions can be seen in Table 3 which are taken from NEN 2767-4 (NEN, 2024). This leaves a list of 114 elements and 818 building or installation components. It shows that within the 114 elements which are still considered a wide range of components can be present. A building or installation component thus does not make an element unique, rather it is the combination of these components results in distinctiveness.

Table 3 Translated definitions of considered assets in research

Code	Asset Name	Definition (translated)
AF	Bridge (movable)	A movable link for traffic between at least two points separated by waterways and offering variable vertical space.
AG	Bridge (fixed)	Fixed connection for traffic between at least two points separated by main waterways and includes a main supporting structure and a top driving surface.
BW	Viaduct	'Kunstwerk'[1] forms a fixed bridge over a road, railway or terrain depression.

In Figure 5, an example is given of how decomposition would in practice occur with a barrier on a movable bridge. The barrier in question consists of 3 components, the barrier, the control panel and the lighting fixture, these in turn have their material properties: plastic, steel and electrotechnical.

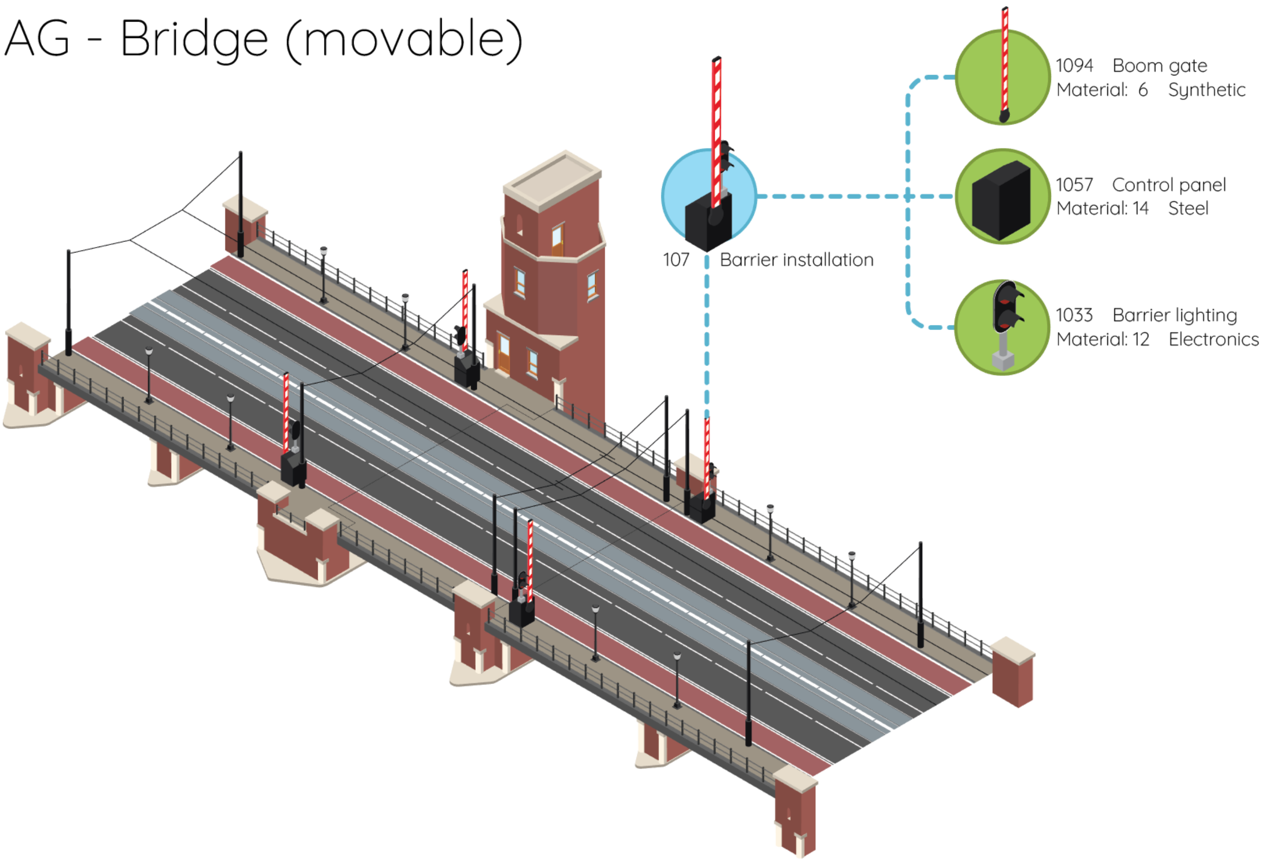


Figure 5 Picture of the decomposition barrier installation of a bridge (movable)

[1] A 'kunstwerk' is a Dutch term for civil infrastructure. Usually referring to bridges.

2.1.2 Inspection documentation method

In this sub-section the inspection documentation of the NEN 2767 is presented and how they define the state of a component. An example of a defect on a control panel is provided in Figure 6. If a component has a defect the standard provides a condition score between 1-6, as presented in Table 4, 1 is a minor defect and 6 is a very bad defect. These are derived through three parameters which determine the condition of the component: Severity, Extent and Intensity. Each component, in an asset is inspected for defects. These defects are then scored on these three parameters (NEN, 2019). A description of each parameter, as well as how the final condition score is determined is provided is described below.

Figure 6 Example of a NEN 2767 defect on a control panel

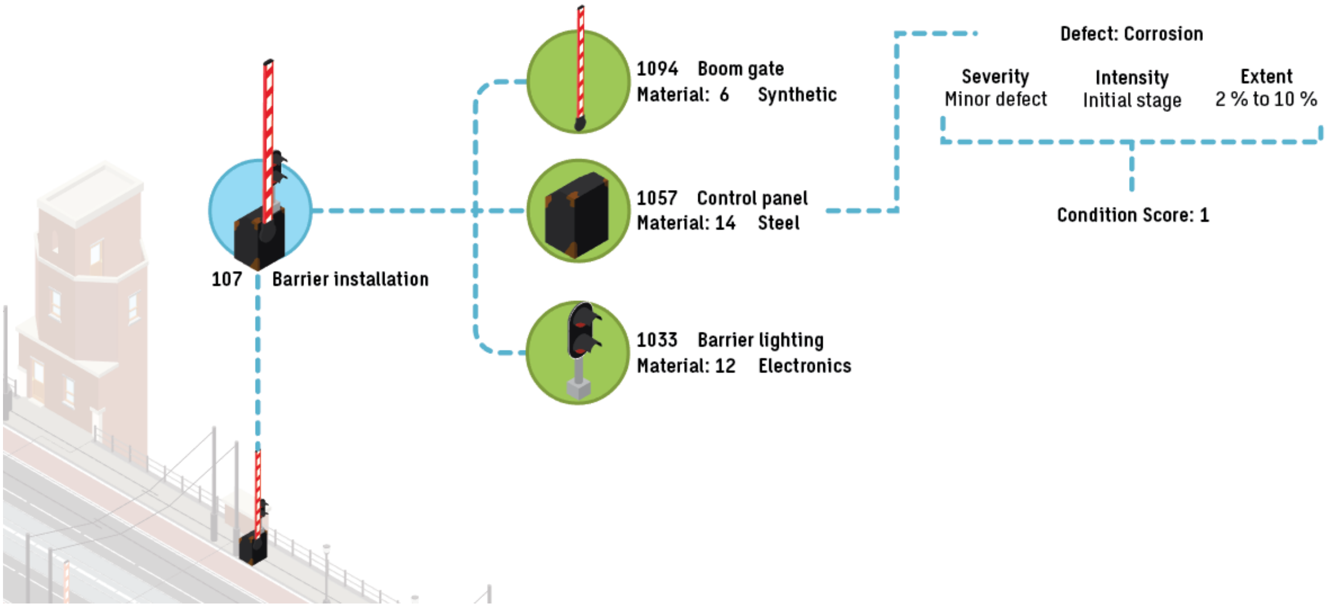


Table 4 Condition scores in the NEN 2767 (NEN, 2019)

Condition score	Description	Elaboration
1	Excellent condition	Defects, usually in the form of slight damage or defects of an aesthetic nature, can occasionally be found.
2	Good condition	Installations function without any faults, apart from a few exceptions.
3	Reasonable condition	Some local repairs may have been carried out using less suitable means. A building or installation component can display visible ageing overall.
4	Poor condition	The reliability of installations is only ensured to a moderate degree. Business interruptions can occur.
5	Bad condition	Many (severe) defects that will lead to a loss of functionality can occur. Business interruptions can occur regularly.
6	Very bad condition	The building or installation component is unfit for use and is technically ready to be demolished.

Severity

Severity, according to the standard refers to the degree to which the defect influences the functionality of which the building or installation component consists (NEN, 2019). Some graffiti art on the column of a bridge does not necessarily, for example, hinder functionality. Three levels exist within this parameter which are presented in Table 5.

Table 5 Severity scores in the NEN 2767 (NEN, 2019)

Severity	Definition	Example
Severe defect	Adversely affects the function of the building or installation component	wood rot, cracks in a central heating flue exhaust
Serious defect	Causes degradation of the building or installation component without directly affecting its functionality	weathering, erosion, a defect that leads to installations leaking
Minor defect	Does not adversely affect the functionality of the building or installation component	discolouration due to ageing, improper attachment of sub-components

Extent

Extent refers to the net quantity in which the defect in question covers the component, expressed as a percentage of the area of the building or installation component (NEN, 2019). The extent is defined by 5 levels which can be seen in Table 6.

Table 6 Severity scores in the NEN 2767 (NEN, 2019)

Extent	Percentage	Description
Extent 1	Less than 2 %	The defect occurs occasionally
Extent 2	2 % to 10 %	The defect occurs locally
Extent 3	10 % to 30 %	The defect occurs regularly
Extent 4	30 % to 70 %	The defect occurs considerably
Extent 5	More than 70 %	The defect occurs generally

Intensity

Intensity describes the current degeneration stage of the defect (NEN, 2019). This parameter consists of three levels which are presented in Table 7.

Table 7 Intensity scores in the NEN 2767 (NEN, 2019)

Intensity	Designation	Definition
Intensity 1	Initial stage	The defect will generally be hard to observe and will only be present superficially.
Intensity 2	Advanced stage	The defect can be observed quite clearly and is present on the surface
Intensity 3	Final stage	The defect is easily observed, the process of degradation is irreversible and can hardly develop.

Final condition score

Three matrices are presented in Table 8 which allow a user to determine the condition score of a component. After inspection, a severity, extent and intensity score is given by an inspector to each building component with a defect. The table first assesses which matrix must be used by looking at the severity score. From this, the extent and intensity guide the user in giving the final overall conditional score of the component.

Table 8 Condition score determination according to the NEN 2767 (NEN, 2019)

Minor defect					
Extent / Intensity	Less than 2 %	2 % to 10 %	10 % to 30 %	30 % to 70 %	More than 70 %
Initial stage	1	1	1	1	2
Advanced stage	1	1	1	2	3
Final stage	1	1	2	3	4
Serious defect					
Extent / Intensity	Less than 2 %	2 % to 10 %	10 % to 30 %	30 % to 70 %	More than 70 %
Initial stage	1	1	1	2	3
Advanced stage	1	1	2	3	4
Final stage	1	2	3	4	5
Severe defect					
Extent / Intensity	Less than 2 %	2 % to 10 %	10 % to 30 %	30 % to 70 %	More than 70 %
Initial stage	1	1	2	3	4
Advanced stage	1	2	3	4	5
Final stage	2	3	4	5	6

If multiple defects occur on one component or an element, a method is presented in the NEN 2767 standard to solve this, this can be found in Appendix D.

2.2 NEN 2767 in practice

In this section, the NEN 2767 standards application in practice is presented. The data which was gathered from government bodies is analysed and presented. Information was gathered from 5 provinces and 7 municipalities. As is presented in Figure 7 the provinces include Noord-Brabant, Flevoland, Utrecht, Limburg and Gelderland. The municipalities include Tilburg, Utrecht, Maastricht, Gorinchem, Arnhem, Deventer and Amsterdam.

Figure 7 Map of gathered data from the Netherlands

Their data includes 2273 bridges and viaducts. The distribution of bridges and viaducts can be seen in Table 9.

Table 9 Number of bridges recorded in NEN 2767 data of considered governmental organisations

Government bodies	Bridges (vast)	Bridges (Movable)	Viaducts	Total
		Provinces		
Noord-Brabant	105	2	19	126
Utrecht	115	0	13	128
Limburg	43	0	101	144
Flevoland	62	0	11	73
Gelderland	8	1	8	9
		Municipalities		
Amsterdam	-	-	-	1537
Tilburg	146	0	14	160
Utrecht	989	28	82	1099
Maastricht	49	2	15	66
Gorinchem	114	1	0	115
Arnhem	272	0	50	322
Deventer	16	0	15	31

This section consists of three sub-sections: Decomposition, inspection data and Additional data. Firstly, the findings are presented for each category, after which the implications of this data are presented.

2.2.1 Decomposition in practice

In this subsection, different approaches which are implemented in practice for the decomposition of the NEN 2767 are presented. In Table 10 an overview is given of what data is included by each governmental organisation. How this data is stored, in terms of documentation style, is presented in Appendix B. From the analysis, 3 main points of interest were identified. These are discussed below.

Table 10 data in bridge decomposition (X = Included, / = Partially included) Green is required by the standard

Government bodies	Asset ID	name	Type asset	Element ID	Elements	Component ID	Components	Component Dimensions	Component main material
					Provinces				
Noord-Brabant	X	X	X		X		X		X
Utrecht	X		X		X		X		
Limburg	X	X	X		X		X		X
Flevoland	X	X	X		X	/	X		X
Gelderland	X		X		/		/		X
					Municipalities				
Amsterdam	X	X	/		X		X	X	X
Tilburg	X	X	X	X	X	X	X	X	X
Utrecht	X	X	X		X		X		X
Maastricht	X	X	X		X		X		X
Gorinchem	X	X	X		X		X		X
Arnhem	X	X	X		/		X		/
Deventer	X	X	/				X		

Different forms of documentation

There appears to be no agreement amongst the data collected from government bodies on how data should be stored. Differences were found in the documenting of the ID for the asset, name, type of asset, elements and often components. 6 different ways of documenting the components and elements were identified; indicating there is no agreement on how information should be stored. In addition, it appears that some government bodies add additional information to fields such as '**' most likely indicating something about the asset. But also, additional information being stored in one field such as with the name of an asset also coming with the street name where the bridge is located.

The results indicate that, although as shown in section 2.1 the NEN 2767-4 does provide a framework for how a decomposition could be documented, different interpretations of how this information could be stored have emerged. There thus, appears to be no agreement, amongst the government bodies which participated in this study, on how information should be documented. For machine learning purposes this can be a particular nuance as the aim is to have an algorithm learn the deterioration rate of components over time; if data is combined from different government bodies and their decomposition is documented in various ways it will require a lot of manual data cleansing to ensure that an algorithm can learn from a uniform set of data.

Dealing with duplicates

Most government bodies do not provide a way in which unique components and elements can be distinguished from each other. Often the same component presents itself under an element and many bridges include the same element many times. Only one government body has full incorporated such a documentation system.

The lack of a unique ID system among data provided by government bodies is unsurprising, as the NEN 2767 standard does not require it. However, excluding this system has a significant impact on the ability of machine learning algorithms to learn from the deterioration of components. Without a way to identify which defect corresponds to which component or to track condition changes of components across different inspection rounds, training algorithms at the component or element level becomes impossible.

The order of information differs

Although Table 10 presents a structured order of information this is not the case in the data sheets provided by government bodies. Each organisation has its way of ordering data in columns with different column names.

This again is not required by the NEN 2767, and government bodies cannot be faulted for storing their information differently. However, it is again an additional nuisance when comparing information and indicates the non-uniformity in data storage practices amongst the data collected of government bodies.

2.2.2 Inspection data

In this subsection how the parameter data, related to defects, are stored is presented. An overview is given in Table 11 of what is included by each government. How this data is stored in terms of documentation style is presented in Appendix C. From the analysis, 7 differences can be observed. These are discussed below.

Table 11 Bridge parameters data (X = Included, / = Partially included) Green is required by the standard

Government bodies	Asset ID	Name asset	Date inspection	Element	Component	Material	ID Defect	Type defect	Severity	Extent	Intensity	Condition score
					Provinces							
Noord-Brabant		X	X		X		X	X	X	X	X	
Utrecht		X		X	X							X
Limburg		X	X		X		X	X	X	X	X	
Flevoland	X		X	/	/		X	X		X	X	
Gelderland	X		X	/	/	X		X	X	X	X	X
					Municipalities							
Amsterdam	X	X		X	X	X		X	X	X	X	X
Tilburg	X	X	X	X	X	X	X	X	X	X	X	X
Utrecht		X	X		X		X	X	X	X	X	
Maastricht	X	X	X									
Gorinchem		X	X		X	X			X	X	X	
Arnhem												
Deventer												

Inclusion of a pointer to the asset

A connection is always included, either in ID or name form. However, there are fewer connections provided than with the decomposition. Whereas all government bodies provided an ID for their assets in the decomposition document these do not necessarily return in the parameter document.

The results indicate that there is a disconnect between the documentation of the decomposition and parameter recording in the data collected from government bodies. As some of these connections rely on the same of the asset spelling mistakes could easily occur, which could require data cleaning before any machine learning could be applied.

Documentation of elements and components

Defects are, according to the standard, always connected to a component by the government bodies who implement defect recording. However, the element connection is only included by 5 government bodies out of the 9 who record defects in their system.

As was already noted in the previous sub-section, without an ID system for components and elements it is impossible to track degradation of components over time. The results from this insights indicate that defects can, if the element connection is not noted, not be located on a bridge simply based on the data and will require additional insights as components will appear in many different locations in a bridge. Making deterioration modelling even harder.

Inclusion of materials

Fourth, the material on which a defect occurs is only included by Gelderland, Tilburg, Amsterdam and Gorinchem. This means that the insights gained about a defect are more limited.

The implications of this are that an important contextual feature is not always recorded for a defect. For example, a tear in a steel beam could deteriorate very differently than a tear in a concrete pillar. This could limit the potential of a algorithms effectiveness as it could be lacking important contextual insights.

Inclusion of Severity, Extent and Intensity

7 government bodies document the three parameters Severity, Extent and Intensity, except for one, which has only a number for damages, Flevoland which documents intensity and extent and the province of Utrecht, which only provides a final condition score.

Although many of the government bodies do document all the parameters related to a condition score, the few that do not still indicate that there are different interpretations of what must be documented.

Different order of data

Similarly to the decomposition data, every government body has a different order in which the information is stored with differently named columns.

This is not a requirement of the NEN 2767, and government bodies cannot be faulted for storing their information in different ways. However, it is an additional nuisance when comparing information and points to the non-uniformity in data storage practices among government bodies.

Different forms of documentation

Just as the decomposition data there are many ways in which data is recorded. Defects are usually documented correctly. However, there are differences in how these defects are recorded; either using the written version or the codified version of the standard and sometimes terminology is applied which is not NEN 2767 compliant. There are 5 different ways in which the data of an inspection is stored.

This provides a challenge when wanting to combine data from different government bodies for the training of a Machine Learning algorithm as the information will have to be standardized.

Date of inspection

The NEN 2767 does not require the date of inspections to be recorded. Despite this most government bodies provide an exact date of the performance of their inspection with the exclusion of the municipality of Amsterdam and province of Utrecht; who both provide an estimated year in which the inspections occurred.

The results mean that a level of abstraction would have to be performed if the exact data is not always available from government bodies. This could in turn affect the accuracy of a model's prediction on how fast deterioration occurs.

2.2.3 Additional data

In this subsection additional data which is stored besides the NEN 2767 standard is presented and discussed. An overview is given in Table 12 of what is included by each governmental organisation. From the analysis, 5 observations can be made; these are discussed below.

Table 12 Bridge additional data stored besides NEN 2767 data (X = Included, / = Partially included)

Government bodies	Name of asset	Image of defect	Risk assessment	General material asset	Build year	Destruction year	General dimensions	Location	Restoration advice
Provinces									
Noord-Brabant	X				X			X	
Utrecht									
Limburg	X			X	X	X		X	
Flevoland	X						/	X	
Gelderland					X		X		X
Municipalities									
Amsterdam	X		X						X
Tilburg	X	X	X		X		X	X	X
Utrecht	X				/			X	
Maastricht	X	X		X	X	X		X	
Gorinchem	X			X	X			X	
Arnhem	X				X			X	
Deventer	X				X			/	

General characteristics of the bridge

Various characteristics, not related to the NEN 2767 are recorded in documents by government bodies. Locations of the bridges and viaducts are often included in many different forms from GIS location to neighbourhood, street and region. There is no unanimity on what location information should be stored. The build year is very often recorded and in two cases the destruction year is also provided. General dimensions and material of assets are also provided. The destruction year of bridges is also documented by certain government bodies.

The additional data indicate that government bodies are interested in other characteristics of their bridges besides the NEN 2767. Especially the build year and location are often recorded with other information being stored more sporadically. The results indicate that the NEN 2767 decomposition does not capture all the information a government body may be interested in.

Additional information on defects

A range of additional data is included by government bodies on the defects they record. Images of defects are included by two government bodies. These could allow for the verification of condition scores which are given. Risk assessments are documented by both the municipalities of Amsterdam and Tilburg. Their form is very different but are linked to component defects. In addition, three government bodies provide restoration advice for defects which are recorded.

The results indicate that more information, besides the NEN 2767, is desired by government bodies on the defects that are found. This could indicate that the information provided by the NEN 2767 is not enough to make a maintenance decision, particularly when considering the risk assessment, images of the defects and restoration advice.

Fever features captured than used in other bridge deterioration models

Overall, the additional data collected, besides the composition and condition scores the number of features captured is much lower than is often applied in bridge deterioration models. as presented in sub-section 1.1.3, studies included a plethora of features such as:

- Geometry features: such as length, width area and skew
- Environmental factors: such as temperature, carbon dioxide concentrations, airborne salt concentrations, snowfall, and rainfall.
- Loading conditions: such as stress on the bridge due to daily traffic volumes, designed load, and the number of large vehicles crossing the bridge.
- And other important information: such as the maintenance history,

The results indicate that currently, there is too little information being captured for determine the deterioration of Dutch bridges, which could lead to underfitting; this is where an algorithm simply does not have enough information to accurately predict what will happen in the future with the bridge.

2.3 NEN 2767 data characteristics

In this section the NEN 2767 data which is gathered is assessed through the 4 Vs of Big Data: Volume, Variety, Velocity and Veracity (Schroeck et al., 2012). This section is divided into 4 sub-sections according to the 4 Vs to reveal the characteristics of the NEN 2767 data.

2.3.1 Volume

In this sub-section, the Volume characteristics of the data are presented. A global overview of how much data was available within the decomposition and parameter datasheets for each government body is presented as well as the number of assets, defects and components. 3 Different notable observations are found.

Table 13 Volume data characteristics from government bodies

Government bodies	# of bridges and viaducts	Total number of defects recorded	Total number of components	Average number of components per bridge	% of assets which have had 2 inspection cycles	The average number of documented defects per component	The average number of defects found per inspection
	Provinces						
Noord-Brabant	126	1167	3528	28.00	54%	0.33	5.95
Utrecht	128	473	1453	11.35	0%	0.33	1.19
Limburg	144	164	1788	12.42	0%	0.09	2.75
Flevoland	73	371	2947	40.37	0%	0.13	6.63
Gelderland	9	475	535	59.44	69%	0.89	6.17
	Municipalities						
Amsterdam	1536	6001	21092	13.73	30%	0.14	1.95
Tilburg	160	845	1475	9.22	0%	0.57	6.02
Utrecht	1099	15921	14183	12.90	51%	1.11	5.24
Maastricht	66	299	608	9.21	0%	0.49	0.56
Gorinchem	115	804	1043	9.07	0%	0.77	3.06
Arnhem	322	-	-	6.01	-	-	-
Deventer	31	-	-	-	-	-	-

Number of assets; limits training data

As can be seen immediately in Table 13 the number of assets each government body manages differs significantly. Particularly when comparing the number of assets provinces manage and municipalities there are large differences; on average the provinces manage 96 bridges and municipalities manage 475. However, numbers such as Gelderland and Deventer, which according to these figures only manage 9 and 31 bridges. This number seems too low and suggests that not all bridges are possibly recorded in their systems.

The results indicate that there are large differences in the number of assets that are managed between government bodies. This directly affects the volume of data an individual government body can collect; say a government body such as Amsterdam can collect 7680 inspection reports if an inspection was performed yearly over 5 years, whereas Tilburg could only collect 800 reports. This means that the training data Amsterdam has is worlds apart from the training data Tilburg has, limiting their potential to implement Predictive Maintenance using Machine Learning in the short term.

Large differences in the number of defects

The number of defects recorded varies greatly between government bodies. This is not only in terms of volume, but also the number of defects found per inspection and component differ greatly. These differences could be due to 3 reasons. Firstly, differences in maintenance regimes, where one government body repairs defects quickly and others do not. Secondly, inspection regimes could differ, where inspectors used by one government body either have different requirements or philosophies, that other government bodies. Third, bridges in one governments asset portfolio, could deteriorate more, than bridges maintained by other government bodies.

Besides the causes of these differences these discrepancies do influence machine learning potential. If less defects are recorded, especially when these are present but not documented, there are less examples for an algorithm to train on; in essence reducing the volume of defects a machine learning algorithm can train on.

Large differences in the resolution of decomposition

There is a large difference in the number of documented components per asset for differing government bodies. Notably, on average provinces have more components than municipalities. It is unclear what causes this as a bridge's complexity would not necessarily be linked with a government bodies type.

This difference in decomposition resolution affects machine learning as it means an algorithm may not have a complete picture of the deterioration affecting the bridge, as defects are linked directly to components. This thus directly affects the feature set and could lead to overfitting, particularly if a data set with a higher resolution decomposition is validated on.

Data class-imbalance of defects

When assessing the number of defects recorded per component it becomes apparent that few defects are found per individual component. This indicates that there is a data-class imbalance problem; an issue where there a few examples of a certain event happening.

This challenge is one which has been addressed frequently in literature and should pose only a minor challenge as algorithms have been developed which can deal with such data class imbalanced tasks. These algorithms should thus careful be chosen to ensure success is more likely.

A low number of repeated inspections

The average number of inspections per asset reveals that most assets have not undergone more than one inspection. Among the government bodies conducting second inspections, the rates vary: Noord-Brabant has re-inspected 54% of its assets, Gelderland 69%, Amsterdam 30%, and the Municipality of Utrecht 51%. This results in the following number of data points for the government bodies with more than one inspection, which can be seen in Table 14.

Table 14 Number of data points available

Government body	Number of data points available
Noord-Brabant	1905
Gelderland	366
Amsterdam	6327
Utrecht	7230

It is required for the Predictive model to have at least a second inspection round, as it otherwise has nothing to base the deterioration rate on. Based on the data that has been provided no government body has even performed one inspection round. When comparing this to the data used in section 1.1.3 for deterioration models the data is very limited. One example is Law (2015) and Setunge and Hasan (2011) who had records dating from between 1995 and 2012; giving a much larger breath of information to work with. Based on the available data, it can be determined that there is simply too little information available to train an algorithm on this information.

2.3.2 Variety

In this sub-section, the Variety characteristics of the data are presented. This includes the number of defects found per inspection and component and the number of unique components and defects. 2 insights were gained.

Table 15 Unique components and defects per government body

Government bodies	# Unique Components	# Unique defects
	Provinces	
Noord-Brabant	263	37
Utrecht	109	-
Limburg	81	8
Flevoland	229	43
Gelderland	19	46
	Municipalities	
Amsterdam	400	75
Tilburg	114	54
Utrecht	255	133
Maastricht	156	-
Gorinchem	159	49
Arnhem	59	-
Deventer	-	-

Table 16 Range of data

Government bodies	Severity				Extent				Intensity			
	Mean	SD	Max	Min	Mean	SD	Max	Min	Mean	SD	Max	Min
Provinces												
Noord-Brabant	2.09	0.82	3	1	1.83	1.27	5	1	1.72	0.86	3	1
Utrecht	-	-	-	-	-	-	-	-	-	-	-	-
Limburg	2.23	0.80	3	1	2.13	1.38	5	1	2.26	0.78	3	1
Flevoland	2.10	0.71	3	1	2.72	1.40	5	1	-	-	-	-
Gelderland	2.00	0.75	3	1	2.43	1.19	5	1	1.94	0.61	3	1
Municipalities												
Amsterdam	2.24	0.75	3	1	2.91	1.02	5	1	2.22	0.70	3	1
Tilburg	2.00	0.85	3	1	3.24	1.36	5	1	1.98	0.44	3	1
Utrecht	2.50	0.72	3	1	2.73	1.32	5	1	2.07	0.48	3	1
Maastricht	-	-	-	-	-	-	-	-	-	-	-	-
Gorinchem	2.31	0.84	3	1	1.62	0.49	2	1	1	0	1	1
Arnhem	-	-	-	-	-	-	-	-	-	-	-	-
Deventer	-	-	-	-	-	-	-	-	-	-	-	-
Average	2.18	0.78	3.00	1.00	2.45	1.18	4.63	1.00	1.88	0.55	2.71	1.00

Differences in unique components and unique defects

There is a large difference in the number of unique components and defects which are recorded by government bodies. This could be caused by the requirements set by government bodies on what should be record, the training of inspectors or simply that unique defects and components only appear in certain locations.

These differences in the number of unique defects and components can make training an algorithm more challenging if little data is available as an algorithm may only see a component or defect once. This further emphasises the importance of collecting enough data to effectively train a Machine Learning algorithm.

Range of parameter scores

The range of mean scores across parameters was relatively large. For severity, the mean range was 0.5 within a possible score range of 1 to 3. For extent, the mean range was 1.62, where scores could vary between 1 and 5. For intensity, the mean range was 0.54, also within a scale of 1 to 3. Maximum and minimum values generally reached the boundaries, except in Gorinchem, which only reported intensity scores of 1 and extent scores between 1 and 2. The wide variation in mean parameter scores indicates significant differences in how defects are scored across government bodies. This disparity could be attributed to a smaller number of recorded defects, which skews the data. Notably, government bodies with the most extensive data, such as the Municipality of Amsterdam and Utrecht, exhibited much smaller differences in mean scores for all parameters.

These results may have 2 different implications on a machine learning. Firstly, the fact that government bodies with more data have smaller differences in mean scores suggests that the volume of data impacts consistency. ML models might perform better on data from government bodies with a lot of data than lower ones. Secondly, the general differences between government bodies in scoring severity, extent, or intensity could lead to data skewness, where an algorithm has seen to many examples of one type; this could result in overfitting.

2.3.3 Velocity

In this sub-section, the Velocity characteristics of the data are presented. The time range of data and the average time between inspections is presented. 4 different observations were made.

Table 17 Data Velocity

Government bodies	Velocity (years)	Source
Provinces		
Noord-Brabant	7	Correspondence.
Utrecht	5	Correspondence.
Limburg	5	Correspondence.
Flevoland	5	Correspondence.
Gelderland	-	-
Municipalities		
Amsterdam	6	Correspondence.
Tilburg	5	Correspondence.
Utrecht	6.62	Data.
Maastricht	-	-
Gorinchem	-	-
Arnhem	-	-
Deventer	-	-

Table 18 Age of assets and earliest available NEN 2767 inspection data

Government bodies	Median Age of bridges	Earliest available NEN 2767 inspection data	Latest available NEN 2767 inspection data
Provinces			
Noord-Brabant	1985	2020	2023
Utrecht	-	2020	2020
Limburg	1992	2018	2019
Flevoland	-	2020	2022
Gelderland	1988	2023	2024
Municipalities			
Amsterdam	-	2019	2024
Tilburg	1995	2023	2024
Utrecht	1968	2007	2023
Maastricht	1961	2015	2023
Gorinchem	1984	2022	2022
Arnhem	1985	-	-
Deventer	1845	-	-

Table 19 Inspections on different bridges per year *Amsterdam didn't have exact years

Government bodies	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Provinces																		
Noord-Brabant														79	37	80	13	
Utrecht														128				
Limburg												55	1					
Flevoland														11	13			
Gelderland																	74	57
Municipalities																		
Amsterdam													308	307	307	307	307	539
Tilburg																	17	37
Utrecht	22	9	1	18	36	23	8	12	12	160	253	467	101	164	227	24	50	
Maastricht									42								65	
Gorinchem																275		
Arnhem																		
Deventer																		

Difference in build year and first inspection year

As can be seen in Table 18 there is a large difference between the mean age of the bridges in government bodies and the first NEN 2767 data inspection. It shows that there is a large period of the bridge's life where its state has not been recorded through the NEN 2767; It is unclear whether data was captured before this in another format.

For Machine Learning purposes this indicates that there has been a long period of influences on the bridge which have not been captured; although it is unclear whether this would have a significant impact on its prediction capacity, it does mean the algorithm will not have all the contextual information that could be available had data been recorded from the beginning.

Inspection interval range

There are large differences in the interval between inspections per government body as can be seen in Table 17. Why these differences are there is unclear at this moment.

The differences in interval inspection means that the data capture between government bodies differs and thus the volume they can capture is different. This means that deterioration can be captured with a higher interval, giving an algorithm more training data.

Inspection history

Table 19 represents the number of inspections performed by government bodies per year. It shows that certain government bodies have been performing NEN 2767 inspections for much longer than others, with most having started since 2019.

The results indicate that most government bodies have only implemented the NEN 2767 for a brief period, meaning that not a lot of information has had the opportunity to be captured. The effect on machine learning means that algorithms have less data to train on, particularly in terms of time. Making it harder for algorithms to currently capture deterioration patterns in components.

2.3.4 Veracity

In this sub-section, the Veracity characteristics of the data are presented. Specifically, the reliability of the data is discussed. Three important points arise from the captured data and the NEN 2767 standard that could affect the reliability of the data: Limitations of a visual standard, Context of defects and changes in decomposition.

Limitations of a visual standard

Because the NEN 2767 is a visual standard there are three points of attention that relate to the reliability of the data.

Firstly, **Because the inspections are only visual it means that only visible defects or manifestations of hidden defects will be found (McRobbie et al., 2015).** In an investigation conducted in the UK, it was found that in a survey of 42 engineers only 50% agreed that a visual inspection would reveal all the defects of interest (McRobbie et al., 2015). According to this same research, 73% of engineers would use tools 60% of the time in inspections. Delamination of the road deck is one defect which occurs often and could be overlooked if just a visual inspection is performed (Graybeal et al., 2002). It suggests that to understand a bridge from more perspectives than just the surface additional information should be gathered from additional sources.

Secondly, **the identification of defects in visual inspection performed by humans is highly subjective.** In the NEN 2767 the standard is referred to as being 'unambiguous' (NEN, 2019). However, due to the nature of the standard involving humans as inspectors making such a statement is quite bold. No studies have been conducted on the unambiguous nature of the standard. There have, however, been studies conducted on the inspection method of the National Bridge Inventory (NBI); this methodology has commonalities with the NEN 2767 as it involves visual inspections with ratings from 0-9, 0 being a failure and 9 being excellent condition. In the study conducted by Phares et al. (2004) where 49 inspectors, from across 25 states, were asked to inspect 7 bridges without using invasive procedures and within a set time limit. It found that 95% of ratings will vary between 2 condition rating points. In addition, there was a significant difference in the amount of damages that were found by inspectors, the highest spotting rate was 88%, with one damage only being noted by 33% of inspectors. Although the NBI and NEN have different methodologies it shows that human subjectivity of how bad a deficiency is can vary and that spotting a deficit visually can be challenging. It could make the results of an inspection much less unambiguous as claimed.

Lastly, **the lack of requirement for images makes verification of defects by government bodies difficult.** Only 2 of the government bodies provide images with their defect documentation; it should be noted however that it could be that images are simply not in the database but are stored at a different location. Images can allow for condition scores to be reevaluated (McRobbie et al., 2015) and improve preparation of interventions and easily accessible overall views of the bridge (Graybeal et al., 2002). In addition, it could allow inspectors to make comparisons between successive inspections possible (McRobbie et al., 2015).

Context of defects

The insights of the NEN 2767 inspections are limited in their scope. Although it records defects it does not say very much besides this. Whether maintenance should be performed, or what implications the defect has on the users, the environment etc. This means that the insights one can gain from the data in the sheets is limited and thus it could be considered hard to make maintenance decisions simply based on this data.

Changes in decomposition

An important aspect, which has not been mentioned so far, is that the list of decomposition assets, elements and components, on which the NEN 2767-4 is based can change upon request of anyone with the approval of the NEN committee. Assets, elements and components can have their names changed, be removed, be merged with another or have additions made (Klepper, 2024; NEN, 2023). If these changes are made it can, however, have profound effects on the data sets of government bodies. Keeping a historical record of one element and components is challenging if the decomposition standard can change. In addition, inspections and data sharing can become even more confusing as an inspector or other government body may apply an older or newer version of the decomposition standard.

2.4 Chapter Conclusion

In this chapter the current state of the NEN 2767 in government bodies was analysed. The sub-question which had to be answered is: What is the current state of implementation of the NEN 2767 in government bodies? To provide an answer to this sub-question, three secondary questions were posed.

1. How do government bodies differ in storing decomposition and inspection data and what implications does this have on machine learning?
2. What additional data is recorded alongside NEN 2767 data in these documents?
3. What are the characteristics of NEN 2767 data, and how do these characteristics indicate data readiness for ML?

In this section the secondary questions will be answered. These secondary questions serve as input for answering sub-question a in the conclusion of this report. This conclusion consists of 3 paragraphs, each which answer one of the secondary questions.

Government bodies store decomposition and inspection data in various ways, some impacting machine learning and some not. Three insights were gained. Firstly, documentation styles differed across bodies; while this has minimal effect on training, it requires extra data cleaning to ensure consistent terminology. Secondly, tracking unique components and their changes over time is vital due to the repeated use of identical components on bridges. However, only one government body has an ID system for linking and tracking components over time, preventing algorithms from monitoring degradation. Third, NEN 2767 defect information is not always recorded in data stored by government bodies. Specifically, information pertaining to what material a defect occurs on, and the severity, extent and intensity are not always record. This means that a Machine Learning algorithm has limited contextual information this would result in underfitting, where a model cannot find patterns due to a limit in information.

A plethora of additional data is collected alongside NEN 2767 inspection data. This includes name of asset, image of defect, risk assessment, general material asset, build year, destruction year, general dimensions, location, and restoration advice. Particularly the built year, location and name of the asset where frequently recorded. The results indicate that government bodies desire to know more about their bridges than is required by the NEN 2767. When comparing the additional data to that used in literature for deterioration models, however, it appears that less contextual information is stored than is used by these models. Suggesting that more should be collected to give a Machine Learning model enough information to provide a accurate prediction of the future state of components.

Various insights were gained about the characteristics of the NEN 2767 from government bodies.

Analysis of the data volume showed there is currently insufficient data to train a machine learning model capable of recognizing all defect configurations and deterioration patterns. This conclusion was drawn from four key insights. Firstly, the main issue was the limited number of repeat inspections, as most assets had yet to undergo a second round. Secondly, differences in recorded assets and components across government bodies impacted data collection; more comprehensive records would allow for faster data collection for predictive maintenance. Thirdly, significant variation in defects found per inspection suggested differences in inspection and maintenance practices, leading to uneven data collection and a need for more training data. Lastly, a class imbalance was identified, with few defects occurring per component, indicating that specialized algorithms and a larger dataset would enhance model effectiveness.

The data variety revealed two key insights. Firstly, government bodies document different numbers of unique components and defects. Since some defects or components may only appear once, sufficient data collection is essential to cover all potential cases. Secondly, differences in the average defect scores between government bodies were noted, diminishing as more defects were recorded. General variations in scoring severity, extent, or intensity could cause data skewness, where an algorithm becomes biased by seeing too many instances of one type, potentially leading to overfitting.

The velocity of the data reveals 3 insights. Firstly, NEN 2767 inspections only cover a small amount of time that most bridges have on average, been in existence; meaning the data covers very little of their deterioration history. Secondly, there are large differences in the inspection intervals between government bodies, this affects the amount of data which could be collected and the resolution at which deterioration is captured. Lastly, NEN 2767 inspections have, except for 2 government bodies, only recently started being recorded. Meaning that a historic database on information is yet to be captured.

The veracity of the data revealed 3 key insights. Firstly, the nature of the standard of the NEN 2767 is visual which means only surface level defects can be recorded, the recording of defects is subjective based on an inspector's perspective and because most government bodies do not record pictures, based on the data collected from them, cannot be verified. Secondly, in comparison to the features used in literature on bridge deterioration modelling, very little contextual information is collected in a NEN 2767 inspection, limiting the insights for a machine learning algorithm to know whether a component will deteriorate or not. Lastly, the NEN 2767-4 can change the terminology used for elements and components and thus it can be difficult to track these overtime if they are documented with a different name.

3. Causes of differences in data and decision-making

In this chapter, the findings from performed interviews with government bodies and inspectors are presented. The aim is to understand what data government bodies store and how decisions are made with that data. This chapter is divided into 4 sections which are related to the four themes in which excerpts were categorized: Potential causes of differences in NEN 2767 data, Additional collected data, Decision-making with data, and Challenges experienced with data. This part ends with a chapter conclusion.

In this chapter the following secondary questions are answered:

1. What causes the differences in the data quality of the NEN 2767 in government bodies?
2. What additional data is collected for maintenance decision-making?
3. How does data play a role in the maintenance decision-making process, and how do these compare in terms of importance?
4. What challenges are experienced when working with the data?

The characteristic of each interviewee is presented in Table 20.

Table 20 Interviewee characteristics

ID	Years of experience in organisation	Organisation	Type of interview
Government representatives			
1	6	Province	Exploratory
2	3	Municipality	Descriptive
3	5	Province	Confirmatory
4	6	Municipality	Confirmatory
5	6	Province	Confirmatory
Inspectors			
1	5	Inspection Bureau	Exploratory
2	10	Inspection Bureau	Descriptive
3	14	Consulting Firm	Confirmatory
4	13	Consulting Firm	Confirmatory

3.1 Potential causes of differences in NEN 2767 data

In this section, the potential causes of differences in NEN 2767 data are explored. The section is divided into 7 sub-sections, each discussing a different possible factor which could have caused the differences in the data collection of the NEN 2767: Purpose of the NEN 2767, NEN 2767 data storage, Interval of inspection, Inspection performer, Choosing inspector bid, Requirements for an inspector, Generation and delivery of data. Table 21 presents a summary of the findings.

Table 21 Potential causes for differences in NEN 2767 data

ID	Purpose of the NEN 2767	Data storage	Inspection interval	Inspection performer	Inspector bid	Requirements for inspector	Data delivery
Government representatives							
1	Uniformity	External system	5	NEN 2767: External Schouw: Internal	Lowest price	Certification	Input data into the system
2	Uniformity	External system	5	NEN 2767: External Schouw: Internal	Lowest price, Trust	CUR 117	Excel and PDF
3	Uniformity, Exchange of info	External system	7	NEN 2767: External Schouw: Internal	Quality	CUR 117, Experience	Predefined data delivery format
4	Uniformity	External system	5	NEN 2767: External Schouw: Internal	Price vs Quality	CUR 117	Input data into the system
5	Uniformity	Internal system	6	NEN 2767: External Schouw: Internal	Quality	CUR 117, Experience	Input data into the system
Inspectors							
1	Uniformity	Own system			Price vs Quality	Internal course	Excel and PDF
2	Uniformity	Paper, Manual camera, Word			Trust	Certification, CUR 117 applied, Experience	PDF
3	Uniformity	Own system			Lowest price	Internal course	PDF but aligned with customer needs
4	Uniformity	Own system				Internal course	PDF and data delivery

1.1.1 Purpose of the NEN 2767: Uniformity

ID	Purpose of the NEN 2767
	Government representatives
2	"Objectively gathering information about buildings and, in our case, bridges, and assigning an objective value to them."
3	"Yes, what it's trying to do is achieve uniformity among all the different things you can find in public spaces. We always say that no object is the same, and even if you place 10 identical objects somewhere, they are still all different." "On the other hand, an objective is also to be able to exchange information. We are a management organization, which is also the department I work in. We also have a project organization, which actually works with and on our objects."
4	"Yes, look, it's a single national standard, right? Many government organizations are starting to conform to it." "For us, decomposition is very important, right? So that we know exactly what a bridge is made of. And, yes, how many meters of railing are on it."
5	"And, you can clearly see that if you don't do it, you end up with a lot of variation, and that's not good for your database, right? Because 'railing' can be written in different ways, right? Railing, railing, construction, railing, balustrade—you name it. But with the NEN standard, you have a single method for that. This way, your database stays clean, and you can perform much better analyses on it as well."
	Inspectors
1	"No, I wouldn't prescribe an inspection method. I would actually... I think the strength of the NEN is precisely that you can identify defects in a uniform way and arrive at a standardized score. That's the strength of the NEN."
2	"Yes. I'm mainly thinking about the inspection report itself and how the inspection is conducted. Yes. I think most people do it in roughly the same way, but ultimately, it's really about the report, right? That's where, well, uniformity in the assessment of the structure comes into play."
3	"It is, I believe, about creating a certain uniformity both in the breakdown of an object's composition and in recording its defects in order to eventually arrive at that score. Yes."
4	"Well, that is about objectivity, so making an effort for consistency. To ensure that it doesn't matter which inspector you have, you can still provide a condition score."

All government bodies and inspectors agreed to the purpose of the NEN 2767: to collect information about structures, including bridges and viaducts, in a uniform manner. All inspectors noted the importance of NEN 2767 in achieving consistency in the results of inspections. This consistency ensures that different inspectors, when evaluating the same object, produce comparable reports, thus reducing subjectivity and ensuring reliability. Inspector 3 highlights that this uniformity is essential not only for consistent documentation of defects but also for enabling comparable scoring across different objects. Another goal highlighted by the representative of Government Body 3 is facilitating the exchange of information. The standard aids in ensuring that different departments or organizations can share and understand data consistently, which is particularly crucial in organizations with both management and project execution roles. Government Body 5 noted a similar note as they mentioned working with multiple inspection bureaus and desiring consistency in results.

Based on these results it can be concluded that all government bodies and inspectors, who were interviewed, agree on the purpose of the NEN 2767: The NEN 2767 provides uniformity and consistency in the results of an inspection. This goal can make working together with inspection bureaus and other governments simpler as was also noted by some of the interviewees. However, when comparing this result to the information revealed in chapter 2 it becomes apparent that there are large differences in how, what and to which level of detail information is collected. Particularly, the way in which data is stored, when inspections are performed and what level of detail in terms of number and uniqueness of components and defects that are considered. Suggesting there is a difference between the perception of government bodies on how effective this uniformity is and what it actually is in practice.

1.1.2 NEN 2767 data storage: Different systems, different origins

ID	NEN 2767 data storage
	Government representatives
1	"Well, we have a management system, [Name], and that's what it's stored in."
2	"How is the standard implemented? We have a management system. In our management system, we will load the data, so that's where we input the decomposition according to NEN 2767-4." "There are differences in the constructions and how the decomposition might be created, and we attach the condition scores to that."
3	"No, we don't report that. That's actually because these types of inspections are loaded into our [name] system, and ultimately, the management system should facilitate us a lot. And that's a nice tip for [organisation] to be able to extract such different notes, for example."
4	"Yes, we have a management system. I won't name any names. Before this, we had a very good management system."
5	"We have a GIS portal. The main system was actually a management system that you purchase, but we also have our own inspection portal, [name], which is an inspection platform."
	Inspectors
2	"Yes. In that sense, we still do it the old-fashioned way. We take the photos separately, and the inspector notes everything on a notepad, so to speak. We don't create the inspection report in the field because we don't find that convenient." "Look, we don't use a software package that includes the NEN, so to speak. We have built our own little system, and we did that intentionally because sometimes you want to override the scores. Because if you fill them out as the NEN requires it may not be what you want."
3	"It's a whole database. Yes, it's just a database. You can access it where everything is stored and thus also reachable."
4	"Yes, what we have for our own system is that you can load the composition into the Relatics system, which you probably know. It has Rijkswaterstaat as well, and we have it as System Matic Insurance and Sweco probably have it too, with a certain layer on top."

A diverse set of asset management systems are applied in government bodies. In the interviews with government bodies at least 4 different Asset Management Systems were mentioned, the names were removed from the findings due to confidentially concerns. 3 of them were created by external parties and one was created internally. The representative of Government Body 2 and Inspector 2 acknowledges differences in how the NEN 2767 standard is implemented and how it should be done 'officially', particularly in the decomposition of structures and scoring. Suggesting that systems not always strictly follow the NEN standard. Inspector 3 noted that their system is probably like that of Sweco, although their 'flavour' may be different; indicating the inspectors believe that the systems differ. In addition, the representative of Government Body 3 indicates that their current system may not fully meet their needs in terms of reporting. Government body 4 noted that they were happier with their previous system, suggesting there are differences amongst them.

The results indicate that interviewees apply different management systems which can have different properties. These results can lead to differences in how the NEN 2767 is applied as was indicated by government body 2 and inspector 2 where they change scores and decompositions which are technically not allowed by the standard. In addition, the quality of the systems may vary amongst government bodies as indicated by inspector 3 and government bodies 3 and 4 meaning that data may not be fully captured in their systems. The different data storage systems could be part of the reason why such variances are observed in how information is stored in chapter 2.

1.1.3 Interval of inspection: Different intervals

ID	Interval inspection
	Government representatives
1	"And, well, that's how the structures were included, and in recent years, we conduct an inspection of our structures every five years. That is done by an external party."
2	"Here in [Government area], it has been decided to inspect every five years, giving you five years to resolve any issues."
3	"Yes, well, what we do is that answers—I can immediately answer a few more questions—but we want to conduct additional inspections every seven years, and we will compare the NEN inspections over time." "Yes, that question will come up again, I believe. But no, well, the choice that is made is actually based more or less on the size of our assets."
4	"And that is the entire determination for maintenance; we do it every five years. We are now going to evaluate whether we might need to change it to four years, and then we will see if that is necessary or not."
5	"Yes. Both. We actually have regular inspections; we do inspections every three years. Now we're moving to once every six years, with exceptions, of course." "The only thing you see then is that it doesn't degrade that quickly, so you end up documenting the same damages very quickly without having repaired them. And that's actually a bit of a waste, also of the money, right? Because you basically get the same condition as three years ago. So, we have now set the interval to once every six years."

All interviewed government bodies have a set interval for performing NEN 2767 inspections, although these vary in time. Three government bodies mentioned an interval rate of 5 years with one mentioning 7 years, and Government body 5 noted they perform inspections either in 3- or 6-year intervals: with them notably switching to 6-year cycles. This was done due to no degradation being captured in the short 3-year intervals. Government Body 4 noted that they were considering switching to an interval rate of 4 years. Government body 2 also noted that the time frame is set due to the ability to then deal with the defect before the next inspection round. Government body 3 noted that their choice was made on the basis of the amount of assets that have to be inspected.

The results indicate that data is collected at different velocities, although 5-year intervals seem the most occurring. These results mean that the velocity of data collection is very low. There are various reasons provided for why inspections are provided in the interval that they are; although there seems to be no agreement and government bodies face reasons for this. This same difference was observed in chapter 2.

1.1.4 Inspection performer: External, but always an internal check

ID	Inspection perfomer
	Government representatives
1	"And in recent years, we conduct an inspection of our structures every five years. That is done by an external party."
2	"We conduct maintenance inspections through an external party, such as an engineering firm, and once a year, we check the structural components for safety. That is a visual inspection, so that's good."
3	"But the visual inspections are conducted by internal staff, while the NEN inspections are carried out by external staff, yes."
4	"Yes, externally. We have a framework contract for engineering services with the [name government body], and yes, every few years, that is re-tendered. That is actually our pool of engineering services from which we have to draw and where we can assign our contracts."
5	"We are now moving to inspections every six years, with exceptions, of course. But since we have such a large portfolio, we need to outsource that."

All government bodies employ external parties for performing NEN 2767 inspections. representatives of government body 2,3,4 and 5 also mentioned the usage of internal staff for an annual safety check, called a 'Schouw'; typically performed once every year. Although this is not in the form of a NEN 2767 inspection they do allow for a form of validation of the externally performed NEN 2767 inspections.

The results of these excerpts show that interviewed government bodies rely on private organisations for their results; suggesting there is a lot of trust in the expertise and objectivity of these external inspectors. However, the use of internal staff for annual safety checks (Schouw) demonstrates a form of internal validation, ensuring that external reports align with the government's own observations and maintaining a level of oversight in the inspection process. In addition, these inspections are once every year, ensuring that there is oversight and that nothing has changed.

1.1.5 Choosing inspector bid: Money, Trust and Quality

ID	Choosing inspector bid
	Government representatives
1	"The results of the tender are handled accordingly. But, well, there are two or three parties that can do that in the Netherlands. Yes, maybe there are a few more, but, well, the contract is awarded based on the lowest price; the lowest price is the most important factor."
2	"And ultimately, we choose different engineering firms that we trust, and they are allowed to bid at the lowest price."
3	"When we have a tender for this, we first look at a plan of approach based on quality, and only then do we open the envelope with the price. That is a deliberate choice because we have the experience that if you invest more in it, you actually get qualitatively better products."
4	Government Body 4 Representative: "Unless, of course, we always ask for a price and a bit of quality. We assess them on that and then apply a weighting factor, and then we always award the contract to the most justified bid." Researcher: "Okay, that's right, so you do take quality into account, but often the price is the final deciding factor. Can I translate it that way, or is it incorrect to say it like that?" Government Body 4 Representative: "Yes, maybe that's a bit oversimplified. We do consider quality, but I have to look at how feasible that is now because they are already awarded based on quality because they are in the framework contract, right? If we know we want a cow, we have to ask for a cow and not something with udders and horns. And that's that."
5	"We always request a sample report nowadays. And if it's a long-term contract, we ask for a pilot inspection. So we say, imagine you have 20 bidders who want the contract, then we say, for that bridge, you need to conduct an inspection according to the NEN in our system, and you have to fully develop it as you think is the best way, because that is actually the best approach." "Price is really the worst factor there is, and I mean that seriously. I have received bids where it was all about price, and then everyone goes for the lowest price, and the one with the lowest bid wins."
	Inspectors
1	"Yes, it's very much about tenders, of course. Governments are awarded tenders, so you often hear about them being invited to those tenders. However, that will depend on the amount; they may need to do it one-on-one, as they have to conduct multiple negotiations to approach several parties. And that is tied to estimates for them; if they think the amount exceeds a certain estimate, they must tender it either European or Dutch. And then, in principle, anyone can bid." "Yes, often, because the price-quality ratio in tenders is very important. Yes, the quality is highly relevant. The Amsterdam region, for example, places a lot of value on the environment, while other municipalities focus more on the quality or the output generated from the substantive products. Well, it varies greatly, as you've already indicated; it seems that each municipality does it differently and distributes data differently."
2	"Yes. I think we get the masterpiece one-on-one, so it's really about the relationship you have and what you've done in the past. So yes, results from the past are indeed the most important reason we get work, and of course, it also needs to be competitively priced."
3	"Nine times out of ten, it's the lowest price, yes."

A difference can be observed in the ways in which Government Bodies choose inspectors, often choosing between price and quality. Government Body 1 and Government Body 2 both emphasize that the lowest price is a primary factor in awarding inspection contracts. Inspector 3 also emphasized that 9 out of 10 contracts are rewarded on lowest price, indicating further that this is a widespread practice. Although price plays a large role in the choice of inspector trust and experience were also often mentioned. Government Body 2 stated that they choose engineering firms they trust, indicating that while cost is crucial, established relationships and confidence in the vendor's capabilities play a role in the selection process. Inspector 2 also mentioned that past performance and relationships often aid in securing contracts. Government Body 3 and 5 mentioned that they place more emphasis on a quality-focused approach, looking at the plan of approach and quality before considering price. A key additional insight into this is the affect that a contracts value has on what procedure can be taken. Government Body 4 says they seek a balance between price and quality, although cost is often the deciding factor. Inspector 1 takes a more nuanced stance and suggests that the price vs quality depends heavily on the government body and its wishes. In addition, it was noted that this flexibility is linked to the contract's estimated value and legal requirements, such as needing to go through European or national tendering if the value exceeds certain thresholds.

The results indicate that there is no agreement amongst the interviewed government bodies on what is the deciding factor for choosing one inspector over another. Assessing whether these variances in priorities were caused by a difference in experience or what organisation a government body worked yielded no clear patterns. Government body 1 and inspector 3 which both noted that price is often the determining factor both had a breath of experience on the high end of their interviewee grouping. However, government bodies 3 and 5, with similar experience levels to government body 1, noted that quality is more of a determining factor. Inspector 2 with similar levels of experience to inspector 3 notes that trust is a key factor in being chosen as an inspector. Government body 4 and inspector 1 note that particularly a nuance between the two factors is required. The lack of a trend suggests that it is simply a choice of government bodies on how they determine what criteria are important when choosing an inspection bid. This could result in government bodies receiving different levels of quality from their inspections. Another question that emerges from this is: What is quality in the context of inspections? Defining quality in this setting requires an examination of both the technical accuracy of the inspections and the consistency of results across different inspectors and organizations. Although the CUR 117 could give a handle on this. These different philosophies in choosing inspectors could be part of the reason why in section 2.3 on data characteristics such differences are seen in the data captured. Having a higher or lower resolution in the number of components per asset as well as the number of unique components and defects recorded could differ due to an Asset Managers decision on price vs quality.

1.1.6 Requirements for an inspector

ID	Requirements for inspector
	Government representatives
1	"Certified; He must be certified."
2	"We do our request for the inspections you need, right? We make a request via the CUR 117, and we set requirements with that." "But no, because I don't think there's any certification in the Netherlands for the inspector."
3	"Additionally, we also have the inspection methodology of the CUR 117, another great abbreviation. I don't know if you've come across that yet." "Exactly, well, we have also declared that applicable to all our inspection standards, which means that you always receive your inspections back in the same standardized manner based on the same standards, and those inspections are then aligned with the NEN."
4	"Also, using NEN 2767 and CUR 117, and based on those inspection results, I create a multi-year plan."
5	"Yes, you have CUR 117, right? That is the standard for all inspections, actually. What we say is that we want condition inspections. It should be B2 with a B5 repair recommendation and a C rating for risk assessment in the C2 MLP (multi-year maintenance plan). That's what we ask for, and the course also states that the lead inspector must have at least five years of inspection experience."
	Inspectors
1	"So, that's not how I see it. We do it internally. Yes, there are parties that offer courses, but we always provide internal training. It's not that a NEN course is required; it is sometimes required in tenders that a course is indeed followed. Well, we try to, yes, we don't find added value in that, so to speak, because it's about the inspection itself."
2	"Yes, yes. Yes, certified; they all have completed the training, right? Or the course, or the training they have completed"
3	"We are pleased with that; every inspector has completed the NEN 2767 inspection course. So, they are informed about the naming of your decomposition, the formulation of defects, intensity, scope—just all the knowledge to fill that out as accurately as possible."
4	"What you see is that I've created my own e-learning for NEN 2767. It lasts about 2.5 hours. In it, the basic things like decomposition and related scores are covered, but also risk assessment is included. And I would actually say, you have that, of course, but there's also just a bit of our own twist on it. How do we do it, right? What I find important is that you..."

There is disagreement whether an inspector can or cannot be certified amongst government bodies. Government Body 1 states explicitly that inspectors must be certified. Inspector 2 confirms that certification is often required, with inspectors needing to have completed relevant training or courses. However, government body 2 emphasized, that to their knowledge, no specific certification requirement for inspectors exists in the Netherlands. Inspector 1, 3 and 4 mentioned that all their employees have followed a NEN 2767 course to ensure they are aware of decomposition terminology and how defects are recorded. While formal NEN courses are not always required, some tenders might request specific training, but this is not uniformly enforced. In addition to this Government Body 2, 3, 4 and 5 emphasizes adherence to the CUR 117 standard for inspection methodology but does not explicitly mention certification as a requirement. The CUR 117 does have aspects to it which allow for setting requirements for an inspector. Inspector 2 also mentions that the inspection requests are often based on the CUR 117 standard, but not always fully complete. Government Body 3, 5 and Inspector 2 both highlighted the importance of experience and past performance. Inspectors are often selected based on their previous work and the relationships they have built with clients.

The results show there is disagreement amongst interviewees what should be expected of inspectors for them to be qualified to perform an inspection. Many inspectors noted that they perform internal training of some kind to ensure their inspectors at least have a basic level of knowledge on the NEN 2767; however, this appears to not be standardised. Despite these differences in certification/training the CUR 177 provides some grip on what can be anticipated of inspectors. Despite the CUR 177 providing some standardisation, is in a way a selection menu, where requirements can be chosen freely by government bodies on what they want; thus, still limiting the standardisation. **It can thus be interpreted that there currently doesn't exist, or that interviewees are not aware of, a standard on what a NEN 2767 inspector must be capable of.** This again can be part of the reason why section 2.3 revealed such differences in the data which is collected by government bodies; an inspector held to a higher standard or with more training than another may spot more and unique defects than one with less experience.

1.1.7 Generation and delivery of data

ID	Generation and delivery of data
	Government representatives
1	"They enter their reports into our system, and they also have the right to do so themselves." "So now we have what's called ILS (Information Delivery Specification). You may have heard of it—it's our specification for information delivery."
2	"We have asked for our data to be provided in Excel, so we request positions that conform to the NEN standards. The requirements related to risk assessment are also included, so we don't have many external requirements on top of those standards. We also receive PDFs, and this is beneficial for various reasons. For instance, when we place all the photos separately in our system, it can be quite cumbersome to open them individually. If we can access everything in a PDF, we can quickly review it and have all the information together."
3	"We receive all reports, both as raw data, which includes an interchangeable CSV format, as well as actual PDF files and Excel spreadsheets. We have already thought about what we include in this, so there are established selection lists in there. These selection lists are based on standards, for example."
4	"It always goes in a PDF; we receive it and it has to be processed in our management system. So we also have management system X. In the request, all the data must be processed in our management system."
5	Government Body 5 Representative: "Yes, yes, with us. We have our own system. The Amsterdam Inspection Portal processes everything directly in there, and that's also their delivery, right? So we actually receive a filled database, and that database contains all the photos, an analysis, a summary of the defects, and your planning and your LP." Researcher: "Okay, so that all goes directly in there, so you guys aren't messing around with PDFs and stuff? " Government Body 5 Representative: "No, no, no, certainly not. No, we don't do that anymore."
	Inspectors
1	"We essentially always deliver a report in PDF format, but we also always provide the data that corresponds to it, so the variable data that you gather. That includes the extent and intensity that I deliver, but we also always provide a recent summary."
2	"We have a Word format where that calculation from the people is included, along with the choice fields from the NEN regarding severity. Well, less than 2%, two out of ten, so we have that, and then we drag the photos in. And then, well, the rest follows naturally, so it's semi-automated." "Well, you have an explanation about the NEN, how it works. Then you have the decomposition with the scores, and the defects, and the scores, and the photos. And then you also have a summary of the different parts, and we provide an overall score. If we need to give a recovery recommendation, you get a list of measures for that. Yes, and those measures go into Excel. Yes, yes, yes, yes."
3	"They always think about which columns and which data fields you need. We can generate a specific export that aligns with the customer's needs" "Nine times out of ten, a delivery report is generated per object. That's also the case for us. It's automated, actually, yes, without a lot of manual actions involved, and there's also a total file for importing into the relevant systems, and that is usually an Excel file."
4	"Well, in any case, the little program we've worked with. And we use a lot of our own tools. For inspections, we use a lot of Fulcrum, so you can set it up completely yourself. You can beautifully integrate that framework with the decomposition." "Just a PDF, so with the legend, showing the decomposition and what the scores are per construction component."

There are different ways in which government bodies receive data as well as how this data is initially recorded by inspectors. Four of the government bodies indicate that they receive both reports, in the form of PDFS of completed inspections, with more provided context as well and raw 'NEN 2767' data, often in the form of Excel. Thus, receiving both structured and unstructured data. Government Body 1 and 4 allows inspectors to input data directly into their systems, whereas Government Body 3 has a structured approach with predefined data formats (e.g., CSV) and choice lists based on specific standards like NEN. Government Body 5 noted that they do not receive any written reports and rather request that all data is immediately imported; they can then themselves generate reports. These findings are supported by interviews with inspectors. All four inspectors note that they provide data in different formats, such as PDFs and/or excels. Inspector 3 notes that they customize data exports to fit the client's needs, which implies that data fields and structures might differ from one project to another, depending on the specific demands of the government body involved. The gathering of data and then creating reports or excels from them differs a lot amongst inspectors. Inspector 2 relies on a more manual process (using a notepad in the field) after which the information is placed in a computer.

Inspectors 1, 3 and 4 note using digital tools for capturing data. Inspector 3 and 4 notes they can generate reports automatically through their software.

The results indicate that there is no uniform process amongst interviewed government bodies on how data is received. This could cause data to be lost, wrongly formulated or stored. Firstly, data is collected in various ways by inspectors either through their own software or manually. Secondly, it is often then processed in various ways, such as generating scores or digitising results. Third, Data is delivered in different formats such as PDF's and Excel sheets, each which can include different information: this will be elaborated on in the next section. Government bodies 1, 4 and 5 do note that they allow inspectors to directly input information into their system; but if data is firstly captured on another system loss may still occur. Government Body 5 was the only one which noted that they expect inspectors to use their system to directly input information; they do not receive any reports or Excel files. These differences could be why certain data is missing in

3.2 Additional collected data

In this section the additional collected data by inspectors and government bodies are explored. The section is divided into 7 sub-sections, which each discuss a type of additional data which could possibly affect decision making: Other types of inspections, RISK assessment, Intervention suggestions, Pictures, Recalculations, Longevity assessment, other information collected by inspectors. Table 22 presents a brief overview of the findings.

Table 22 Noted additional data which is collected from excerpts.

ID	Other types of inspections	Risk assessment	Intervention suggestions	Pictures	Recalculations	Longevity assessment	Other information
Government representatives							
1	Schouw, Concrete testing	X	X		X		Physical Characteristics
2	Schouw	X	X	X			Dangerous situation
3	Schouw	X	X	X	X	X	Possible failure modes
4	Schouw, Electrical systems	X	X				Physical Characteristics, Technical drawings
5	Schouw, Electrical systems	X	X	X			Physical Characteristics, Dangerous situation
Inspectors							
1	Electrical systems, mechanical inspections	X	X	X	X	X	Dangerous situation,
2	Electrical systems, mechanical inspections, Underwater inspections	X	X	X		X	Dangerous situation,
3		X	X	X			Dangerous situation,
4		X	X			X	

3.2.1 Other types of inspections

ID	Other types of inspections
	Government representatives
1	"Or well, should we maybe do something additional, right? We've done similar things with bridges too. Conducted additional studies, so we know from the concrete what concrete quality was used at the time, pulled out pieces of reinforcement to check, like, okay, what is it now, right?" "The quality of the reinforcement used back then, right? Then you know exactly, right, what's in it, and also followed up with the scan, right? Because you can do that really nicely nowadays too." "During that interim period, we also have to keep a close eye on things, of course. So we do, let's say, an annual check-up for the yearly maintenance, then they do a walk-through, right? Because it's a structure."
2	"...and once a year, we inspect the structural parts for safety. That's an Schouw, so that's good."
3	"There's a distinction between a Schouw and a more thorough assessment. There's still some occasional confusion about that, but we do a yearly schouw of our objects and assets, while the more technical assessments occur on a seven-year cycle, or according to the seven-year condition-based frequency."
4	"Multi-year budgeting, right? The data from the inspections follows a five-year inspection cycle. That's essentially the main part, but it can still be supplemented based on what we observe quarterly outside. And yes, we handle that internally; our own people take care of it." "Yes, those kinds of things, like asbestos inspections, we always do separately, right?" "Yes, a follow-up inspection is based on the measures, right? We conduct an inspection, and, for example, it shows that we need to do some conservation work. A follow-up inspection would then check for things like the presence of chromium-6." "Yes, with asphalt replacement, right, you also have to do drilling, then you start digging, take soil samples, so there's that." "Yes, we see a certain scale of damage, and if it's quite serious, then we look into whether there's more going on. For example, is there chloride ingress or similar issues, right?"
5	"Once every two years, we have a regular inspection, and then I also monitor the follow-up studies, right? Diving investigations, concrete assessments, deformation measurements—those are all studies that you often conduct as well." "Additionally, we do conduct an inspection every year, right? So because we carry out that inspection, we stay informed about the safety risks that are present, and we can then perform the regular inspection once every six years."
	Inspectors
1	"Besides the NEN 2767, we also conduct electrical safety inspections and various other standard inspections." "But basically, we do everything in movable infrastructure, inspecting or monitoring with sensors, measurements, and hydrological analyses. Yes, we cover everything that you can actually inspect on a bridge or anything related to maintenance. Yes, we are often asked for our opinion on that."
2	"Yes. Yes, we use an underwater drone." "And if a recommendation for further investigation is desirable, we provide that as well." "And we also use AI to assess damages."

Different forms of inspections, besides the NEN 2767, are mentioned by government bodies and inspectors. A 'Schouw' is mentioned by all five government bodies, which is yearly check of their assets. Notably, these inspections are noted to be performed by internal employees by all government bodies. No government body mentioned that data is generated from these inspections. All five government bodies differentiate between regular inspections, which is the Schouw and more thorough, technical inspections, which can be those of the NEN 2767 or further investigations. Government Body 1 noted conducting additional investigations on structures like bridges, such as testing the quality of the concrete and scanning technologies to verify the actual presence and placement of rebar. This involves physical sampling and analysis to understand the material's condition and whether it matches original specifications. Both Government body 4 and 5 noted that additional investigations into electrical systems are also conducted as these fall outside of the scope of the NEN 2767. Inspector 1 and Inspector 2 discuss conducting inspections beyond those required by NEN 2767. These include electrotechnical safety inspections, mechanical inspections (such as on gearboxes and bearings), and even hydrological analyses. Inspector 2 mentions the use of an underwater drone with imaging sonar to inspect underwater structures in conditions where visibility is poor, as well as using AI to identify damages.

The results indicate that from the body of interviewees, government bodies require more insights than simply the NEN 2767. The electrical systems, as well as the mechanical inspections are specifically performed because of the limitations of the NEN 2767 in its breath; the standard might not be able to capture the nuances required from complex technical systems. In addition, the Schouw is, likely, performed due to the NEN 2767 being too in-depth and thus requiring an extensive inspection; government bodies want to keep an eye on assets and ensure they are safe all year around. What is revealing is that it is unclear whether any information is stored on these inspections. Chapter 2 only analysed NEN 2767 data, and it could be that additional information is collected on, for example, the Schouw, which if in a similar format to the NEN 2767 could improve the data velocity significantly. However, based on experience it is believed that his is not the case currently.

3.2.2 Risk assessment

ID	Risk assessment
	Government representatives
1	"In the last two inspection rounds, we also had the structural safety assessed, so the risk assessment of how the structural safety is, meaning the calculations in our management system—do they provide sufficient assurance?"
2	"Yes, yes, except that it doesn't quite cover everything, so we still have additional risks on top of that." "Yes, we don't have a principle, so we have, yes, it's a—what is it? It's a kind of Rijkswaterstaat RAMS risk assessment. Those are simply the disk risks. I recognize [Confidential statement]. They are actually more important; how something looks good or not is secondary. The risks that are present are more important than the visual quality. So if there is a risk, it's addressed immediately. Yes, exactly."
3	"Yes, well, we base it on CUR 117, so we request a B3 and B5, C1, and C4 inspection. Long live standardization, because every report looks exactly the same based on the standard." "But we create an FMECA scheme for each object. The findings made by the inspector outside are based on risks and are applied accordingly. Then, RAMSHEEP is overlayed on top of that."
4	"We have conducted a risk inventory at the object level, and it shows, right? The movable structures have a very high risk because if they fail, the consequences are significant. And we have, yes, assessed other types as well, whether it's a small bridge or a viaduct." "We have indeed used a RAMSHEEP as well. I believe we left out one or two letters; I'm not exactly sure how or what, but we have conducted some FMECA analyses on that."
5	"We also have the object data verified. So, length, width, number of spans (...), and risks and measures, and then you have it, yes." "The inspection plus, as I like to call it, right? Because we conduct the condition inspection, we do the risk assessment, and we also carry out the MLP."
	Inspectors
1	".....Then it may be that we have agreed to conduct an additional risk analysis based on defects in our case, but usually, that is also very superficial." "Well, those risks are often reviewed. Yes, of course, you can make it very detailed, using the defects from the NEN for a complete risk analysis for the lifespan. Yes, those are analyses we do not conduct on-site."
2	"[Talking about their software] We can also incorporate risks into it, which I think is the best part. But yes, well, that will go beyond NEN, right?"
3	"One client has their own RAMS sheet in order, as we need to use; sometimes they don't. Then we propose this, which is a general one that we often apply, and then an [not understandable] is overlayed, and it gets implemented."
4	"And the problem is that you think, oh, it's not that bad, while it really is a risk. So that score needs to be polished up in a risk analysis, as you mentioned." "Well, it's not a condition inspection that you typically conduct a standard risk analysis with. I would recommend it, though; we have often done that to establish prioritization."

All government bodies note some form of risk assessment in the interviews. Government body 1 Mentions incorporating structural safety assessments and risk assessments into their inspection rounds. Government Body 2 References that the NEN 2767 doesn't cover all risks, so additional risk assessments are conducted, particularly using a method like Rijkswaterstaat's risk assessments. Government Body 3 mentions the specific modules of the CUR 117 which they request, one of which is a risk assessment. All four inspectors also mention performing RISK assessments. Inspector 1 Mentions performing additional risk analyses, especially when safety issues are identified, such as loose railings on a bridge. Inspector 2 Talks about integrating risks into their reporting and mentions using an external risk assessment framework when needed. Inspector 3 Mentions using a RAMS (Reliability, Availability, Maintainability, and Safety) framework, which includes risk assessments as part of the maintenance planning process. Inspector 4 noted the contextual importance of a risk assessment "The problem is that you think, 'Oh, it's not that bad' while it actually is a real risk, so that score [The NEN 2767 score], needs to be improved in a risk analysis."

The results indicate that the consideration of risk is a large factor amongst the interviewed government bodies and inspectors when considering maintenance actions. How this risk is quantified was not made apparent by all interviewees although inspector 3 mentioned RAMS. This could suggest these risk assessments are performed in different ways; indeed, the analysis performed in chapter 2 shows that, for example, Tilburg and Amsterdam perform these differently. However, it is surprising that only these two have the information stored in their excel sheets if this additional form of information is so prevalent. It suggests that this information is stored differently, perhaps in PDFs as these were often mentioned in subsection 3.1.7.

3.2.3 Intervention suggestions

ID	Intervention suggestions
	Government representatives
1	"Only then we leave it up to the market, like, okay, well, this is the sum of it. This is the bridge, now tell us, what would you advise? Well, is it wise to reinforce it, but how are you going to reinforce it? Because there are, of course, different methods for that, right? Can you raise it? You can apply pressure layers, or do you need to put laminates underneath? Or, well..."
2	Yes, yes, except that it doesn't quite cover everything, so we still have additional risks on top of that? Yes, we have photos; we have that, and then estimated costs as well."
3	"Yes, well, we base it on CUR 117, so we request a B3 and B5, C1, and C4 inspection. Long live standardization, because every report looks exactly the same based on the standard." "And in addition to that, advisory maintenance costs were included with a yearly plan."
4	"I also follow the NEN 2767 and CUR 117 standards, and based on those inspection results, I create a multi-year plan and a multi-year budget. I indicate how much money is needed. I am also a budget holder for the maintenance budget, and each year we create an implementation plan where I specify what needs to be done. I group the maintenance tasks a bit and assign them to project leaders."
5	"The inspection plus, as I like to call it, right? Because we conduct the condition inspection, we do the risk assessment, and we also carry out the MLP (multi-year maintenance plan)."
	Inspectors
1	"Because there is also a difference in the compositions; some clients want everything to be decorated, everything that is physically present, while some policy makers only want the costs." (The costs hint that intervention suggests are asked for)
2	"Yes, I... yes, we do indicate that. Usually, we then create a a a a a list of implementation measures based on our findings for the next five years."
3	"An explanation regarding the condition, maintenance costs, the inspector's data, and the [unclear what is said] is recorded, along with the decomposition of defects." "A list and a multi-year maintenance plan with costs, if that is desired."
4	"And what happens next is that the function, function failure story, and the causes are linked to the maintenance tasks that have been established as the standard. The MTFS, right, which indicates how long something lasts. Based on, for example, the current year and this year's installation, the probability is also determined, right? The probability scores. There are specific steps in that: a score of 1 is for more than 20 years, 2 is for 6 to 20 years, and so on; the probability increases that something could fail." "Part of a fixed team are described. Well, and what you then see is that you have the boss, and we often try to have two or three people with a specialization as well. So, for example, we have three concrete maintenance experts and a few steel experts who have graduated in structural engineering."

All government bodies within the study ask for intervention suggestions in some form from inspection bureaus. Government Body 1 notes that the decision on specific interventions is left to the market. They provide a general description of the problem but rely on external experts to suggest precise methods for addressing the issue, such as structural reinforcement options. Government Body 2 and 5 supplement their Risk assessments with estimated costs for interventions. Government body 3 and 4 through the CUR 117 ask for interventions, cost estimations together with their risk assessment. All inspectors note that they also perform some service which includes intervention suggestions. Inspector 1 notes that the level of detail in recommendations varies depending on the client's requirements and policies regarding decomposition. Some clients may request detailed, itemized suggestions, while others may only need higher-level cost estimates. Inspector 2 and 3 provides a list of maintenance measures based on their findings but does not usually consider aesthetic aspects or broader risks unless specified. Inspector 3 notes that they prepare detailed maintenance plans, including cost estimates and future upkeep schedules. Inspector 4 noted they have specialists in materials, such as concrete experts, who can determine what maintenance will be required for a given defect.

The results indicate that the interviewed government bodies place a level of trust in inspectors to choose the right interventions based on their experiences. Although the way this data is delivered differs the goal is the same: To provide the government bodies with some guidelines on what money they can expect to spend on a bridge. This data was also seen in subsection 2.2.3 where three government bodies stored this information in their system. However, this is still not many government bodies based on the fact that all government bodies and inspectors mention this additional data being collected; suggesting again the information is stored somewhere else, perhaps again PDF documents as mentioned in sub-section 3.1.7.

3.2.4 Pictures

ID	Pictures
	Government representatives
2	"Those are PDFs, and it actually relates to various things. If we store all the photos separately in our system, it can be quite cumbersome to open each one individually. If we can open a PDF, you can quickly go through everything. You have that information all together."
3	"Then all the general object data, including a description, overview photos, characteristics, dimensions, and location, are shared. The inspection results then come forward, along with any comments, followed by the NEN 2767 decomposition of that object. Additionally, all photos of all elements are shared. We have a separate chapter with all analyses, where defects and measures are included."
5	"Yes, yes, with us. We have our own system. [municipality name] Inspection processes everything directly in there, and that serves as their delivery, right? So we actually receive a filled database, and that database contains all the photos. It includes an analysis, a summary of the defects, and your planning and LP."
	Inspectors
1	"On one hand, we always take photos of all the construction parts we see. This is partly to show what we mean by a construction element. However, we don't take photos of elements because an element is, of course, a collection of construction parts."
2	"We don't find that convenient. We have experience with it when working for large firms. But, well, then you need to take a front view photo of a bridge as the first photo for the report. Then you take that photo, and it has to be uploaded. You have to wait because the system only proceeds once that photo is uploaded."
3	"Nine out of ten times, it's the client's wish to have every construction part photographed. We also have clients who only want it at the element level. Well, that's fine; as I said, you ask, we deliver, but the standard is to photograph at the construction part level."
4	"You can also include your old defects so you can say, okay, it has remained the same or add a few new photos."

Images are a common part of the process of performing a NEN 2767 inspection amongst interviewees. Government bodies 2,3 and 5 mention being provided pictures or taking them when inspecting. Government body 2 and 3 note that their pictures are all saved within the PDF reports which are received. Government body 5 noted that their images are directly stored within their digital system. All inspection bureaus mention taking images when inspecting. Inspector 1 mentions that photos are taken of building parts to document the findings accurately. While detailed photos of components are taken, elements, being collections of components, are generally not photographed in isolation. Inspector 2 describes a more manual approach where photos are taken with a separate camera and then uploaded to a system, where pictures are chosen. Inspector 3 standards practice involves taking photos of each building part, though some clients may request photos only at the element level. Inspector 4 notes that even if nothing has changed, they take pictures to prove that they were at that given location.

The results indicate that interviewed inspectors take pictures mostly for purposes of validating that they have been at a location and to document defects. Most of the note taking pictures regardless of whether a defect is present or not. Of the government bodies which noted that they received images of their defects their storage solution differed; having them locked in PDFs could make purposes such as machine learning from defect images more difficult but also tracking these defects overtime and verifying their scores. Images are stored by two government bodies as revealed in sub-section 2.2.3; this is again most likely due to the images being stored in PDFs.

3.2.5 Recalculations

ID	Recalculations
	Government representatives
1	"That the calculation made at the time meets, let's say, the current Euro guidelines, or do you assess that in a completely different way? And so that check is also something we are doing now."
3	"Enthusiastically, the combination of that—when you look at a recalculation, we do not blindly recalculate our entire inventory. We first look at what information we have about an object; that is straightforward. Then, based on the NEN condition score, we assess what the current condition is."
	Inspectors
1	"Yes, we sometimes do a calculation for certain clients where we do a lot of work. In those cases, we do not conduct the recalculation ourselves, but we arrange for it."

Two government bodies note that they have been in situations where recalculations of assets was necessary; this is where bridges are tested on their carrying capacity. Government body 1 notes that recalculations are performed to ensure that existing structures meet current regulations and guidelines. An example is given where a bridge's structural capacity was re-evaluated by a different firm after initial concerns were raised. Government Body 3 mentioned that rather than recalculating every object, this body prioritizes recalculations based on the condition and available information of the object. If an object shows no significant damage or risk, recalculation is not deemed necessary. Inspector 1 also mentioned that recalculations are sometimes performed based on specific client needs or conditions. These are, however, not performed directly by the inspection bureau and more often by other organisations.

The results indicate that sometimes structural evaluations are required in the context of asset management. What is notable is that the two government bodies who did note they conduct these investigations were both part of provinces. These roads tend to experience more and heavier traffic than for example small bridges mostly meant for pedestrians or cyclists in cities. Although it cannot be concluded from the limited number of interviews it is believed that these recalculations play a large role in maintenance decisions for asset managers in provinces. This additional data was not found when investigating government data in chapter 2; most likely as it does not pertain to the NEN 2767 and recalculation data was not requested when contacting these government bodies.

3.2.6 Longevity assessment

ID	Other information collected by inspectors
	Government representatives
3	"Additionally, we advise maintaining the cost with a plan each year, and that is in addition to extra questions that also come from a risk analysis, a preliminary estimate, and a remaining lifespan analysis. All that information is included in a report and a data system."
	Inspectors
1	"....Those risks are often looked at in detail. Yes, of course, you can make it very extensive, using the defects from the NEN for a complete risk analysis, indeed, for the lifespan. Yes, those are analyses that we do not perform on-site."
2	"Well, everything we know for now, the type. Well, the length obviously comes from the length of the shapefile, the condition, the defects. Well, expected remaining lifespan, all those things. Also indicate that in the shape, which I personally find a very nice method. Only then, the client must be able to work with it as well."

4	"Knowing something about the remaining lifespan of components. We have sometimes, in a very rough manner, discussed with the client, saying, okay, we'll use that curve, right? Score one is new, score two is halfway through its lifespan, score three is 75%, score four is 87%, and so on down to 100%, but yes. That is very rough, so that is extremely basic. It's like fixating on certain standard steps while actually overlooking whether it is truly realistic."

A diverse set of interviewees noted that they consider or provide longevity assessments. Government body 3 noted that based on the CUR 117 data they require of an inspection reports include a Longevity assessment. Inspector 1 noted that the focus of longevity assessments often includes evaluating safety risks and structural integrity. Inspector 2 also noted that they provide a longevity assessment through QGIS data. Inspector 4 noted that they have used the deterioration curve, which is included in the NEN 2767 standard to determine the degradation rate of a component; although this was to illustrate a point that this most likely does not capture reality.

The results indicate that the interviewed inspectors have been requested to estimate the longevity of bridges, as well as one government body asking for such estimates: thus, illustrating a demand for such predictions. How such assessments were made was not entirely clear and could be done based on experience by inspectors. This information was also seen in some way in sub-section 2.2.3 where the destruction year of bridges was recorded. However, longevity assessments on a component basis were not revealed.

3.2.7 Other information collected by inspectors

ID	Other information collected by inspectors
	Government representatives
1	"Yes, because I thought, well, if the person is already there, just check what might be missing in our system and add it. I mean, length, width, height, color, and so on."
4	"Of course, archive records from construction, structural drawings, and such are also important. We have a large paper archive, and we've fully digitized it so that everything can be viewed digitally through our management system. We know all the drawings we have and have an overview of them, so we can quickly look things up." "We always check the passport information—like length, width, and height. We also did it last time, and it was completely clear. All clearance heights, widths, drive-through heights, and widths were all measured."
5	"We also have the object data verified—like length, width, and number of spans. Those sorts of things, because ideally, it should be static information. However, you often see that it's not always accurate. For instance, it might be because something was renewed, widened, or frequently replaced, but it hasn't yet been updated in the system. So we also have that checked. Yes, essentially, and as for risks and measures, that covers it." "Yes, they must report any serious defects that pose a safety risk immediately. They will also record these in their inspection, but if safety is an immediate concern, they must call right away." "There are longitudinal beams, but, for example, you don't always know the type of longitudinal beam, or what colour coating it has. Do they have RAL colours? That's interesting information, because if I'm going to paint the bridge, I want to quickly see, okay, it's that RAL colour, so the contractor can immediately order that paint. Chrome-6, which isn't included in the standard, should also be registered as part of the inventory. So we have added some details to the NEN standard to have more information. You'll notice that the standard, particularly with movable structures, is very focused only up to the construction part level, but for movable assets, you often need to go a bit deeper. This allows you to register sub-parts. We refer to them as appearance forms, and we also use those."
	Inspectors
2	"Yes, yes, what we can also do, though it depends on the type of project—look, we work a lot with retaining walls and so on, and we do that via QGIS. Do you happen to know it? Well, we load the retaining walls as shapes into QGIS and then include all relevant information, like the type, length (taken from the shapefile), condition, defects, expected remaining lifespan, and so on. I personally think that's a great way to present it. But of course, the client needs to be able to work with it as well." "Yes, if we, if we come across an, an, an, an unsafe situation, we call the client right away."
3	"Everything location, GPS." "Sometimes a location description is desirable for a construction part, whether it's the span or which support point it concerns." "From that, it's often safety and structural, right? If there are really strange things, then we raise the alarm as an emergency."

There is a range of other data which is uniquely collected by different government bodies and inspectors. Government Body 1, 4 and 5 noted that Inspectors are asked to record detailed characteristics of objects, such as dimensions (length, width, height), colour, and other relevant features. Government body 4 also noted that they store historic technical drawings and information of their bridges. Government Body 3 noted the usage of a Failure Modes, Effects, and Criticality Analysis (FMECA) is used to assess risks based on inspection findings. Q-GIS files were mentioned by inspector 2 as being provided to government bodies if they had the capacity to work with them. Q GIS data was noted to include detailed attributes such as type, length, condition, and expected lifespan. Inspector 3 also noted location data and could provide additional location descriptions are needed, such as specific details about the construction elements being inspected. Government Body 2 and 5 mentioned that Immediate communication is prioritized when a direct danger is identified during inspections. Inspector 1, 2, 3 mentioned that they would also immediately provide information if an inspection revealed a dangerous situation. Inspector 3 even noted that inspectors are expected to notify clients immediately about critical issues, such as structural safety concerns, rather than waiting for formal reports.

Ther results indicate that the interviewed government bodies desire more information about their assets that is required from a NEN 2767 inspection. Different attributes were mentioned but all pertain to physical characteristics of the bridge. In addition, government body 3 noted a deeper insights into what possible failure modes may occur on bridges; giving them heads-up on challenges which could occur. Mediated communication if a serious problem occurs was mentioned by both government bodies and inspectors. It remains unclear whether information from such occurrences is stored in a system. Some of this information was also stored in sub-section 2.2.3, but not all of the unique data was found.

3.3 Maintenance decision making with data

In this section the additional collected data by inspectors and government bodies are explored. The section is divided into 4 sub-sections, which each discuss a different form of data which affects the maintenance decision process: NEN 2767, Risk assessment, Contextual Information, Changes in situation.

3.3.1 NEN 2767: The first step

ID	NEN 2767: The first step
	Government representatives
1	"Yes, look, if you have that NEN inspection, I mean, then you're talking about... God, what am I missing? Well, then I'm still not missing €20,000. Yes, for the bridges in, in, in [Location of a dike]. So, the inspection, yes, about €20,000. And if you're talking about replacing the bridge, then you're already talking about 300.000..."
2	"So, then we receive the inspection reports and the info, and then it is time to get to work. Yes, we say 'No, more is needed,' or 'The quantities are actually a bit less.' And, oh yes, we need traffic measures and aids? Yes, so yes, that."
3	"Based on the condition score, but what we also have are our risk analyses per object. In those analyses, we look much more at the environment of such an object rather than just the technical side, and we also consider the structural safety. We know everything about that object; we have all the drawings, we know what types of classes are in it, which concrete classes, all those starting points together actually ensure that you can make a good decision about an object." "Well, based on the NEN, for example, an additional investigation comes forward. This additional investigation does not fit into the NEN system for certain damage patterns that are observed in the Netherlands. However, the investigation indicates, and the two other aspects will be the risk analysis, you know."
4	"But it is a measurable instrument, and all our structures have a condition score of one, two, or three at the object level. Previously, with the NEN, this couldn't be done; it was only at the component level. Now it can be determined at the object level. And we always look at what the risks are when we schedule maintenance. We always weigh performance, costs, and risks." "Also, we use NEN 2767 and CUR 117, and based on those inspection results, I create a multi-year planning."
5	"Well, that is the technical condition. Yes, that is the most important thing for us to make a decision on. If something needs maintenance, all those other factors are secondary; you think about them, but if a bridge requires maintenance..."

All five government bodies noted that the NEN 2767 is often the initial step for investigations and can lead to further inquiries to be conducted. Government body 1 mentioned that the investment costs of such inspections, per asset, are very low when compared to other studies such as a recalculation of structural safety of a bridge; thus, it makes sense to firstly determine whether any problems are present at the bridges. Government body 2 and 3 note that from their inspection reports, which include the NEN 2767, additional investigations are conducted. Government Body 4: "Also, NEN 2767 and CUR 117 are part of it. Based on those inspection results, I create a multi-year plan." Government body 5 noted that the technical state (What defects it may have) of an asset, is the most important factor; this technical state is determined through the NEN 2767.

The results indicate the important foundation that the NEN 2767 sets for maintenance decisions and further investigations according to the interviewed government bodies. Each government body uses NEN 2767 primarily as an entry-level inspection to identify obvious issues in infrastructure but also gain insights into what the bridge is made from. The findings suggest that the NEN 2767 stands fundamental in the Asset Management workflow for all interviewed government bodies.

3.3.2 Risk Assessment: Always coupled with NEN 2767 data

ID	Risk assessment: Always coupled with NEN 2767 data
	Government representatives
1	"Not, no, at least not in my time. I haven't experienced that here. No, no, no, we have had the last [Location]. There have been 4 bridges that came out, you know, with that risk scan. They do not comply with, let's say, the guidelines that if you were to do the calculations, then they just don't meet the requirements. So, we would need to impose a restriction, let's say 45 tons and an axle load of 9 tons. Yes, I program, let's say, the bridge. Well, the bridge I was just talking about that needs to be replaced or reinforced. Well, those come out of the inspection; they came from that risk scan, right? "
2	"Actually, it does meet the criteria. However, based on risk, a defect does emerge. So basically, the most important thing we receive is the defects, and in addition, we request a maintenance plan, so a defect also immediately comes with an interval."
3	"Based on the condition score, but in addition to that, we also have our risk analyses for each object. In those, we look much more at the environment of such an object than at the technical side, and we also consider the structural safety. In that regard, we know everything."
4	"But it is a measurable instrument, and all our artworks have a condition score of one, two, or three at the object level. Previously, with the NEN, this was not possible; it was only at the building component level, and now it can be determined at the object level. And of course, we always look at what the risks are when we plan maintenance. We always weigh performance, costs, and risks."
5	"So, I actually don't run the entire dataset from the inspection; I throw it into my prioritization sheet. And what it will do is provide a sort of weighted average, a weighted score based on the NEN score and the risks, taking into account the types and locations. For my bridges, the score ranges from one to 1650, so then I know that one is the worst." "And well, the second is the NEN for risk assessment. It's a must. I think without that risk assessment, you can't apply the NEN either. I use the example of a wooden deck. If the deck plank is completely rotten, I might get a score of good due to the wood being less than 2% in the final stage. But when I then set up my risk assessment, you see that it scores very high in terms of safety. And it shows that you need to repair it immediately."

The risk assessment is a crucial part in maintenance decision making, and although not part of the NEN 2767, interviewees indicate that they always consider the two together. Government body 2, 3, 4 and 5 noted that, based on the NEN 2767 and risk reports they could often already determine maintenance actions. Government Body 1 notes that from their risk inspection they can impose restrictions on the weight that can pass over a bridge. The NEN 2767 inspections, as have been shown, always come directly paired with a risk assessment. Government Body 5: "I think without that risk assessment, you can't apply the NEN either." Government Body 2, 3, 4 and 5 noted that the NEN 2767 defects simply do not provide enough information to know whether a maintenance decision is necessary.

The results from the interviewed government bodies indicate that interviewees require more context on a defect than is provided by the NEN 2767. Several interviewees described cases where either a defect was overlooked by the NEN 2767 or was rated low despite being serious, suggesting that a broader set of information is required beyond the NEN for understanding defects. None of the interviewees identified a specific standard for conducting risk assessments, and it appears that the concept of a "risk assessment" varies across bodies. For example, government body 1 reported that its risk assessment revealed non-compliance of bridges with safety guidelines, while government body 5 emphasized that their assessment considers the broader significance of a defect. The findings suggest that, however these risk assessments are part of an asset manager's maintenance workflow, they play a critical role in decision-making.

3.3.3 Contextual information: Often plays a role

ID	Contextual information: Other plays a role
	Government representatives
1	"Well, the information that needs to be known is how many square meters it is, how many locations, how many square meters? Is it easily accessible? Will I need traffic measures? This might be less relevant for the municipality, but for us, it's essential. Do I need to close off a waterway? Yes or no, if it crosses a waterway? So that is information that is also price-determining. And then there are the environmental measures you need to take nowadays, especially if you're above water. So these are really price-determining measures. And I know with concrete maintenance, you might as well add about 10% on top, because once you start checking what's loose, that circle only gets bigger. When you're already at it, it's better to say, 'well, let's budget a little extra on the safe side,' then at least I won't run out of money." "But what is crucial, and this is very difficult to estimate at the front end, is what environmental measures you need to take." "Like, what measures do I need? Do I need to have a lift? Do I need paint or a device for support, or do I need a platform with scaffolding? I mean, yes, all those are cost-increasing provisions, and that really adds up."
2	"Can you imagine there's an underpass somewhere here under the tracks where there's a built-in light fixture in a housing, and water was coming back there? Then you have a danger with electrical safety. It was freezing then, so there was ice over everything, creating dangerous situations. So that, combined with the high groundwater level, has just brought some issues to light."
3	"In that, we look much more at the environment of such an object than at the technical side, and we also consider the structural safety. We know everything about that object; we have all the drawings, we know what types of steel classes are in it, what concrete classes, and all those starting points together ensure that you can make a good decision about an object."
4	"We have more maintenance within the province of Utrecht. We always try to combine as much as possible, so if some asphalt work is being done, we also try to combine maintenance of structures. So that is always a bit of a puzzle. Based on inspection data, the condition score allows us to look at what the risks are, and we also consider what else is happening in the environment or if perhaps partners nearby are carrying out maintenance that we can combine." "Yes, we see a certain scale of damage and in a way that is quite serious, and then we look to see if there is more going on. Is there, for example, chloride intrusion or such matters, so then you have to..." "We have, of course, a section of provincial road at the [street name], and that needs to be... You have the monuments, which also need to be maintained every five years, I think. So that needs to be a bit neater than the rest of the road. So that's a very specific example, but we have policies where we conserve all railings in red and white, the colours of the province. However, if it really doesn't fit the environment, if it's a rural area or if there are monumental houses around, then we choose to use a different colour."
5	"We look at the function, whether that function is still current. I see, for instance, in the past. I live in [city], and it's quite funny. When I look at my street, I see eight bridges. As a manager, you need to maintain those bridges. When you assess their function, for example, you find that only three are sufficient. However, maintaining eight bridges can get quite expensive. So with that thought in mind, we now also look closely at [interviewees city]. Does a bridge still serve a purpose, or is there another one further down? If it no longer has a function, we opt to remove it instead of maintaining it. We use that as input and also consider the environment. For example, if I'm doing maintenance on one bridge and there are three others nearby, I often take them into account, especially if they are in a fair to poor condition. You might as well include them. What's also important are the other assets. We often work jointly on projects with, for instance, roads. If a whole street is being resurfaced, we usually take the bridge into account as well. Lastly, I think the policies are also very important—yes, the policies from the municipality."

The interviewed government bodies each, when discussing how they make maintenance decisions mentioned a lot of different contextual information which is used in maintenance decision making. These have been categorised into 5 themes.

Firstly, Government Bodies 1 and 2 both mentioned that they consider traffic intensity and forecasting when making a maintenance decision. Representative 1 talks about truck traffic intensity with regards to a structures safety and how that is affected. Both representatives particularly mention, the safety of workers that must be considered.

Secondly is the area around the bridge and accessibility of maintenance. Government 1 through 4 discussed various aspects which are considered such as. Government body 1 mentioned needing space for painting which can affect waterway access, Government Body 2 and 4 both spoke of interaction with other asset owners such as rail. Government Body 3 and 4 mentioned that they consider the area surrounding the bridge in their maintenance evaluation; An example provided by 4 is that of a street with 'monuments', where maintenance quality was kept higher because of the location's association to this.

Third are environmental factors and measures associated with these. The representative from government body 1 noted that they had to consider environmental regulations when working above water or with concrete; showing that a maintenance decision is not easily made. Similarly, government body 4 spoke of the safety and health of workers who would be present at the maintenance operation. Government body 2 discussed the problems related to defects which could interfere with systems outside of their control; specifically, water damage on their asset could cause electrical wires of ProRail to be damaged if the defect was not cared for. Fourth,

Fourth, effective cost management and the challenges surrounding this were discussed by government bodies 1, 4 and 5. Government body 1 noted that it is incredibly difficult to estimate the cost of a maintenance decision based on similar previous interventions. They note that many factors affect the cost such as safety protocols, environmental considerations, traffic considerations and what and how much material is necessary for the maintenance. Government body 4 and 5 spoke of trying to, as efficiently as possible, combine maintenance activities or remove redundancies. Government body 4 and 5 gave an example of combining their work with the renewing of asphalt on roads; they note actively seeking out other partners performing maintenance in the region. Government Body 5 also noted a situation where there were 8 bridges, where 3 were enough to deal with the demand that was required; this way they could save money on maintenance.

Fifth, material knowledge and technical drawings can also play a role in maintenance decision making. Government bodies 1 notes that if a certain material is maintained, in this case concrete, they already estimate an increase in maintenance costs. Government bodies 3 and 4 also note that when making maintenance decisions they take a look at the technical drawings of the bridge.

The results indicate that from the interviewed government bodies a wide range of different information is considered when making maintenance decisions. The grouping results that traffic, maintenance activity considerations, environmental factors, cost management and material knowledge and technical drawings were used for the decision on how maintenance should be performed. It indicates the complexity of organising maintenance activities and estimating their costs. Contextual information such as safety and environmental measures for maintenance activities would be difficult to implement into a model as these depend strongly on the activity, location, surroundings, and setup of the bridge. However, information such as traffic intensities, other maintenance activities taking place, estimated costs, material properties and properties extracted from technical drawings, could be incorporated into a machine learning model.

3.3.4 Changes in situation: Sometimes maintenance is not enough

ID	Changes in situation: Sometimes maintenance is not enough
	Government representatives
1	"There was a bridge replacement where the profile no longer met standards. At that time, there were separate bike paths; in the past, people used to race on bikes. However, those roads have all become wider. The bike traffic is now separated, but on the bridge, the bikes still had to share the space with vehicle traffic because the bridge was too narrow. This situation led to the conclusion that it was simply dangerous. For traffic safety, the bridge needed to be made wider. Although the bridge wasn't fully depreciated, we still prioritize traffic safety. So, they decided to replace the bridge with a wider one." "Yes, and what I always find important is, well, I wanted to know the date of the bridge, and I always had them inspected because I think I want to know. We had many bicycle bridges, wooden bicycle bridges, and yes, they last 25 to 30 years, and then they reach the end of their lifespan. Yes, then they had to be replaced. Nowadays, we also had the last wooden bridge replaced with composite last year."
3	"But 9 out of 10 of our objects are either demolished or removed because they no longer fit functionally within the environment." "That is perhaps an addition for you [researcher]; what we see a lot is that we, as BV Nederland or BV techniek, are still designing with a century-old perspective. Meanwhile, our society has developed significantly over the last 50 years. Yes, we are either not keeping up with that, or you find yourself replacing your structures even before they reach their first maintenance cycle." "The society is changing faster than our structures, and that doesn't mean we aren't keeping up. However, the reason for changing, demolishing, reserving, or reconstructing an object has much more to do with the environment than with the object itself." "Enthusiastic about that combination, when you look at a recalculation, we do not mindlessly recalculate our entire portfolio."

Government body 1 and 3 noted changes in the overall situation play a large role in maintenance decisions. Both representatives noted that although defects are found on assets it is often found, through additional information, that these assets do not fulfil the structural or capacity requirements anymore; this makes replacement necessary. Government body 3 noted that the society is changing and that the assets cannot keep up; this results in those assets needing replacement before they are due for a maintenance cycle. A similar sentiment was noted by government body 1. Recalculations were mentioned by two of the government bodies, these play a large role in this decision making.

Based on the findings it can sometimes be the case that maintenance is simply not feasible anymore based on a change in situation. What is interesting from these insights is that these comments were both made by provinces. It could be suggested that municipalities, which often in the Netherlands deal with smaller bridges, historic centres all of which are trending towards a reduction in car traffic, are experiencing less of the challenges noted by these two government bodies. It is however, still important to consider that bridges can simply reach the end of their live or not be suitable for the context in which they are placed anymore.

3.4 Challenges experienced with NEN 2767 data

In this section the challenges experienced with the data are discussed.

In this section the challenges experienced with the NEN 2767 as found through the interviews with government bodies are explored. The section is divided into 3 sub-sections, which each discuss a different challenge experienced by interviewees: Subjectivity of the extent scoring, Decomposition and Real life and Data Challenges.

3.4.1 Subjectivity of extent scoring

ID	Subjectivity of extent scoring
	Government representatives
1	"No, because I've experienced so many times that they started with, well, let's say 10 m² in total, and then we ended up at 30. I think, yes, can that be? Then you really underestimated it as an inspector. So, I also believe that when you go outside, you should quantify what the damage is right away."
2	"It has surprised me quite a bit in the past. We have a standard from which we can objectively say what the condition should be, but it still provides a fairly reasonable picture. For example, if there's a 150 m guardrail and 1 m is missing, that's extremely dangerous. However, it could very well have a condition score of one or two, while the risk is enormous. Yes, so it's rare for a railing that is 80 cm. It can look perfectly fine and score a one, but it does not meet the requirements. So, there are many cases where that occurs, and you can analyse that." "Yes, we will have a list of deficiencies soon, right? You have a railing again, 100 m long, and it has 1 m of issues with some spots. We still need to physically check the photos and the report to see what we are really going to do here because we are not going to address just that meter."
5	"Because, yes, if you only see that the wood is at 2%, you might think that's nice. But where is it, right? A critical deficiency, I need to do something about it; I need to plan a measure for it. And that indicates that it shouldn't be like that, so that's why you need to supplement the NEN."
	Inspectors
1	"Interpretation by people who see that. It is not always interpreted correctly by everyone. Then you also see with the collapses and damages how, yes? How do you determine the extent of the damage? Yes, that's quite a discussion. Just people who, I think, don't do it well." "If you have damage on a table leg, say 2 cm, then you have to compare that 2 cm difference to all the table legs. This is often done with certain defects. A defect is observed on one of the four table legs, and it's immediately stated that there's an issue with that leg. If it's a defect like rust, then you should actually consider that as a surface issue. We should calculate the total area of all those table legs and then determine the percentage of the area of that one leg. Yes, that definitely raises some questions."
2	"I personally find the scale distribution of 0-2%, 2-10%, 10-30%, and 30-70% to be too broad; I would like to see it changed. I think the 2-10% range could be a bit higher, perhaps 2-25% or something like that. I would like to see the scale distribution adjusted because I find the difference between 10-30% and 30-70% to be quite significant. It would be nice if there were a bit more consensus or prudence about how to approach certain issues. For example, if you have a crack in a wall, the problem with damage related to surfaces is that if someone says they have a crack in the wall, they might argue it's more than 70% because the entire wall is cracked. In that case, they would be correct according to the NEN. On the other hand, if they say, 'Well, the crack is 1 cm wide, and the entire wall is 10 m wide, so less than 2% of the surface is affected,' they would also be right. Yet the outcomes are very different, and both can be correct, resulting in differing conclusions. That's something we need to address."
3	"You have something about graffiti, for example, where it's determined that if there is more than 30% graffiti present, it doesn't meet the required image quality. Only then do we decide whether to remove the graffiti or not."
4	"So, let's say you have a wall of 200 m². You have a crack that is 2 m long, then we say, okay, that's 2 m² compared to the 200, so it's 2%. This gives it some context because otherwise, cracks always seem to be less than 2%. But you also see this with the load-bearing capacity. It still won't be that significant because if you have a table that is 100 m² and a crack of 30 cm, it still won't account for much."

A reoccurring theme regarding the challenges with scoring extent of defects correctly occurred in the interviews with government bodies and inspectors. The ambiguity in defect quantification, regarding extent, was noted by government body 1,2 and 5 and all inspectors as being a challenge. They all noted examples where the extent of a defect could be interpreted in different ways. An example given by inspector 2 discussed a crack which can be interpreted as having a surface area of 1 cm but also of 10 meters dependant on how the defect is interpreted. Inspector 1 and government body 1 and 2 mention that this can often lead to discussions. In addition to this inspector 1 noted that aggregation of defects, which is based on coverage of a defect over a component, is also often mishandled which can result in varying scoring results. Inspector 2 noted that he would like to see a more distributed scale of extent scores. In their opinion the current scale is skewed too much in certain ranges.

The results indicate that, although the NEN 2767 provides a clear scoring system for defects, this system can still be interpreted in different ways due to the nuances of real life. The challenges with the extent score, and how these are interpreted by different inspectors can thus affect the final condition score of a component. This in turn makes the creation of a deterioration model more challenging as it could be fed data with different interpretations of score, potentially making it harder to spot patterns.

3.4.2 Decomposition and real life

ID	Decomposition and real life
	Government representatives
1	"Every little bolt you need to see. Yes, at that level, I don't need to know. Look, I want to know that the railing needs to be good, the concrete needs to be good. Well, the bearings, what's going on with them? Oh yes, the joint constructions, what's happening with them? Those are the components that are important to me, yes." "Yes, because the NEN doesn't always provide 100% clarity, especially with construction components. Sometimes, it's unclear which component we're using for this particular element and why we're using a different component elsewhere, even if it's essentially the same part. You definitely notice some variation between different parties in this regard, and you'll likely hear similar things in the other interviews as well."
4	"We're not going to chew through the entire bridge in the decomposition of every bolt and nut, but you do have to deal with quickly built components that don't need joint maintenance and separate computers, a fan, or whatever else." "For example, there's a tunnel basin, right? Where the underpass belongs to the province, and the deck belongs to ProRail. So, how are you going to set up your decomposition? Do you just consider the tunnel basin, or do you also include the deck and reflect somewhere in the decomposition that the deck belongs to ProRail? That's always tailored work, especially regarding access."
	Inspectors
1	"The decomposition parts that need to be inspected include everything that is not visible or that actually exceeds the lifespan of an object, such as the foundation. You can assume that the lifespan of the object exceeds that. Should you then include that in your decomposition? You can't see it immediately. Yes, there are different opinions on that. This is often the most discussed aspect of decompositions." "That's the easy part to manage, and often I can immediately see other defects in a construction element. Yes, that varies in perception. However, it has a significant impact on the workload, let's say, the administrative burden. Having a very extensive decomposition of more than 300 or 400 components means you're spending a lot more time. If you also have to rely on defect registrations for each component, it becomes even more time-consuming."
2	"Yes, what makes sense to the inspector as an outcome is sometimes not logical for me, as I wasn't there on-site. So, we need to discuss why that is. Hey, why did you choose this decomposition?"
3	"And with railings, yes, you can record each railing twice. You can record it twice in terms of color, conservation, and such. Yes, that is possible, but it also has to be manageable." "Perhaps they thought of recording each support point as a separate component. Yes, then you end up with a long list of components, which may not be desirable or makes no sense, and that can be decided." "Or simply to apply a logical component somewhere, which sometimes doesn't seem possible according to the NEN." "It happens that I sometimes encounter situations where the NEN specifies certain materials for components, which can be problematic. Well, is that the rule? Sometimes you want to use a different material. Theoretically, that may not be allowed, but it can work."
4	"And for the same object, you see up to five decompositions coming through, and what problem do you have then? Is it maintenance contracts? You don't have one maintenance contract; you have different parts. Do you have a maintenance contract with ProRail? And then you have your own decomposition that deviates from the decomposition on the drawing, and then you have to try to make the translation." "And we need to work with the same decomposition, but where a nuance would come in is that the depth means that you say, 'I have public lighting.' As an element, public lighting is generally considered as a construction part, for example, the fixture."

Three general aspects of decomposition which harbour challenges when working with the NEN 2767: Choosing the right decomposition, the level of detail and how to deal with domains not covered in the NEN 2767.

All inspectors mention challenges with defining decompositions when choosing to use a certain component to describe a part in bridges. Inspector 1 and 2 both mention that discussion and confusion can arise from chosen components in a decomposition. Inspector 4 further emphasises this with an example where they had 5 decompositions which varied greatly but where in essence the same bridge. Inspector 3 notes that because specific components can only be linked to prescribed elements, which can only be connected to prescribed assets. This means that they are limited to how a bridge may be decomposed, which can incorrectly reflect the realities.

Government representatives 1, 4 and inspectors 1, 3 and 4 note the challenge between needing detailed breakdowns of components (like bolts and joints) and the impracticality of assessing every minor element. Particularly the practicality of this was discussed as inspectors noted that a too detailed inspection can cost government bodies a lot of money.

The need for a tailored approach when dealing with components belonging to different domains can also be a challenge according to government body 4, inspector 4. Both interviewees noted having challenges regarding decomposition of rail parts but also where their decomposition begins and ends. If the two domains are interconnected a defect in one can affect the other.

The interview excerpts indicate that creating a decomposition is not as straightforward as could be imagined and requires a lot of decisions on the part of inspectors and government bodies. These decisions can result in varying decompositions on similar structures as indicated by inspector 4 who experienced this first hand; this could make it harder to track degradation patterns amongst similar structures. In addition, there is no set level of detail that is required by the NEN 2767 as a bridge can have all its individual railings documented or grouped as one. This again affects how deterioration is documented and could even affect the way extent of a defect reported. A bridge is not a structure which exists in a vacuum and the challenges of other domains interacting with the bridge makes decompositions even harder.

3.4.3 Data challenges

ID	Data challenges
	Government representatives
1	"If that doesn't happen, then you notice both outside and inside that a contractor wants to complete a job, and that's a business. But the administration and providing data, yes, that's what you notice with all those contractors. Yes, they are not so keen on that, right? I mean, the big bulk is great, but then the paperwork switch, yes, I think that's not, well, not sexy or appealing." "Well, often you really have to follow up to get things done properly, yes, because we also keep pushing. And yes, then you also see with us at the engineering firm that the next project is already coming up, and they are busy with that, but the other one is not completely finished yet. Yes, and what happens then? Yes, then you think, 'Well, this, this, this gets pushed aside again.'" "And so, sometimes we encounter situations where we think, 'Hey, we don't have any data at all. How is that possible?'" "And that is also dependent on the individual. I have been in many municipalities with management systems, and you really notice that some people see the importance of keeping things in order, because it brings them a lot of convenience. But then there are others who believe it, and they think, 'Okay, whatever.' And if you have such people involved, your system can become polluted very quickly. That's a shame."
2	"Yes, yes, we have requested quite a lot. Yes, but that's also because the data in our system is not great at the moment." "There are multiple [NEN 2767-4] updates, so sometimes new components are added, and existing components change. You often have components that are commonly used, but those can sometimes disappear. So, there are indeed changes with each update."
3	"Yes, we always report the most recent version in use [most recent NEN2767-4]. The only problem is that you can't work backward; what was observed seven years ago is different from what you observe now. So, there are differences, and you have to deal with those discrepancies. It's that simple, and a 100% functional system doesn't exist. There are some other questions related to this, which we can also address later." "No, we don't report that. This is because these types of inspections are loaded into [management system], and ultimately, the management system should facilitate us a lot. And that's a nice tip for [same] to be able to extract such different notes."
4	"And coincidentally, I'm now starting the assignment for next year. Next year, we'll be doing the technical inspection again, which we do every five years, and I always let them start with a clean slate. I have the entire decomposition redone from scratch." "Yes, we have a management system. I won't name names. Previously, we had a very good management system. Well, you know how that goes, right? We have contracts that eventually expire, and you deal with threshold amounts that determine how you can award contracts, and this had to be publicly tendered. No, we requested it through a multiple negotiated procedure, and now we have received a software package, but I am less satisfied with that. But well, we naturally provide a program of requirements."

5	"That if you don't do it, you get a diversity, and that's not good for your database, right? Because you can write 'railing' in different ways, right? Railing, railing construction, railing balustrade."
	Inspectors
3	"Yes, if the decomposition is in order, you can basically start right away. But if the decomposition is unknown, incomplete, or incorrect, you really need to address that first. That will take some time. "

Government bodies identified several data challenges, including organizational issues, difficulties with management systems, and challenges related to decomposition.

Government Body 1 notes that although inspections are performed adequately, they experience often that information is not actually collected and stored into a system and that the representative struggled getting people to think more data conscious. It was also noted by this interviewee that this difference is mostly a cultural one and that the problems vary amongst government bodies. Government body 2 Notes that their database is currently not up to standard; suggesting that they also experienced problems with collecting the data they need, although this is changing.

Government Body 3 notes that their system doesn't allow for all the information they have on bridges to be stored; resulting in multiple places where information is gathered. Government Body 4 noted that they are currently not happy with the data management software package that they have; They noted that the system currently doesn't allow them to gain the insights they would want.

Decomposition challenges were noted by Government Body 2 and 4. Gov. 2 noted that because the NEN 2767-4 sometimes changes it requires them to change their definitions of the decomposition as well. Government body 4 noted that they completely redo their decompositions every inspection round; this can result in the tracking of changes being very difficult. Government body 5 and inspector 3 further emphasises this point

These interview excerpts reveal a need for improved data management practices, better software solutions, and a cultural shift towards valuing and utilizing data effectively within government bodies.

The challenges experienced with regards to data collection show that data can be lost if inspectors and government bodies do not see the added value of storing this information. The complains by government body 3 and 4 on their data systems suggests that current systems could in cases not facilitate the needs of Asset Managers; thus, limiting that insights they can gain. Lastly the difficulties experienced with decomposition in terms of changes in the terminology or the complete redo of the decomposition by government body 4 makes tracking changes in condition scores difficult. Some of these insights could explain the limited amount of data stored but also the problems found in the excel sheets received by government bodies in chapter 2.

3.5 Chapter conclusion

In this chapter the current state of the NEN 2767 in government bodies was analysed. The sub-question which had to be answered is: What are the causes of different data quality of government bodies in the NEN 2767 and what data is used to make maintenance decisions? To provide an answer to this sub-question, four secondary questions were posed.

1. What causes the differences in the data quality of the NEN 2767 in government bodies?
2. What additional data is collected for maintenance decision-making?
3. How does data play a role in the maintenance decision-making process, and how do these compare in terms of importance?
4. What challenges are experienced when working with the data?

In this section the secondary questions will be answered. These secondary questions serve as input for answering sub-question b in the conclusion of this report. This conclusion consists of 4 paragraphs, each which answer one of the secondary questions. 5 government bodies and 4 inspectors were interviewed with a range of experience between 3 and 14 years.

Despite all government bodies and inspectors agreeing on the purpose of the NEN 2767, there are 5 causes which could have caused the differences in data quality. Firstly, NEN 2767 data is stored in different systems by different government bodies, this can result in data being stored in different ways as there exists on data standard on how NEN 2767 data must be stored. Secondly, different intervals of inspections were revealed to be performed; why these were chosen was often because they need to be able to perform maintenance in between inspection rounds but also because otherwise degradation cannot be observed. Third, why external inspectors are chosen to perform inspections for government bodies differed amongst interviewees; Often choosing between price, trust and quality or a combination. This means that government bodies receive different levels of quality with their inspections. In addition, what quality means is highly subjective and was not defined by government bodies. Fourth, the expectations of what experience or certification and inspector must have differed amongst interviewees. This could result in different levels of quality from inspectors in terms of the spotting of defects and performing decompositions. Lastly, the delivery of data differed quiet a lot between government bodies, some allowed inspectors to immediately input data into their system, others received excel sheets and often PDFs were delivered.

Seven different types of additional data are collected by government bodies that were interviewed. Firstly, additional inspections, outside of the scope of the NEN 2767, are performed. Of these there are more technical inspections such as for electrical systems but also the 'schouw' which is a yearly check up on bridges to ensure they are still safe. Secondly, data related to risks are collected often in combination with NEN 2767 inspections; these provide more contextual information to defects but also problems which fall outside of the scope of the NEN 2767. Third, intervention suggestions are always collected by the interviewed government bodies and provided by interviewed inspectors. This indicates that government bodies place a lot of trust in the experience of inspectors to not only collect the current state of their assets but also suggest interventions which may be suitable. Fourth, pictures were mentioned by 3 of the 5 government bodies and by all inspectors. Inspectors often noting that these images were taken for verification purposes. Fifth, Recalculations were collected by 2 government bodies and provided as a service by 1 inspector. Notably, this information was collected by provincial government bodies, suggesting their bridges may be impacted heavier by changes in traffic load intensities. Sixth, Longevity assessments were mentioned by one government body and 3 inspectors, who were asked how long they believe components would last. This suggested that there is a demand for such estimations. Lastly, a plethora of other information is requested by government bodies and collected by inspectors. Including physical characteristics, possible failures modes of components and direct communication if there is an imminent danger.

Four main findings were observed when assessing how maintenance decisions are made with the collected data. Firstly, the NEN 2767 appears to be the starting point of a maintenance decisions. The defects found in these inspections can be enough to prompt a response or result in further investigations. Secondly, risk assessments are always linked with NEN 2767 and are an important factor when deciding on making a maintenance decision. One government body even states that without a risk assessment the NEN 2767 is simply not enough to decide on anything. Showing its importance in contextualising a defects severity. Third, a lot of different contextual factors were mentioned by government bodies pertaining to traffic, maintenance accessibility, safety and environmental considerations, cost management and material knowledge. These are challenging to include in a machine learning model and indicate the importance of an Asset Managers knowledge for making the right maintenance decision. Lastly, changes in situation, pertaining to changes in traffic intensities or changes in regulations sometimes simply mean that maintenance is not the right action and that replacement in the most logical step.

Although the NEN 2767 is implemented by all government bodies and used by al inspectors that were interviewed issues still arise with the standard. Three different challenges were identified from the interviews. Firstly, challenges related to NEN's extent scoring were often mentioned by both government bodies and inspectors. Particularly on how this extent score should be interpreted there are uncertainties which can result in completely different condition scores being documented for the same defect. Secondly, challenges with decomposition scores were identified. The findings reveal that creating a decomposition involves complex decision-making by inspectors and government bodies, leading to variability in decompositions even among similar structures. This variability, as highlighted by inspector 4's experience, complicates the tracking of degradation patterns. Additionally, the lack of a defined level of detail in NEN 2767, where a bridge's railings can be documented individually or as a single unit, impacts how deterioration is recorded and may influence defect reporting. The interconnectedness of a bridge with other domains further complicates the decomposition process. Lastly, challenges related to data were mentioned frequently. The results underscore a pressing need for enhanced data management practices, improved software solutions, and a cultural shift within government bodies to better value and utilize data. Two government bodies complained that their Asset management software solutions do not meet the needs, thereby limiting the insights they can obtain. Furthermore, the difficulties encountered by government body 4 regarding terminology changes and the need to completely redo decompositions complicate the tracking of condition scores. These insights may clarify the limited data storage, and the issues identified in the Excel sheets received from government bodies in Chapter 2.

4. Additional data used in deterioration models

In this chapter, the data which can enable predictive maintenance with the NEN 2767 is presented. Firstly, an overview is provided of the identified papers and their characteristics. Which is followed with a description of what can be found in this chapter.

In this chapter the following secondary questions are answered:

1. What features are used in bridge deterioration models?
2. Which of these features should be gathered to enable bridge deterioration modelling in the Netherlands?

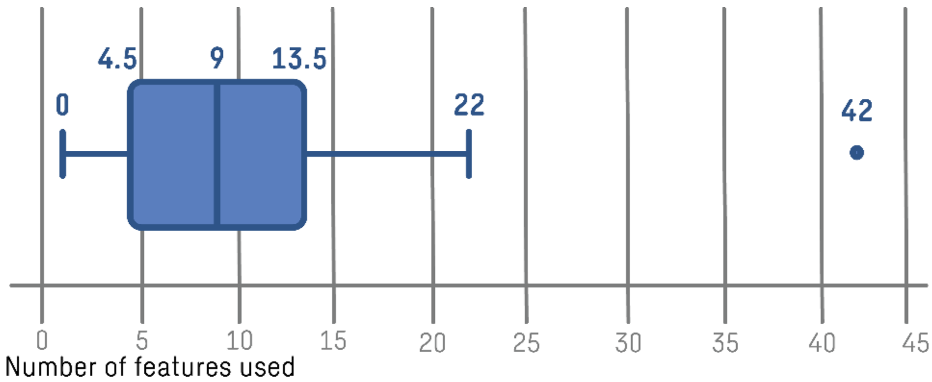


Figure 8 Number of features used per paper

As presented in Figure 8 large difference in the number of features used can be observed. As little as 1 feature was used; this was always just the condition score of an element or bridge. The median at 9 features with the average at 9.76 features. A maximum of 42 features were used; this is significantly higher than the third quartile, thus is considered an outlier.

Table 23 Data source or standard found in the literature study

Country	Data source or standard	Number of times applied in papers
USA	National Bridge Inventory (NBI)	24
China	JTG/T H21-2011	5
UK	National Rail standard (SevEx)	3
Korea	National Road Bridge Management system (KHBMS)	2
Spain	AURA BMS	1
Canada	BCI	1
Japan	RPIBMS	1

Table 24 Similarities and differences between standards

Standard	Inspection interval (years)	Condition rating	Additional info	Decomposition
NEN 2767	NOT SET	(Good) 0-6 (Bad)	Type of defect Intensity Severity Extent Material	64 Assets, 415 element, 818 components
NBI	2	(Good) 9-0 (Bad)	116 features (Abu Dabous, Alzghoul, et al., 2024)	Deck, Superstructure, Substructure, Culverts.
JTG/T H21-2011	3	(Good) 1 – 5 (Bad)	Estimated 60-80 features	3 elements, Broken down in components

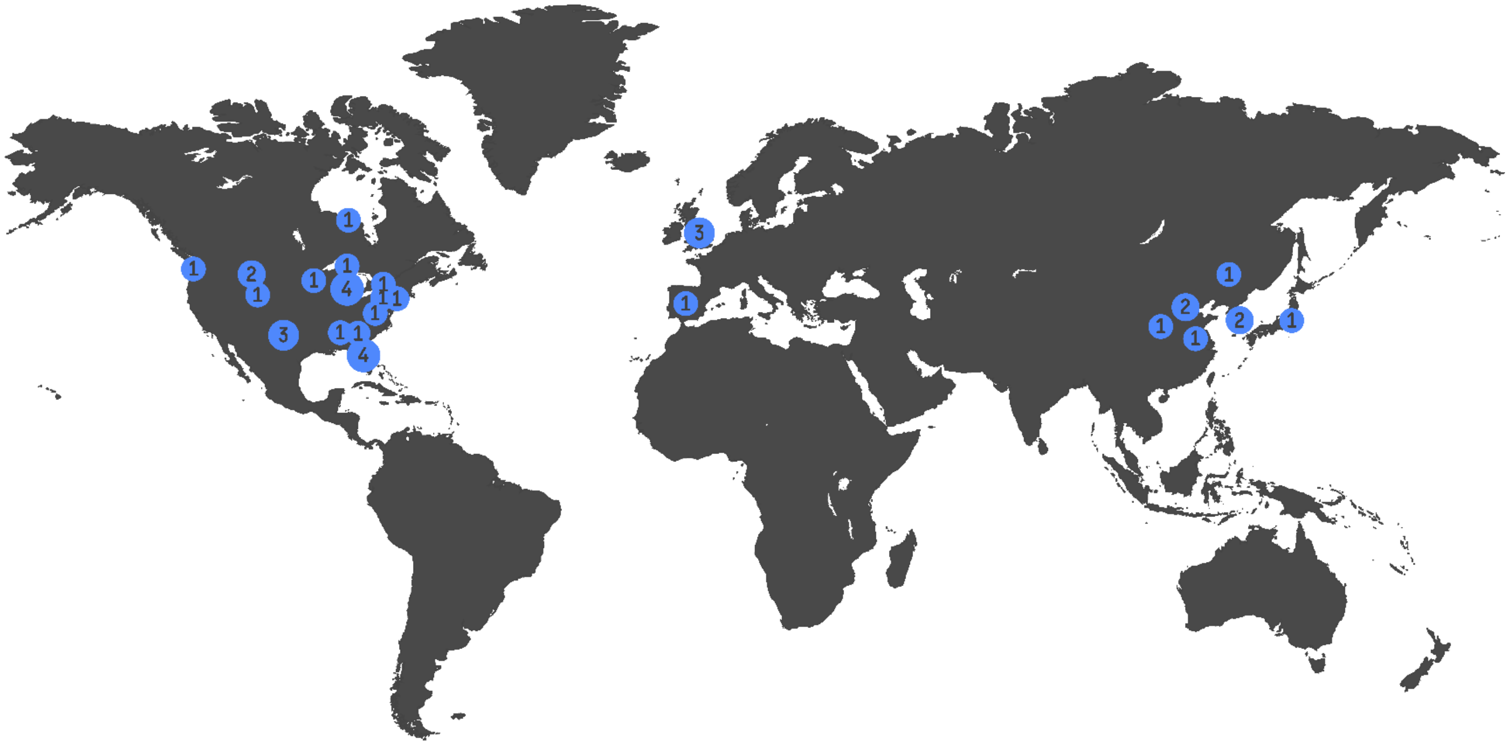


Figure 9 Locations of case studies in literature study (An additional 3 papers cover all of the USA and 2 papers consider the 10 coldest states in the USA)

What becomes apparent in Table 23 and Figure 9 is that there is a bias towards research which applies data from the United States of America, specifically the NBI standard. Secondary is data from the Chinese inspection standard code named 'JTG/T H21-2011'. The apparent bias is most likely due to the NBI being one of the largest repositories of bridge data (in terms of features and volume) in the world which is also openly accessible; this could result in the NBI being attractive to work with when experimenting with different features, volumes of data and machine learning algorithms. Literature applying the Chinese standard is most likely in Chinese and thus more likely to be underrepresented in this research. What is clear from

Table 24 is that the standards work in similar ways, using some form of decomposition to which a condition score can be attached.

Table 25 Element which is focus of papers case study

Element/component	Number of papers that consider the element
Deck	23
Superstructure	12
Substructure	9
Bridge total score	9
Coating	4
Girder	3
Expansion joint	3
Column	2
Bearing	2
Abutment	2

The chapter continues as follows: Firstly, the various features found are discussed in section 4.1. In 4.2 a discussion is held on which features should be a 'must have' and a 'Nice to have'. This is followed by the conclusion where the sub-question is answered.

4.1 The features used in Bridge Deterioration models

In this section the various features which were identified in the literature study. 125 unique features were identified. An overview of all features found to have been used is present in Appendix E. After combining similar features and excluding ones not applicable in the context of the Netherlands, 37 groupings of features were left. These are presented in Figure 10. This section is divided into sub-sections which discuss features that fall into various categories. Features were discussed considering their occurrence in the literature. If features were ranked in the papers, The element or component which is the focus of the research, along with the location of the case study for each application. In the discussion the must have and nice to have features are argued for. The chapter ends with a conclusion and the answering of the sub-research question.

Figure 10 Sunburst graphic of all the found features after combining similar ones. The size of the segment relates to the number of occurrences in literature

4.1.1 Physical Characteristics

This sub-question presents the features related to the physical characteristics of bridges. 12 unique features are analysed: Lanes on structure, lanes under structure, Approach roadway width, road width, bridge total length, maximum span, minimum vertical clearance, number of spans, skew angle, total area, deck width, thickness of overlay.

Lanes on structure

The lanes on structure feature (LOS) refers to the amount of driving lanes a bridge has. LOS was applied in 5 different papers. There are 3 reasons for the inclusion of this feature. Firstly, 2 authors believed that the feature had impact on a bridges deterioration rate (Abu Dabous, Ibrahim, et al., 2024; Lei et al., 2022). Secondly, Rajkumar et al. (2023) based their selection of what was found in literature. Lastly, two papers provided no reasoning for including the feature (Liu et al., 2023; Liu & Zhang, 2020).

Only the paper by Rajkumar et al. (2023) investigated the features impact when compared to others. The results are provided in Table 26. The paper provided no further elaboration on its findings; although it could be suggested that more lanes mean more traffic and thus could affect traffic in this way.

Table 26 Impact ranking of Lanes on Structure feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Rajkumar et al., 2023)	Top 5	16	Florida, USA.	Multiple components.	Preliminary feature selection

The feature could simply be captured once in an inspection where a count could be made.

Based on the results it is hard to draw a conclusion on whether the feature should be included in a bridge deterioration model. Only one paper provided any insights into the importance of the feature and deemed that it was a feature to consider. Although the feature could be in relation to traffic intensity as more lanes suggest more traffic. However, without any further elaboration on its findings, and little other papers applying the feature or providing insights it is difficult to recommend with confidence.

Lanes under structure

Lanes under structure (LUS) refers to the amount of driving lanes under a bridge. LOS was applied in 2 different papers. Both Abu Dabous, Ibrahim, et al. (2024) and Moscoso et al. (2024) applied LUS due to their believe that it impacted the deterioration of their bridge models.

Moscoso et al. (2024) compared the impact of the feature to others. The results are provided in Table 27.

Table 27 Impact ranking of Lanes under structure feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Moscoso et al., 2024)	3	8	Indiana, USA.	Deck	Author believes the feature impacts deterioration.

Moscoso et al. (2024) suggested that the significant scoring of LUS could be due to corrosion processed which are affected by the placing of chlorides due to heavy traffic under the bridges and perhaps de-icing slats in winter climates. Although it is not clear how de-icing salts is related to a bridge's lanes under the structure. The author does thus suggest that traffic intensity could be related to the number of lanes; like what was suggested for LOS.

The feature could simply be captured once in an inspection where a count could be made.

Based on the findings in literature it is challenging to know whether the feature should be considered for inclusion in a bridge deterioration model. This is based on two reasons. Firstly, If the arguments made by Moscoso et al. (2024) hold then it is more logical to add the data for traffic intensities, under and above the bridge directly, rather than relying on a relational feature. In addition, the feature is used very little which makes it hard to reliably say whether the feature is important for consideration.

Approach Roadway Width

The approach roadway width feature was applied in one paper by Ghafoori et al. (2024). The paper provides no definition for the feature but it is assumed that this refers to how wide the road is before it connects to the bridge. The feature was included because it may affect deterioration.

Ghafoori et al. (2024) assess the impact of the feature which is described in Table 28. No further insights are shared by the author.

Table 28 Impact ranking of Approach Roadway Width feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Low impact					
(Ghafoori et al., 2024)	12	18	Colorado, USA.	Multiple components.	Preliminary feature selection

Based on the results this features impact is inconclusive. This is based on the fact that the feature was only applied in one paper and did not score particularly high in terms of impact. No additional insights were provided by the author either.

Road Width

Road with refers to the width of the road from curb to curb, so not for individual lanes but the total road surface. Approach Roadway width was also included in this feature, as they have similar properties. This feature was applied in 5 different papers. There were 2 unique reasons for including the feature. Firstly, three of the papers considered Road width to be an important for deterioration (Abu Dabous, Ibrahim, et al., 2024; Ghafoori et al., 2024; Lei et al., 2022). The last two papers provided no reason for its inclusion (Liu et al., 2023; Liu & Zhang, 2020)

Ghafoori et al. (2024) provided an impact assessment of the feature when compared to others. This can be found in Table 29.

Table 29 Impact ranking of Road Width feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Low impact					
(Ghafoori et al., 2024)	11	18	Colorado, USA.	Multiple components.	Preliminary feature selection

Overall, the feature had low impact on the components which were analysed. However, Ghafoori et al. (2024) found that road width this have a significant impact on the deterioration rate of reinforced concrete pier wall element; contributing 13.9% to the impact scoring. However, it was still out shunned by the bridge age feature. Why this is the case was not discussed by the author and remains relatively unclear.

The feature could simply be captured once in an inspection where a count could be made.

Based on the results, it's difficult to determine whether the feature should be included in a bridge deterioration model. Although the feature was deemed important for deterioration by three authors the impact assessment scored the features importance as overall not as important. Despite this is did contribute to the deterioration of one element; however, a feature which only affects a single component may not be worth including.

Bridge Total Length

Bridges total length (BTL) is one of the features which was found to have been applied the most times besides the number of spans at a total of 12 unique papers using it. There were 4 reasons why the feature was applied. Firstly, Leiva-Maldonado et al. (2023) applied the feature as it was commonly used in literature. Secondly, 4 authors believed the feature to be important for deterioration modelling (Abu Dabous, Alzghoul, et al., 2024; Lei et al., 2022; Xia et al., 2022a; Zhang & Marsh, 2020). Third, 3 authors found that BTL had an impact based on a preliminary feature selection (Althaqafi & Chou, 2022; Ghafoori et al., 2024; Rajkumar et al., 2023). Lastly, 4 papers provided no explanation for why they added the feature (Asghari & Hsu, 2022; Liu et al., 2023; Liu & Zhang, 2020; Lu et al., 2022).

4 papers compared the features impact to other features used in their studies, the results are presented in Table 30.

Table 30 Impact ranking of Bridge Total Length (BTL) feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Ghafoori et al., 2024)	4	18	Colorado, USA.	Multiple components.	Preliminary feature selection
Average Impact					
(Abu Dabous, Alzghoul, et al., 2024)	6	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.
(Rajkumar et al., 2023)	Top 8	16	Florida, USA.	Multiple components.	Prevalence in literature
Low Impact					
(Zhang & Marsh, 2020)	6	6	Texas, USA.	Deck	Preliminary feature selection

Only Ghafoori et al. (2024) provided any notes on the impact that was found. They noted that bridge length had a strong correlation with the deterioration of of steel protective coatings, steel bridge rails, reinforced concrete decks, prestressed concrete girders/beams, reinforced concrete pier caps, and reinforced concrete bridge rails. This indicates that the feature can affect various elements.

Bridge length can easily be captured through a single measurement when inspecting a bridge or can be found through technical drawings of the bridge.

Based on the provided information total bridge length could be an interesting feature to include in a deterioration model. This is based on 3 reasons. Firstly, four of the papers which included the feature suggested that the feature could have an important impact on bridge deterioration, this was further empirically proven by 3 paper which identified it as an important feature. Secondly, the impact rankings suggest that the feature can have some impact on deterioration modelling, though it is not extremely high. Although Zhang and Marsh (2020) scored the feature relatively low for the features which were implemented in their model, initial feature selection ranked it 6th out of 21 different features; providing a fairer assessment of the features importance. Third, the feature appears to affect multiple components to a decent degree as shown by the impact assessment and the insights provided by Ghafoori et al. (2024).

Maximum span

Maximum span refers to the maximum distance between two spans which occurs on a bridge. This feature was applied in 7 different papers. The feature was applied for 2 different reasons. Firstly, 4 papers suggested that the authors believed it to be an important feature (Abu Dabous, Ibrahim, et al., 2024; Choi et al., 2020; Goyal et al., 2020; Lei et al., 2022). Secondly, 3 papers implemented a preliminary feature selection, where Maximum span was found to be important (Almarahlleh et al., 2024; Ghafoori et al., 2024; Rajkumar et al., 2023).

2 papers compared the impact of the feature to other features, this can be found in Table 31.

Table 31 Impact ranking of Maximum Span feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Ghafoori et al., 2024)	5	18	Colorado, USA.	Multiple components.	Preliminary feature selection
(Rajkumar et al., 2023)	Top 5	16	Florida, USA.	Multiple components.	Prevalence in literature

Ghafoori et al. (2024) notes that maximum span has effect on the deterioration of steel protective coatings, steel bridge rails, reinforced concrete decks, prestressed concrete girders/beams, reinforced concrete pier caps, reinforced concrete bridge rails, and reinforced concrete columns. A significant number of features.

Bridge maximum span can easily be captured through a single measurement when inspecting a bridge or can be found through technical drawings of the bridge.

The results of the literature study indicate that maximum span should be an interesting feature to include in a bridge deterioration model. This is based on two reasons. Firstly, the choice of feature inclusion indicates that the feature is considered important by the authors who implement it and is backed up by empirical feature selection. Secondly, the impact that the feature has on deterioration is relatively high in the two papers that assessed it. In addition, Ghafoori et al. (2024) shows that the feature affects a wide range of components, indicating that its impact on deterioration prediction is broad.

Minimum vertical clearance

Minimum vertical clearance (MVC) is a feature which measures the clearance from the bottom to the top of the bridge where the smallest value is taken. 3 papers applied this feature. Abu Dabous, Ibrahim, et al. (2024); Choi et al. (2020) applied the feature as they thought it could be important for determining bridge deterioration. Asghari and Hsu (2022) provided no reason for its inclusion. None of these papers provided an impact assessment of the feature when compared to others.

MVC can easily be captured through a single measurement when inspecting a bridge or can be found through technical drawings of the bridge.

Based on the results it cannot be argued that the feature should be included in a deterioration model. Although it was included in some papers the number is very limited, and its impact isn't quantified.

Number of spans

The number of spans is a frequently occur feature having been implemented in 12 different papers. The feature was included for 4 unique reasons. Firstly, Leiva-Maldonado et al. (2023) applied the feature due to its frequent usage in literature. Secondly, 4 papers considered the number of spans important for the deterioration rate (Abu Dabous, Alzghoul, et al., 2024; Abu Dabous, Ibrahim, et al., 2024; Choi et al., 2020; Goyal et al., 2020). Third, 3 papers applied a preliminary feature selection and found that the feature was important for deterioration (Althaqafi & Chou, 2022; Rajkumar et al., 2023; Xia et al., 2022b). Lastly, 4 papers provided no reasoning (Asghari & Hsu, 2022; Liu et al., 2023; Liu & Zhang, 2020; Lu et al., 2022).

From these papers 2 assessed the impact of the feature in comparison to others. These results can be found in Table 32.

Table 32 Impact ranking of Number of Spans feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Average Impact					
(Rajkumar et al., 2023)	Top 10	16	Florida, USA.	Multiple components.	Prevalence in literature
Low Impact					
(Abu Dabous, Alzghoul, et al., 2024)	11	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.

Although Rajkumar et al. (2023) shows the feature did not score highly, they author did recommend including the feature in a deterioration model besides the other top features.

Based on the results of the literature review, the number of spans has not proven to be an important feature to consider for deterioration modelling. This is because the feature does not score very highly when compared to other features in the impact assessment table. If more evidence is presented the feature could be considered. But it does not currently provide any suggestion that it could be applicable in Dutch context.

Skew angle

The skew angle refers to the angle at which, from a top-down perspective the bridge is angled from its starting point to its end point. The feature was applied in 9 unique papers.

The Skew was added for 3 different reasons. Firstly, (Leiva-Maldonado et al., 2023) applied the feature due to its prevalent usage in literature. Secondly, 5 papers applied the feature due to it being identified as an important feature based on the a preliminary feature selection (Almarahlleh et al., 2024; Althaqafi & Chou, 2022; Ghafoori et al., 2024; Rajkumar et al., 2023; Zhang et al., 2024). Third, 3 papers provide no arguments for why they include the feature (Asghari & Hsu, 2022; Liu et al., 2023; Liu & Zhang, 2020).

4 papers compared the features impact to others within their study. The results are presented in Table 33.

Table 33 Impact ranking of Skew Angle feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Average Impact					
(Rajkumar et al., 2023)	Top 10	16	Florida, USA.	Multiple components.	Prevalence in literature
Low Impact					
(Almarahlleh et al., 2024)	7	8	Michigan, USA.	Deck	Preliminary feature selection
(Ghafoori et al., 2024)	14	18	Colorado, USA.	Multiple components.	Preliminary feature selection
(Zhang et al., 2024)	4	6	Texas, USA.	Deck	Preliminary feature selection

3 further insights are shared by the authors of these papers. Almarahlleh et al. (2024), despite the low impact score, notes that Skew Angle is one of the top features to affect bridge deterioration. Ghafoori et al. (2024) found that no component has a strong correlation between the feature and degradation rate. Zhang et al. (2024) notes that Skew is an important feature for determining deterioration rates, however, when looking at different accuracy scores when including and excluding skew, it appears that skew has a negative effect on the score.

The feature could simply be captured once in an inspection where a measurement could be made or through an inspection drawing.

The findings from literature provide a somewhat unclear result, it is thus inconclusive whether the feature should be included. Based on the impact scoring within papers it appears that the feature does not impact deterioration significantly. However, when authors discuss the feature, they often noted its importance. There appears to be a disconnect between the results and interpretation; this could be due to the feature being important when comparing it to all possible features which could be added to the prediction algorithm. However, for the once's that are chosen the feature scores low. This could explain the significant number of papers which included skew due to a preliminary feature selection.

Total area

Total area of a bridge is a feature which was applied in 3 different papers. Almarahlleh et al. (2024) added the feature due to a preliminary feature selection. Abu Dabous, Alzghoul, et al. (2024); Miao and Yokota (2024) included the feature as it could affect the deterioration rate of bridges.

Two of the studies assessed the features impact when compared to others; this resulted in Table 34.

Table 34 Impact ranking of Total area feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Average Impact					
(Almarahlleh et al., 2024)	4	8	Michigan, USA.	Deck	Preliminary feature selection
Low Impact					
(Abu Dabous, Alzghoul, et al., 2024)	7	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.

Almarahlleh et al. (2024) noted that total area did have a significant effect on the deterioration rate of decks; although the impact ranking score is 4th it's importance score is very similar to the 2nd and 3rd most important features. (Abu Dabous, Alzghoul, et al., 2024) score is also slightly biased as only 11 features were used for training, but total area was firstly assessed against 22 different features; from this it came out as 7th most impactful; indicating that it is important to consider. It should be noted that all these papers assed decks.

The feature could simply be captured once in an inspection where a measurement could be made or through an inspection drawing.

Based on the results from the literature study, total area could be interesting to add to a deterioration model. The impact table in this case shows a bias towards the feature not being significant in its importance but as indicated in the above paragraph it becomes apparent that the feature is impactful.

Deck width

Deck width refers to the width of a bridge. The feature was applied in 9 different papers. Three different reasons are provided for its inclusion. Firstly, 2 papers considered the feature to be important for their deterioration model (Abu Dabous, Alzghoul, et al., 2024; Choi et al., 2020). Secondly, 5 added the feature after a preliminary selection process (Almarahlleh et al., 2024; Althaqafi & Chou, 2022; Ghafoori et al., 2024; Omar & Moselhi, 2022; Rajkumar et al., 2023). Lastly, two provided no explanation (Asghari & Hsu, 2022; Lu et al., 2022).

5 different papers provided an impact assessment of the feature in comparison with other features they applied. This can be found in Table 35.

Table 35 Impact ranking of Deck width feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Ghafoori et al., 2024)	6	18	Colorado, USA.	Multiple components.	Preliminary feature selection
Average Impact					
(Almarahlleh et al., 2024)	5	8	Michigan, USA.	Deck	Preliminary feature selection
(Rajkumar et al., 2023)	Top 8	16	Florida, USA.	Multiple components.	Prevalence in literature
Low Impact					
(Omar & Moselhi, 2022)	6	7	Iowa, USA.	Deck	Prevalence in literature
(Abu Dabous, Alzghoul, et al., 2024)	10	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.

Two further insights were provided in the literature. Abu Dabous, Alzghoul, et al. (2024) noted that roadway width and deck width were highly correlated; suggesting that one of the features could be chosen for inclusion. Ghafoori et al. (2024) found that deck width was a major contributor to the degradation of reinforced concrete girder/beam element, but also impacted reinforced concrete bridge rail. Showing that the feature is an important factor to consider.

The feature could simply be captured once in an inspection where a measurement could be made or through a inspection drawing.

Based on the findings from the literature review, incorporating Deck width into a deterioration model could be beneficial. This is based on two reasons. Firstly, the results of the impact assessment suggest that in certain contexts the feature can be important, although there was no consensus amongst literature of its importance. Secondly, Ghafoori et al. (2024) provided insights that the feature has a strong impact on two components which often occur in bridges within the Netherlands, making it an important aspect to include.

Thickness of overlay

This feature refers to the thickness of the layer which is placed on top of a deck for cars to drive over. This feature was applied in 2 different papers. Choi et al. (2020) and Xu and Azhari (2021) both included the feature as they believed it affected the deterioration of decks.

Neither of these papers provided insights into the impact the feature had on the results but also did not provide any further insights.

Based on the found results it cannot be concluded that this feature could or couldn't impact the deterioration rate of bridges. There simply is too little information to make a fair assessment on the features importance.

4.1.2 Properties

In this sub-section the features related to a bridge's properties are described. Such features are not physically measurable and are most abstract. These include bridge age, Operating rating, type of service, Functional class, design load and component design type.

Bridge Age

The most occurring feature is that of the bridges age. The feature was used 21 times with an additional 3 papers using another form of documentation called 'bridge-built year' (Althaqafi & Chou, 2022; Lei et al., 2022; Rajkumar et al., 2023). The high usage suggests that a bridges age has a big impact on a bridge's life span. Bridge age was implemented in papers for 4 different reasons. Firstly, from the papers only two added the feature based on findings in literature (Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023). Secondly, 5 papers added the feature because of the authors believe that age was important (Goyal et al., 2020; Lei et al., 2022; Miao & Yokota, 2024; Shen et al., 2023; Xia et al., 2022a). Third, 9 papers, applied a form of preliminary feature selection from which the age of the bridge came out as an important feature (Abu Dabous, Alzghoul, et al., 2024; Almarahlleh et al., 2024; Althaqafi & Chou, 2022; Chang & Maguire, 2020; Ghafoori et al., 2024; Omar & Moselhi, 2022; Rajkumar et al., 2023; Zhang & Marsh, 2020; Zhang et al., 2024). Lastly, three papers provided no reasoning for why they added age as a feature (Asghari & Hsu, 2022; Liu et al., 2023; Liu & Zhang, 2020).

The impact of the age of a bridge, in comparison to other features, was compared by 9 different papers, this comparison is presented in Table 36.

Table 36 Impact ranking of Bridge age feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Zhang & Marsh, 2020)	2	6	Wyoming, USA.	Deck	Preliminary feature selection
(Abu Dabous, Alzghoul, et al., 2024)	2	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.
(Ghafoori et al., 2024)	1	18	Colorado, USA.	Multiple components.	Preliminary feature selection
(Rajkumar et al., 2023)	Top 5	16	Florida, USA.	Multiple components.	Prevalence in literature
(Chang & Maguire, 2020)	1	27	Wyoming, USA.	Multiple components.	Preliminary feature selection
(Zhang et al., 2024)	1	6	Texas, USA.	Deck	Preliminary feature selection
(M. A. Rahman et al., 2023)	1	16	Florida, USA.	Steel Coating	Prevalence in literature
Average Impact					
(Omar & Moselhi, 2022)	4	7	Iowa, USA.	Deck	Prevalence in literature
(Md. Ashiqur Rahman et al., 2023)	24	42	Florida, USA.	Steel Coating	Prevalence in literature

A further 4 papers provided additional insights into the findings. (Abu Dabous, Alzghoul, et al., 2024) found that age was highly correlated to superstructure and substructure conditions as well as structural evaluation. They also found that simply using the age of a bridge and the superstructure condition rating could estimate the condition rating to a reasonable degree with a Mean Average error score of 0.435. (Ghafoori et al., 2024) found that age has a strong correlation with the deterioration of reinforced concrete abutments, steel protective coatings, stell bridge rails, wearing surfaces, reinforced concrete decks, prestressed girders/beams and much more. The author specifically mentions however, that this age is not directly related to these elements and is rather an overall age of the bridge; thus reducing its accuracy. (Chang & Maguire, 2020) grouped their bridges by age to determine their distribution of conditions scores; their study found that condition ratings tend to drop significantly at the beginning of a elements life and then stays consistent. (Zhang et al., 2024) further suggests that grouping bridges into age groups is a desirable thing to do as their ages often correlate with certain steps in their deterioration process. (M. A. Rahman et al., 2023) Noted that as age of a bridge increases a coatings bond tends to decline due to the effects of corrosion, which was demonstrated in the importance of the feature.

In terms of geography there doesn't appear to be a general trend in locations where the feature may or may not be more useful. There is a limitation in the fact that this feature was only compared to other features in the context of the USA. Whereas the future was used in other locations such as China (Lei et al., 2022; Shen et al., 2023; Xia et al., 2022a) and Korea (Han, 2021). Perhaps the features importance may vary here due to a different maintenance strategy where bridges are more maintained; thus, resulting in a less obvious relationship between time and condition score.

What is aimed at predicting seems to show that the feature is useful in many contexts. The feature is impactful for predicting both Decks, Multiple components and steel coatings. The paper by Ghafoori et al. (2024) also highlighted this through its assessment of the feature against many types of components. It should be noted that it might be useful to take the ages of individual components rather than of the whole bridge as components may be replaced.

Based on the findings from the literature study it is believed that the bridge age feature has an important impact on predicting the future condition state of a bridge. This argument is based on three primary reasons. Firstly, while some studies relied on findings from existing literature, a larger portion incorporated bridge age based on either authors' beliefs in its importance or preliminary feature selection methods that highlighted it as significant. This varied basis for inclusion, particularly the prevalence of empirical validation in feature selection methods, underscores that age is not only assumed relevant but is statistically supported as a crucial factor. Secondly, several papers (Abu Dabous, Alzghoul, et al., 2024; Ghafoori et al., 2024; Chang & Maguire, 2020; Zhang & Marsh, 2020; Zhang et al., 2024) found strong correlations between bridge age and condition scores of various components. For instance, Ghafoori et al. (2024) noted that age is significantly correlated with the degradation of concrete abutments, steel coatings, and bridge decks and many more. Third, the literature also suggests bridge age as a versatile feature with application across multiple structural prediction goals, including deck condition, multiple components, and steel coatings. In addition, it is recommended that this bridge age is transformed to an element or component-based age metric, and these may be replaced over time; thus providing a clearer picture of the degradation of individual parts of a bridge.

Operating Rating

The operating rating is the maximum permissible loads on the bridge, which is higher than the design load. This feature was used a total of 8 times. 3 different reasons were presented for the inclusion of the feature. Firstly, (Leiva-Maldonado et al., 2023) implemented the feature due to its usage in literature. Secondly, 5 papers included the feature as the authors believed it to be important for determining deterioration rate (Abu Dabous, Alzghoul, et al., 2024; Abu Dabous, Ibrahim, et al., 2024; Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023; Xia et al., 2022a). Lastly, two papers included the feature as it was found to be important through a preliminary feature selection (Ghafoori et al., 2024; Omar & Moselhi, 2022).

5 papers compared the operating ratings impact to other features. These are presented in Table 37 below.

Table 37 Impact ranking of Operating rating feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Omar & Moselhi, 2022)	3	7	Iowa, USA.	Deck	Prevalence in literature
Average Impact					
(Ghafoori et al., 2024)	8	18	Colorado, USA.	Multiple components.	Preliminary feature selection
Low Impact					
(Abu Dabous, Alzghoul, et al., 2024)	9	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.
(M. A. Rahman et al., 2023)	15	16	Florida, USA.	Steel Coating	Prevalence in literature
(Md. Ashiqur Rahman et al., 2023)	35	42	Florida, USA.	Steel Coating	Prevalence in literature

Ghafoori et al. (2024) found that operating rating is found to have the a strong correlation on steel protective coatings, steel bridge rails, and reinforced concrete decks; interestingly Md. Ashiqur Rahman et al. (2023); M. A. Rahman et al. (2023) do not share these findings as their study on steel coatings resulted in the feature having a low impact.

The feature could be captured by existing knowledge on the bridge's maximum capacity or through a calculation of its capacity in a 'recalculation' as described in chapter 3.

The findings suggest that, while the feature may be useful in certain situations, it generally has a low impact. Therefore, its inclusion could be worthwhile, though its implementation cannot guarantee significant influence on the deterioration model. This is based on 2 reasons. Firstly, the impact results indicate that operating rating often does not have a large impact on deterioration rate. Secondly, the results indicate that there is disagreement amongst authors on the impact the feature has on different components. Omar and Moselhi (2022) and Ghafoori et al. (2024) found that deck deterioration is strongly correlated with operating rating, however the results from Abu Dabous, Alzghoul, et al. (2024) shows this less so. In addition, Ghafoori et al. (2024) found that steel coatings are strongly related to the feature but the results from M. A. Rahman et al. (2023) and Md. Ashiqur Rahman et al. (2023) indicate this is less the case.

Design Load/Inventory Rating

The Design load represents a capacity level indicating the maximum load that a structure can safely carry over an indefinite period (Zhang & Marsh, 2020), the inventory rating refers the truck loads that the bridge can carry safely on a regular basis (Md. Ashiqur Rahman et al., 2023); these two features are thus very similar to each other and will therefore be combined and considered as 'design load' from now on. The feature was applied in 9 papers. The reasons for inclusion were the following. Firstly, 2 papers included design load due to its prevalence in literature (Omar & Moselhi, 2022; Md. Ashiqur Rahman et al., 2023). Secondly, 3 papers added it as the authors believed the feature to be important for determining the deterioration rate of their component (Abu Dabous, Alzghoul, et al., 2024; Choi et al., 2020; Moscoso et al., 2024). Lastly, 4 papers added the feature after a preliminary selection and finding Design load to be important (Almarahlleh et al., 2024; Althaqafi & Chou, 2022; Ghafoori et al., 2024; Zhang & Marsh, 2020).

7 papers investigated the design loads impact in comparison to other features, this is presented below in Table 38.

Table 38 Impact ranking of Design Load feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Md. Ashiqur Rahman et al., 2023)	13	42	Florida, USA.	Steel Coating	Prevalence in literature
Average Impact					
(Ghafoori et al., 2024)	10	18	Colorado, USA.	Multiple components.	Preliminary feature selection
(Abu Dabous, Alzghoul, et al., 2024)	5	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.
(Zhang & Marsh, 2020)	4	6	Wyoming, USA.	Deck	Preliminary feature selection
Low Impact					
(Omar & Moselhi, 2022)	5	7	Iowa, USA.	Deck	Prevalence in literature
(Almarahlleh et al., 2024)	8	8	Michigan, USA.	Deck	Preliminary feature selection
(Moscoso et al., 2024)	6	8	Indiana, USA.	Deck	Author believes the feature impacts deterioration.

A further 2 papers provided insights on these findings. Abu Dabous, Ibrahim, et al. (2024) noted that Design load only was deemed a significant factor in 5 of the 8 different feature selection algorithms which were investigated; suggesting that it is not always considered an important factor and depends on how features are interpreted by these algorithms. Although in general Design Load scored lower in the paper by Moscoso et al. (2024) the feature did have a higher impact on different types of decks; it had a higher significance score for concrete slabs, steel and prestressed concrete box girders.

The results from the literature study indicate that design load could be a feature worth considering when creating a deterioration model; however, its impact could be limited. This is based on 2 reasons. Firstly, the impact in various papers indicate that the feature does have an impact in certain contexts; but most papers find that it is not highly significant. Secondly, its impact seems to also vary when considering a single type of component. Design Load had different impact amongst studies concerning decks with Moscoso et al. (2024) providing insights that this could be due to the type of deck that is predicted on.

Functional Class

The functional class refers to the context for which a bridge is designed; for example rural or urban (Zhang & Marsh, 2020). The feature was applied 6 different times. The feature was included in 3 different papers. Moscoso et al. (2024) included the feature as they believed it could impact their components deterioration rate. Ghafoori et al. (2024); Zhang and Marsh (2020) applied a preliminary feature selection and found this feature to be the most important. Lastly, three papers provided no explanation for their inclusion of functional class (Asghari & Hsu, 2022; Liu et al., 2023; Liu & Zhang, 2020).

3 papers investigated the impact functional class had in comparison to other features applied. This comparison is presented in Table 39.

Table 39 Impact ranking of Functional class feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Moscoso et al., 2024)	2	8	Indiana, USA.	Deck	Author believes the feature impacts deterioration.
Low Impact					
(Zhang & Marsh, 2020)	5	6	Wyoming, USA.	Deck	Preliminary feature selection
(Ghafoori et al., 2024)	15	18	Colorado, USA.	Multiple components.	Preliminary feature selection

Two further insights can be gained from these papers. Moscoso et al. (2024) presented that the functional class affects all types of decks they investigated a significant amount. Suggesting all types and materials may be affected by the feature. Ghafoori et al. (2024) showed that the feature however had no strong correlation to the degradation of any component they inspected.

The results indicate that the features impact cannot be determined based on the findings in literature. From the literature it seems functional class has either had an impactful result or a low impact on the prediction accuracy. This is further strengthened by the polar opposite conclusions of the papers by Moscoso et al. (2024) and Ghafoori et al. (2024) in terms of deck impact. It therefore is not clear whether the feature does or doesn't affect deterioration to a significant degree.

Type of Service

The type of service refers to what type of traffic goes over the bridge, usually either rail, maritime or car traffic. The feature can be considered under and over a bridge. This feature was applied in 4 different papers. The feature was included for 2 reasons. Firstly because it was often applied in literature (Leiva-Maldonado et al., 2023; Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023) and secondly because it was believed to impact the deterioration rate of bridges (Moscoso et al., 2024).

Three of the papers evaluated the features impact against others used in their studies. These results can be seen in Table 40.

Table 40 Impact ranking of type of service feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Md. Ashiqur Rahman et al., 2023)	1 (Under bridge)	42	Florida, USA.	Steel Coating	Prevalence in literature
(Md. Ashiqur Rahman et al., 2023)	6 (Over bridge)	42	Florida, USA.	Steel Coating	Prevalence in literature
(M. A. Rahman et al., 2023)	4 (Under bridge)	16	Florida, USA.	Steel Coating	Prevalence in literature
(M. A. Rahman et al., 2023)	6 (Over bridge)	16	Florida, USA.	Steel Coating	Prevalence in literature
Average Impact					
(Moscoso et al., 2024)	5 (Under bridge)	8	Indiana, USA.	Deck	Author believes the feature impacts deterioration.
Low Impact					
(Moscoso et al., 2024)	8 (Over bridge)	8	Indiana, USA.	Deck	Author believes the feature impacts deterioration.

Moscoso et al. (2024) shows that the type of service under the bridge does have a significant effect on deterioration it is not the case for all types of decks; namely steel bridges are less effected as well as concrete slabs, although both still score relatively high. M. A. Rahman et al. (2023) argues that the type of service affects deterioration due to a bridges transport type indicating near which environment it is situated; for example, if the under service is maritime the bridge must be located near water and perhaps even oceans. This could mean that moisture, salts and microorganisms could affect the structure. Submerged elements in these cases could be even further affected.

This feature could easily be captured in an inspection round if it is not already known by the owners of the object.

Although the type of service has not been applied frequently, the results indicate that the feature should be considered in a deterioration model. This is due to 3 reasons. Firstly, the impact scores indicate that the feature has a strong impact on the studies which included it. Although the limited papers suggest that steel coatings are more affected than decks Moscoso et al. (2024) has shown that the feature can also affect different decks more. Secondly, many environmental considerations could be captured in this feature as argued by M. A. Rahman et al. (2023). Lastly, although the feature seems to affect the type of service over the bridge less this difference could be reduced in the Netherlands as many aqueducts also exist in the country.

Component Design Type (also deck geometry)

Component Design type (CDT) refers to features which makes distinctions between a components different possible design styles. A wide range of this feature were incorporated in literature, each is described below in Table 41. There were 4 reasons for including the different features. Firstly, two papers included the feature due to its prevalence in literature (Leiva-Maldonado et al., 2023; Md. Ashiqur Rahman et al., 2023). Secondly, 4 papers added it as the authors believed it affected deterioration (Anderson et al., 2021; Choi et al., 2020; Miao & Yokota, 2024; Xia et al., 2022a). Third, 2 papers added the feature after preliminary feature selection (Althaqafi & Chou, 2022; Ghafoori et al., 2024). Lastly Lu et al. (2022) provided no reason for including the feature.

Table 41 different forms of design type applied in papers

Type of	Frequency	Sources
Deck Geometry	3	(Choi et al., 2020; Ghafoori et al., 2024; M. A. Rahman et al., 2023)
Bridge	3	(Althaqafi & Chou, 2022; Xia et al., 2022a; Zhang et al., 2024)
Girder	1	(Choi et al., 2020)
Support	2	(Althaqafi & Chou, 2022; Choi et al., 2020)
Overlay	1	(Choi et al., 2020)
Deck Structure	6	(Althaqafi & Chou, 2022; Anderson et al., 2021; Lu et al., 2022; Miao & Yokota, 2024; Md. Ashiqur Rahman et al., 2023; Zhang et al., 2024)
Membrane	5	(Liu et al., 2023; Liu & Zhang, 2020; Lu et al., 2022; Md. Ashiqur Rahman et al., 2023)
Deck Protection	4	(Anderson et al., 2021; Leiva-Maldonado et al., 2023; Lu et al., 2022; Md. Ashiqur Rahman et al., 2023)
Main span physical makeup	1	(Lu et al., 2022)
Span interaction	1	(Lu et al., 2022)
Structural configuration main span	1	(Lu et al., 2022)
Deck rebar	1	(Lu et al., 2022)

From these papers 9 provided an impact scoring in comparison to other features which were implemented. This can be seen in Table 42.

Table 42 Impact ranking of Component design type feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Md. Ashiqur Rahman et al., 2023)	3 (deck structure)	42	Florida, USA.	Steel Coating	Prevalence in literature
Average Impact					
(M. A. Rahman et al., 2023)	10 (deck geometry)	16	Florida, USA.	Steel Coating	Prevalence in literature
(Md. Ashiqur Rahman et al., 2023)	20 (Membrame)	42	Florida, USA.	Steel Coating	Prevalence in literature
Low Impact					
(Ghafoori et al., 2024)	19 (deck geometry)	20	Colorado, USA.	Multiple components.	Preliminary feature selection
(Zhang et al., 2024)	6 (Bridge)	6	Texas, USA.	Deck	Preliminary feature selection
(Zhang et al., 2024)	5 (Deck structure)	6	Texas, USA.	Deck	Preliminary feature selection
(Anderson et al., 2021)	1/3 phases of life (Deck structure)	11	Oregon, USA.	Decks	Author believes the feature impacts deterioration
(Md. Ashiqur Rahman et al., 2023)	41 (deck protection)	42	Florida, USA.	Steel Coating	Prevalence in literature
(Anderson et al., 2021)	1/3 phases of life (Deck protection)	11	Oregon, USA.	Decks	The author believes the feature impacts the deterioration

The following 3 insights were shared by the authors. (Zhang et al., 2024) found that adding the deck structure feature to its used feature grouping increased the accuracy of the model by a few percent. They also argue that deterioration must be modelled for a certain type of bridge; suggesting that the type affects the deterioration rate. However, this is not seen in the model's performance as the type of bridge was only the 6th most important feature. (Anderson et al., 2021) found that deck structure was a significant contributing factor for decks with a medium condition score, suggesting that the feature can be influential in different parts of a deck's life. The study also found that cast-inplace deck structure type was nearly six times more likely to be assigned a lower CR at any given time than were other deck structure types; indicating that the feature did in fact have a strong impact in certain contexts. . (Anderson et al., 2021) found that bridge decks, with a high condition score, with no protection are 22.5% more likely to be assigned a lower CR at any given time; indicating that this feature could be important for bridges at a certain time in their life.

The type of component that is installed could be captured simply in a inspection round, Set terminology must be created beforehand to ensure that this is captured in a systematic way and could be used for Machine Learning purposes.

Based on the results from literature it could be argued that the feature can have impact on deterioration, but that this impact may vary. This is based on 2 reasons. Firstly, the impact assessment indicates that most papers find the feature to be low to average in its impact. However, this contrasted by papers such as by Md. Ashiqur Rahman et al. (2023) which found that the type of deck structure realy matters for the deterioration rate of steel coatings. It is thus perhaps important in some contexts. Secondly, the paper by Anderson et al. (2021) indicates that these types of features may be important in certain life phases of bridge components and their impact is this limited to those phases; this could give a skewed perspective on the impact that a feature has if one looks over the entire life cycle of a bridge.

4.1.3 Material

In this sub-section features related to the type of material which is present in bridges are presented; two different features are assessed: Type of material and wearing surface.

Structural material

The structural material refers to the most common material present on a bridge. This feature was included in 12 unique papers.

3 different reasons were mentioned by authors for the inclusion of the feature. Firstly, 5 papers added the feature due to its popularity in literature (Kale et al., 2021; Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023; Wang et al., 2022; Zhang et al., 2024). Secondly, 4 papers added the feature as the authors believed it to be an important factor to consider in deterioration modelling (Anderson et al., 2021; HADJI, 2020; Shen et al., 2023; Wei et al., 2024). Lastly, 4 papers provided no reasoning (Asghari & Hsu, 2022; Liu et al., 2023; Liu & Zhang, 2020; Lu et al., 2022).

5 papers assessed structural materials impact against other features. These results are presented below in Table 43.

Table 43 Impact ranking of structural material feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Md. Ashiqur Rahman et al., 2023)	4 (approach material)	42	Florida, USA.	Steel Coating	Prevalence in literature
(Md. Ashiqur Rahman et al., 2023)	8 (main material)	42	Florida, USA.	Steel Coating	Prevalence in literature
(Kale et al., 2021)	1	9	The entire USA.	Superstructure	Prevalence in literature
Average Impact					
(M. A. Rahman et al., 2023)	8	16	Florida, USA.	Steel Coating	Prevalence in literature
(Zhang et al., 2024)	3	6	Texas, USA.	Deck	Preliminary feature selection
(Anderson et al., 2021)	2/3 phases of life	11	Oregon, USA.	Decks	Author believes the feature impacts deterioration

Md. Ashiqur Rahman et al. (2023) noted that the material approach and main material used have a significant impact on bridges in their initial stages of life. Kale et al. (2021) believes that material quality improves over time thus they considered this feature; if age was constant material had the largest impact on deterioration rate. It was found that young bridges are often made of prestressed concrete, which overall performed significantly better than other material types. A further analysis was also conducted where the precipitation was compared to the type of material and what affect this had on material choice; it was found that the distribution of material types changed depending on whether the region has high or low precipitation. Anderson et al. (2021) found that material type had a large effect on bridges with a high or medium condition rating and significantly affected their deterioration rate. In addition, the authors note that unobservable characteristics such as the materials properties and construction practices are not accounted for in this feature which could mean that the feature does not capture significant factors on its quality.

The features information could be captured in an inspection round and is already part of the NEN 2767-4 which means its incorporation is relatively simple.

Based on the results from literature the feature should be included in a deterioration model. This is based on 3 reasons. Firstly, the impact assessment indicates that the feature is important in many papers with differing prediction goals. Secondly, insights from Md. Ashiqur Rahman et al. (2023) Anderson et al. (2021) indicate that bridge component deterioration rate is especially affect by material in its initial stages of life; thus it is important to consider. Lastly, the feature is already captured by the NEN 2767-4 and would cost no additional effort to implement.

Wearing Surface

The type of wearing surface refers to the material used on decks for cars to drive over. This feature was used in 8 different papers. Three different reasons for provided for including the feature in the studies. Firstly, Md. Ashiqur Rahman et al. (2023); M. A. Rahman et al. (2023) added the feature due to its popularity in literature. Secondly, Anderson et al. (2021); Goyal et al. (2020) added the wearing surface as they deemed it an important feature for modelling deterioration. Third, Ghafoori et al. (2024) conducted a preliminary feature selection and found it was important to add. Lastly, three papers provided no reason for including the feature (Liu et al., 2023; Liu & Zhang, 2020; Lu et al., 2022).

4 papers provided a comparison of the wearing surface impact in comparison to other applied features. This evaluation is presented in Table 44.

Table 44 Impact ranking of Wearing surface feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Anderson et al., 2021)	3/3 phases of life	11	Oregon, USA.	Decks	Author believes the feature impacts deterioration
(Md. Ashiqur Rahman et al., 2023)	7	42	Florida, USA.	Steel Coating	Prevalence in literature
Low Impact					
(Ghafoori et al., 2024)	16	18	Colorado, USA.	Multiple components.	Preliminary feature selection
(M. A. Rahman et al., 2023)	11	16	Florida, USA.	Steel Coating	Prevalence in literature

A further 2 insights were provided. Anderson et al. (2021) found that the feature had a significant impact on the deterioration of decks throughout any phase of its life. Ghafoori et al. (2024) also found that reinforced concrete deck deterioration is strongly linked to the wearing surface present on it. Although it did not affect other parts of the bridge as much.

The features information could be captured in an inspection round and is already part of the NEN 2767-4 which means its incorporation is relatively simple.

Based on the results the feature could impact a deterioration model significantly, but only for deck deterioration. This is based on 2 reasons. Firstly, the results of the impact assessment indicate that the feature has either a significant or low impact on deterioration modelling. However, when taking a closer look at these results it becomes apparent that the feature mostly affects decks. As decks are an important part of a bridge it should thus be considered. Secondly, as this information is captured in the NEN 2767-4, and it has been shown that including the material type can be important this feature is not difficult to implement.

Material characteristics

Material characteristics are addition properties stored about materials which can be useful in deterioration modelling. Different types of this information exist such as chloride related properties of the material (Xu & Azhari, 2021; Yang et al., 2024), Concrete strength (Yang et al., 2024; Yuan et al., 2020), and various other properties (Lai et al., 2024). Two reasons were provided for including the feature. Yang et al. (2024); Yuan et al. (2020) included the feature because of its proven effectiveness in previous literature, Lai et al. (2024); Xu and Azhari (2021) believed the features to be important for determining the deterioration process.

None of these papers provide an impact assessment of the features importance for predicting deterioration rates.

Such information could be captured through specialised inspections or technical reports which are stored by the government bodies.

Based on the results it cannot be concluded whether additional characteristics of materials should be included in deterioration models. Although the papers which these features seem to have success it is unclear to which extent these additional properties contribute to that success. In addition, some of these papers look at very specific deterioration on one small part of a bridge and do not consider the whole bridge; making it difficult to know whether this information could be worth storing for an entire bridge.

Soil type

The soil type is the material which the bridge is constructed on. This feature was only applied once by Asghari and Hsu (2022) with author provided no reason for why the feature was included.

The capture of this information would require soil inspections to a certain depth to determine the types of soil layers that are present near the bridge.

The features impact cannot be determined based on the results, and this cannot be recommended to be included in a deterioration model. It should be noted that this feature could have an impact on bridges in the Netherlands as most of our soil is made of peat and clay, which are challenging materials to build on. There have been several cases of tunnels collapsing due to soil shifts. It thus could still have an impact but cannot be proven through the literature study.

4.1.4 Traffic data

In this sub-section the features which are related to traffic data are presented. Traffic features appeared in many papers within the literature study.

Average Daily Traffic.

One of the most occurring features which appeared in the literature study was that of average daily traffic (ADT). The feature was used in 21 papers, which makes it the most used feature besides historic condition scores. Abu Dabous, Ibrahim, et al. (2024) noted different, though related features which they also applied such as year of future ADT, Annual ADT and Future ADT. The high occurrence suggests that ADT plays an important role in estimating the deterioration of bridges. The feature was applied for 4 reasons. Firstly, 8 papers chose to include ADT because of its prevalent usage in literature (Almarahlleh et al., 2024; Kale et al., 2021; Liu et al., 2023; Liu & Zhang, 2020; Omar & Moselhi, 2022; Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023; Rajkumar et al., 2023), suggesting that the feature has a recognised impact on bridges in a wide context. Secondly, 8 papers included ADT Because the component, which it aims at predicting, is impacted by the feature according to the author (Abu Dabous, Alzghoul, et al., 2024; Abu Dabous, Ibrahim, et al., 2024; Goyal et al., 2020; Lei et al., 2022; Miao & Yokota, 2024; Moscoso et al., 2024; Shen et al., 2023; Xu & Azhari, 2021; Yang et al., 2024). It suggests that including ADT is a form of 'common' sense. Thirdly, 3 papers performed a form of preliminary feature selection through algorithms, where a large group of features was reduced to a smaller subset (Althaqafi & Chou, 2022; Ghafoori et al., 2024; Zhang & Marsh, 2020). These papers show that ADT is thus a feature which is worth using. Lastly, 2 papers provided no explanation (Asghari & Hsu, 2022; Kossieris et al., 2024).

Nine papers compared ADT's significance to other features, which are presented in Table 45.

Table 45 Impact ranking of Average Daily Traffic feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion	Number of registered vehicles (FHWA, 2022)
Significant Impact						
(Zhang & Marsh, 2020)	1	6	Wyoming, USA.	Deck	Preliminary feature selection	890,285
(Rajkumar et al., 2023)	Cluster 1	4 Clusters	Florida, USA.	Multiple components.	Prevalence in literature	19,663,462
(M. A. Rahman et al., 2023)	2	16	Florida, USA.	Steel Coating	Prevalence in literature	19,663,462
Average Impact						
(Abu Dabous, Alzghoul, et al., 2024)	8	15	10 coldest USA states	Deck	Author believes the feature impacts deterioration.	21,655,843
(Ghafoori et al., 2024)	7	18	Colorado, USA.	Multiple components.	Preliminary feature selection	5,116,858
(Md. Ashiqur Rahman et al., 2023)	17	42	Florida, USA.	Steel Coating	Prevalence in literature	19,663,462
Low Impact						
(Moscoso et al., 2024)	7	8	Indiana, USA.	Deck	Author believes the feature impacts deterioration.	6,256,479
(Omar & Moselhi, 2022)	7	7	Iowa, USA.	Deck	Prevalence in literature	3,779,422
(Kale et al., 2021)	9	9	The entire USA.	Superstructure	Prevalence in literature	283,400,986

Four papers provided further elaboration on their significance findings. M. A. Rahman et al. (2023) noted that the feature being so important was not surprising as previous literature had also indicated that ADT had a large effect on corrosion induced failure due to frequency and volume of traffic. Ghafoori et al. (2024) found similar findings as their paper also identified that ADT has a strong correlation with the deterioration of steel protective coatings, but also steel bridge rails, and reinforced concrete decks. Moscoso et al. (2024) further presented the importance of the ADT feature when compared to differing structural materials; having a much higher impact on concrete slabs and steel than other types of bridges. Kale et al. (2021) noted that they were surprised by their results as they observed a very low association between ADT and bridge performance as it does not correlate with the findings of other studies.

It appears from Table 45 that there is no correlation between the component which the paper seems to want to predict and the impact of ADT. As most components are present in both papers which suggest ADT has a high impact and a low impact.

Papers which had their case study in Florida found that ADT was a more impactful feature than other locations; this could be due to the state having the third largest population in the USA and having a large number of registered vehicles; suggesting a lot of traffic. (Zhang & Marsh, 2020) which used data from Wyoming, the least populated state, does not support this argument by finding ADT the most important. Suggesting that this does not necessarily have to correlate.

ADT can be captured in many ways such as through camera's, sensors and manual surveys. Data could thus be captured in real time and be stored as an average over a year or exact numbers for each day of the year. The Netherlands has a many open sources of traffic data such as the National Road Traffic Databank (NDW), Central Bureau of Statistics (CBS) but also sources such as Google Maps could be applied to collect this data.

Based on the gathered information from literature, ADT could be included in a deterioration model for The Netherlands, as it holds potential predictive value for understanding bridge deterioration patterns.

This argument is based on 3 primary reasons. Firstly, Authors of 8 papers suggested that the feature does have an impact on the deterioration of bridges. There was some empirical validation for through feature selection where 3 papers selected ADT due to its impact when performing initial selection. Overall, the justification for including ADT in multiple studies indicates its value as a reliable predictor of bridge deterioration. Secondly, the features impact seemed to be varied amongst studies; exactly three studies found ADT to have significant, average and low impact. Studies such as those by M. A. Rahman et al. (2023) and Ghafoori et al. (2024) offer insight into ADT's impact on specific bridge components, such as steel protective coatings and concrete decks. However, variability exists across different studies regarding ADT's impact. For instance, Kale et al. (2021) found a low association between ADT and bridge performance, contrasting with other findings that report a high correlation between ADT and deterioration rates. This discrepancy suggests that while ADT could be significant, its impact might depend on context, such as bridge type, material, and specific environmental conditions.

Average Daily Truck Traffic

Average Daily Truck Traffic (ADTT) is another feature which occurred a lot in the literature, being applied in 18 of the investigated papers. Other features which were very similar to ADDT are overloading rate, which investigated the percentage of traffic which overloaded a bridge (Yang et al., 2024). This suggests that this feature also can play a significant role in determining the future state of bridge elements and components. Five papers added ADTT due to its prevalence, or proven effectiveness in literature (Kale et al., 2021; Leiva-Maldonado et al., 2023; Liu & Zhang, 2020; M. A. Rahman et al., 2023; Wang et al., 2022). A larger set of authors, 7 papers, added ADTT due to their believe that the feature affects bridge deterioration (Abu Dabous, Alzghoul, et al., 2024; Anderson et al., 2021; Choi et al., 2020; Goyal et al., 2020; Miao & Yokota, 2024; Xia et al., 2022a; Xu & Azhari, 2021). Two papers conducted a preliminary feature selection and found ADTT to be impactful (Ghafoori et al., 2024; Zhang et al., 2024). Two papers provided no explanation for the inclusion of Truck Traffic (Asghari & Hsu, 2022; Liu et al., 2023; Lu et al., 2022).

Five papers compared ADTT's significance to other features, which are presented in Table 46.

Table 46 Impact ranking of Average Daily Truck Traffic feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion	Registered trucks (FHWA, 2022)
Significant Impact						
(Lu et al., 2022)	1	14	Pennsylvania, USA.	Deck	No explanation	6,703,261
(Zhang et al., 2024)	2	6	Texas, USA.	Deck	Preliminary feature selection	15,202,307
(M. A. Rahman et al., 2023)	3	16	Florida, USA.	Steel Coating	Prevalence in literature	11,190,120
Average Impact						
(Kale et al., 2021)	4	9	The entire USA.	Superstructure	Prevalence in literature	172,932,334
(Anderson et al., 2021)	2/3 phases of life	11	Oregon, USA.	Decks	Author believes the feature impacts deterioration	2,625,318
Low Impact						
(Ghafoori et al., 2024)	13	18	Colorado, USA.	Multiple components.	Preliminary feature selection	3,481,941

A further 3 papers provided further elaboration on their findings. (Lu et al., 2022) suggested that ADTT could be a better dependant variable to apply when modelling deterioration, rather than time; suggesting that truck traffic has more of an influence than age on the bridges deck state. The paper did find that their fitted deterioration curve decreased in accuracy when taking ADTT as the dependant variable once

ADDT cumulatively became higher than 5 million trucks; suggesting that the feature is only effective to a certain extent of loading. M. A. Rahman et al. (2023) noted that that their finding that ADTT was an important feature was supported by literature that showed that steel coatings are indeed affected by the frequency and volume of heavy traffic. . Kale et al. (2021) noted, the same as Average Daily Traffic, that they were surprised by their results as bridge performance was less affected by ADTT as they had expected; however, ADTT shows a significantly higher impact when compared to ADT.

When assessing the impact against the prediction goal it appears that decks are more likely to be affected by heavy traffic than other parts of bridges. Particularly the highest impact scores are scored in papers related to decks; suggesting that this feature is worth adding for these.

Based on the found paper there seems a correlation in terms of Truck registrations and effects on deterioration. The studies which present a high impact all have higher registrations of trucks than the lower impact studies. Suggesting that these states have bridges with more truck traffic passing over them. Like the ADT, ADTT can be collected annually and averaged over the days. The volume would be that of 365 data points per year where velocity could depend on how the counter is set up, either through manual collection or through an IOT device.

Based on the gathered information from literature it can be deduced that ADTT may have a higher potential for predicting deterioration when compared to ADT and should thus be included for deterioration modelling. There are 4 reasons why this feature may be found to be important. Firstly, seven papers included ADTT based on the authors' reasoning that heavy traffic impacts bridge deterioration, showing how ADTT is seen as inherently tied to structural stress and wear (Abu Dabous, Alzghoul, et al., 2024; Anderson et al., 2021). The inclusion of ADTT in two papers after feature selection (Ghafoori et al., 2024; Zhang et al., 2024) further demonstrates its relevance, with data-driven methods identifying it as a priority variable for deterioration prediction. Secondly, the impact scoring of the feature demonstrated that the feature is less divided in its impact than ADT. Lu et al. (2022) suggested that ADTT might be an even better predictor of deck condition than age, as heavy truck traffic poses a substantial load on these structural components. This aligns with the findings of Kale et al. (2021), who found that while bridge performance generally showed a lower correlation with ADT, ADTT had a significantly greater impact on bridge deterioration. Third, the impact of ADTT appears particularly significant in predicting the deterioration of bridge decks. Studies like Lu et al. (2022) observed that bridge decks were especially susceptible to the wear associated with high truck traffic volumes, indicating that ADTT might be prioritized in models focusing on deck condition predictions, which is a part of the NEN 2767. Lastly, there appears to be a relationship between the impact the feature has an the case studies location amount of registered trucks; suggesting that the feature impacts a bridge more the more trucks drive over it.

National Highway System

The National Highway System (NHS) defines what type of traffic system the bridge is a part of; either primary/interstate or secondary. This feature was used 4 times. Suggesting it is not considered an important feature in the literature. 3 different reasons were mentioned by authors for the inclusion of this feature. Firstly, Goyal et al. (2020) added the feature for classifying bridges for their deterioration model. Secondly, Liu et al. (2023); Liu and Zhang (2020) provided no reasoning for the inclusion. Lastly, Moscoso et al. (2024) applied the feature as they believe it affected bridge deterioration.

Only 1 paper investigated the features importance in comparison to others. This is presented in Table 47.

Table 47 Impact ranking of National Highway system feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Moscoso et al., 2024)	1	8	Pennsylvania, USA.	Deck	No explanation

the USA NBI dataset was the only context in which the feature was used; although the Netherlands also has different categories of roads: Municipal, Provincial and National roads. This characteristic is inherently captured in the data from the NEN 2767 as the data is provided by the organisations which govern these categories individually. If data would be combined their NHS ranking could be worth capturing.

NBI is a constant feature; it does not change over time, unless the contextual situation changes dramatically. Thus, it is simple to implement.

Based on the literature the inclusion of the National Highway System (NHS) as a feature in bridge deterioration models could be considered; however, within the Dutch context it is inherently part of the data and thus is not necessary. This is based on three reasons. Firstly, NHS was used in only four studies, indicating that it is not widely recognized or valued as a significant factor in bridge deterioration assessments. Among the studies that included NHS, only one paper provided a rationale for its inclusion. Secondly, the feature does show high impact in the one paper which assessed its impact score in comparison with other features in their study; indicating it could be important. Lastly, while the Netherlands has its own categories of roads (Municipal, Provincial, and National), these classifications are already inherently considered if a bridges owner is documented; thus, there is no need for a unique feature for this.

4.1.5 Maintenance

In this sub-section the features which are related to maintenance are described. 3 unique features were identified: maintenance actions, maintenance responsibilities and maintenance costs.

Maintenance actions / improvement

The maintenance Actions feature refers to maintenance activities which are performed on bridges. In addition to this we have included maintenance improvement, which refers to the increased condition score of an element after maintenance. This was done as these two are almost identical in their purpose. These features will be referred to as Maintenance Action (MA) These features were used in a total of 10 literature sources. MA was applied for 3 different reasons. Firstly, Wang et al. (2022) applied MA to compensate for the change in condition score of elements. Secondly, deterioration rate may be affected by maintenance activities (Alonso Medina et al., 2022; HADJI, 2020; Kale et al., 2021; Lei et al., 2022; Oyegbile et al., 2021; Shen et al., 2023; Wang et al., 2022; Yosri et al., 2021). Lastly, it was applied to predict when maintenance will be required (Alonso Medina et al., 2022; HADJI, 2020; Han, 2021).

Only one paper ranked MA's impact in comparison to other features, which is presented in Table 48.

Table 48 Impact ranking of Maintenance action feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Kale et al., 2021)	3	9	The entire USA.	Superstructure	Prevalence in literature

Kale et al. (2021) noted that maintenance, in combination with bridge material type and snowfall were able to explain a bridges deterioration. In addition, it was found that considering these MAs could account for missing records. However, their work did not consider specific maintenance actions, which could be a limitation; it was suggested that such a thing could easily be implemented in the future.

It is not believed that either geography or what component or element will have any impact on the importance of this feature.

Maintenance actions could be captured by Asset Managers or civil engineers working in the field. Their change in condition score could be recorded and at what date it was performed. Such maintenance activities could be linked to individual components so to create a more thorough maintenance history of an element or component.

Built on the findings in the literature study it can be argued that MA must be included in a deterioration model as it provides significant impact on deterioration prediction. This is based on 3 primary reasons. Firstly, MA has direct effect on the condition scores of bridge elements. As observed by Wang et al. (2022), MA can compensate for changes in condition scores resulting from maintenance activities. This relationship highlights that maintenance not only prevents deterioration but can actively improve the state of bridge components. By integrating MA into prediction models, researchers can account for these positive changes, leading to more accurate forecasts of bridge health and longevity. Secondly, several studies suggest that maintenance activities significantly influence deterioration rates of components and bridges (Alonso Medina et al., 2022; HADJI, 2020; Kale et al., 2021; Lei et al., 2022; Oyegbile et al., 2021; Shen et al., 2023; Wang et al., 2022; Yosri et al., 2021). Understanding how different maintenance actions affect the rate of deterioration allows for better modelling of how long bridges can remain serviceable. Third, MA can serve a crucial role in predicting when future maintenance will be required (Alonso Medina et al., 2022; HADJI, 2020; Han, 2021). This predictive aspect is essential for asset management, allowing for proactive maintenance strategies rather than reactive ones.

Maintenance responsibilities

Maintenance responsibilities refer to who must maintain the bridge and ensure it is in functioning order. This feature was used in 7 different papers; ranking it relatively high in how frequently the feature is applied. The feature was applied for 4 different reasons. Firstly, 4 papers applied the feature due to its popularity (Kale et al., 2021; Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023). Secondly, (Anderson et al., 2021) argued that it was an important contributing feature. Third, (Zhang & Marsh, 2020) performed a preliminary feature selection. Lastly, the remaining two papers provided no explanation (Liu et al., 2023; Liu & Zhang, 2020).

5 papers compared the features impact to other features. An overview of these scores is provided in Table 49.

Table 49 Impact ranking of Maintenance Responsibilities feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Anderson et al., 2021)	Top 5	11	Oregon, USA.	Decks	Author believes the feature impacts deterioration
(M. A. Rahman et al., 2023)	5	16	Florida, USA.	Steel Coating	Prevalence in literature
(Md. Ashiqur Rahman et al., 2023)	2	42	Florida, USA.	Steel Coating	Prevalence in literature
Average Impact					
(Zhang & Marsh, 2020)	3	6	Wyoming, USA.	Deck	Preliminary feature selection
Low Impact					
(Kale et al., 2021)	8	9	The entire USA.	Superstructure	Prevalence in literature

3 papers provided additional insights into their findings. Anderson et al. (2021) found that the organisation who had Maintenance Responsibilities had a large effect on bridges condition rating dropping. Whether a county or state had responsibility affected deterioration both in early, medium and late life of the bridge, where different affects were observed for different organisations. M. A. Rahman et al. (2023). Zhang and Marsh (2020) compared the differences of owner of the structure to the maintenance responsibility and found that there was a strong correlation between the two; however, the maintenance responsibility feature had a stronger correlation to bridge deterioration and was thus used.

Geography and element/component most likely are not affected by this feature.

Maintenance responsibilities could be captured per bridge and changed overtime if contracts are provided to a different maintainer. This feature could also be applicable if data from different municipalities and provinces are combined as each organisation may have different maintainers and maintenance regimes. In addition, it could provide insights into the performance of maintainers as their deterioration rate can be compared to others.

Based on the findings from the body of literature which included the feature it can be determined that the feature should be worth including in a deterioration model in the Netherlands. This is based on 3 reasons. Firstly, the reasoning for the features inclusion was quite ambiguous with only one author suggesting that the feature was important for prediction impact and this only being empirically validated by (Zhang & Marsh, 2020). Secondly, the impact scoring of different papers did reveal that the feature does hold significance in certain contexts. As highlighted by Anderson et al. (2021), the organization responsible for maintenance significantly affects the condition rating of bridges. The findings suggest that different maintenance regimes employed by counties or states can lead to variations in deterioration rates, underscoring the feature's importance in accurately modelling bridge health. The comparative analysis conducted by Zhang & Marsh (2020) revealed a strong correlation between the owner of the structure and maintenance responsibility, with the latter showing an even stronger correlation to deterioration. Third, Including Maintenance Responsibilities allows for the possibility of benchmarking the performance of different organizations responsible for maintenance. By comparing deterioration rates across various maintainers, stakeholders can identify best practices and potentially enhance maintenance strategies. The feature could thus hold some relevance, but it is not completely clear if this would be the case within the Dutch context.

Maintenance cost

Maintenance cost refers to the cost which is related to a maintenance action. Although this does not influence deterioration it can be an important factor to consider when predicting maintenance. 3 papers considered this feature. There are 3 reasons why this feature was considered. Shen et al. (2023) applied maintenance cost in their model to estimate the allocation of funding in the future, HADJI (2020) applied it to estimate the cost of maintenance for bridges and Han (2021) applied it to estimate the lifetime cycle cost of bridges. This shows how the feature can be applied for estimating different things.

Because the feature does not affect deterioration no paper investigated its importance to other features. Maintenance cost is, however, an important feature to consider in maintenance data as it can provide important insights for Asset managers.

The feature would be recorded in maintenance actions and could then also become part of the maintenance history of the bridge's asset or feature.

Based on the findings it can be determined that the feature would not pose any benefit for a deterioration model but could be a valuable feature for aiding government bodies in predicting the cost of maintenance. This is bassed on 2 reasons. Firstly, the inclusion in literature shows that the aim of including this feature was to estimate budgets, predict maintenance or life cycle costs. Secondly, if the maintenance actions feature is used including this information could be relatively simple and thus be worth including for government bodies to gain further insights.

4.1.6 Geographical

In this subsection features related to a geographic location are presented. Two distinct features were identified: Latitude/longitude and region/district.

Latitude/Longitude

Latitude and Longitude provides a means of locating a bridge in the world. This feature was applied in 3 different papers. There was only one paper which provided a reason for including this feature. Ghafoori et al. (2024) performed a Preliminary feature selection and the remaining two papers provided no explanation Liu et al. (2023); Liu and Zhang (2020).

Ghafoori et al. (2024) also provided a ranking of the feature when compared to others. This can be seen in Table 50.

Table 50 Impact ranking of latitude/longitude feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Ghafoori et al., 2024)	2 and 3	18	Colorado, USA.	Multiple components.	Preliminary feature selection

Ghafoori et al. (2024) notes that Latitude and Longitude have significant impacts on the deterioration of various bridge elements. This is most likely due to the correlation this feature has with various factors such as climate and weather. The components which are most impacted by this feature are made of reinforced concrete and steel.

The latitude and Longitude of a bridge can easily be captured through software such as GIS, where often this type of data is already stored. In addition, it could also be captured simply in an excel sheet. This is a feature which only must be captured once.

Based on the findings from the literature study it can be suggested that this feature could play a role in deterioration modelling in the Netherlands. This is based on two reasons. Firstly, the work by Ghafoori et al. (2024) which shows that this feature can affect many different components; listing 15 different components. Showing its significant contribution to modelling deterioration for a wide range of components. Secondly, However, it should be noted that this paper is the only one which presents a case for the feature in terms of its impact and whilst the feature is applied in 2 other papers the contribution the feature made in their studies is not documented. Therefore, it cannot be guaranteed that this feature would necessarily play a role in a deterioration model in the Netherlands.

Region/District

The region/district of a feature refers to the area in which a bridge is located. This could be a state, province or biome. It is thus like latitude/longitude but takes a more abstract measure of where a bridge is located. A similarly applied feature was used in the paper by Anderson et al. (2021), which applied 'climate group' in its study. The feature was used in 6 different papers. There were 4 unique reasons for including the feature. Firstly, Kale et al. (2021) included the feature as it was prevalent in literature. Secondly, three papers added regions/district as these had different climates that could affect deterioration effects (Anderson et al., 2021; Goyal et al., 2020; Wang et al., 2022; Xia et al., 2022a). Lu et al. (2022) provided no explanation for using the feature.

Two papers compared the ranking of region/district against other features applied in their research, this is presented in Table 51.

Table 51 Impact ranking of Region/District feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Anderson et al., 2021)	3/3 phases of life	11	Oregon, USA.	Decks	Author believes the feature impacts deterioration
Low Impact					
(Kale et al., 2021)	7	9	The entire USA.	Superstructure	Prevalence in literature

Kale et al. (2021) notes that the climate of a region is shaped by several factors, including latitude, elevation, topography, and prevailing winds. They took that as a generic term of 'region' but only had a slight association and noted they wanted to test geographic locations on a finer level in the future. Anderson et al. (2021) found that the feature had an impact on bridges in all stages of its life; suggesting that the feature does have a significant impact on bridges. In addition, their study showed that different climates affect bridges in different ways dependant on their condition score. For example, bridges in cascading mountains with a high condition score would be less likely to drop in condition score than those with an already lower condition score. It should be noted that Ghafoori et al. (2024) also compared the latitude/longitude feature to those of region/district and found that latitude/longitude had more impact on bridge deterioration.

This feature would be captured similarly to the latitude and longitude feature but would be more abstract. Asset Managers could group their assets into regions themselves or could be done by a coordinate system. This feature would be set once and forgotten.

The literature study reveals that the feature could be considered for a bridge deterioration model in the Netherlands; however, a more finely tuned location may be desirable. This is based on two reasons. Firstly, the results indicate that the climate in a region can have impact through a decks entire life cycle based on the study by Anderson et al. (2021), however the study Kale et al. (2021) suggests that its impact could perhaps be less significant. Interestingly, these two papers both consider different parts of the structure, a deck is usually more affected by the climate as it is more exposed whereas a superstructure is covered by the deck and thus more covered. Secondly, the interpretations of results by Kale et al. (2021) indicate that a finer measure of location could perhaps be suitable and was also suggested by Ghafoori et al. (2024).

4.1.7 Inspection

This sub-section presents any feature which in some way involves inspecting bridges. The section consists of 3 unique features: Historic condition scores, structural evaluation, sensors.

Historic condition scores

Historic condition scores (HCS) are one of the features considered in many studies. This refers to a long-term record of a bridge's condition, of the same or different components, over time, which is used to help predict its future state. In contrast, one could also predict a bridges condition score based simply on its current state and other features. Historic condition scores were applied in 17 unique papers. The feature was applied for 4 reasons. Firstly, 5 sources applied HCS because it had previously been applied in literature (Collins & Weidner, 2023; Leiva-Maldonado et al., 2023; Omar & Moselhi, 2022; Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023). Secondly, three papers included HCS after a preliminary feature selection (Abu Dabous, Alzghoul, et al., 2024; Almarahlleh et al., 2024). Third, 9 papers applied the feature because it was the only feature which was trained on, where some used other features to group bridges into different categories; think of deterioration curves being modelled (Alonso Medina et al., 2022; Asghari & Hsu, 2022; Calvert et al., 2020; HADJI, 2020; Han, 2021; Oyegbile et al., 2021; Shen et al., 2023; Xia et al., 2022a; Yosri et al., 2021). Lastly two papers provided no reasoning (Liu et al., 2023; Liu & Zhang, 2020)

4 papers provided an impact evaluation of the feature compared to others used in their study, these are described below in Table 52.

Table 52 Impact ranking of Historic Condition Scores (HCS) feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Omar & Moselhi, 2022)	1	7	Iowa, USA.	Deck	Prevalence in literature
(Abu Dabous, Alzghoul, et al., 2024)	1 and 4	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.
Average Impact					
(Md. Ashiqur Rahman et al., 2023)	11 and 33 and 37	42	Florida, USA.	Steel Coating	Prevalence in literature
Low Impact					
(M. A. Rahman et al., 2023)	14 and 16	16	Florida, USA.	Steel Coating	Prevalence in literature

3 further insights are provided by the authors of these papers. Omar and Moselhi (2022) found that their aim of predicting deck deterioration was mostly influenced by the condition scores of superstructures. Abu Dabous, Alzghoul, et al. (2024) investigation into the influence of features found similar results where the condition score of superstructures was the most important feature to influence decks, with substructure condition scores being the 4th most important. Md. Ashiqur Rahman et al. (2023); M. A. Rahman et al. (2023) both investigated the features which affect steel coatings. Both these found that condition scores of superstructure, deck and substructure did have some influence on the coatings, although their impact was more limited. Although not part of the papers which provided an impact scoring table Calvert et al. (2020); Shen et al. (2023) also investigated the defect transmission of defects in specific components to others. This paper for, example found that particularly defects in deck pavements, expansion joins and bearings can lead to defects occurring in other parts of a bridge.

Condition scores are captured in different velocities dependant on what is required by a countries standard. The NBI in the USA and the Korean standard require an inspection to be performed every 2 years (Choi et al., 2020; Lu et al., 2022; Xu & Azhari, 2021; Yosri et al., 2021). In China and France it is usually every 3 years (HADJI, 2020; Xu & Azhari, 2021). Volume of data also depends on the standards decomposition requirements. Typically, the NBI and Chine standard require 3 different elements conditions to be recorded; Deck, Superstructure and substructure (Abu Dabous, Alzghoul, et al., 2024; Lei et al., 2022; Omar & Moselhi, 2022). Although a slightly different standard exists called the NBE, where elements are broken down into components (Ghafoori et al., 2024); giving a higher resolution image of defects occurring on bridges. The Korean standard also taken a 'higher resolution' approach with bridges being divided into more components (Choi et al., 2020). The NEN 2767 already captures this information but usually as shown in chapters 2 and 3 with an interval of around 5 years. The Schouw which was discussed in 3.2.1 presents an inspection type where data is also collected on a yearly basis.

Based on the findings from the sources it can be strongly recommended that historic condition scores should be included in a deterioration model for the Netherlands. This is based on 3 reasons. Firstly, the impact table shows a bias towards prediction goals with decks. It is believed that this is caused because steel coatings are more likely to be influenced by other factors such as the environment. Thus, the features impact could simply just be limited due to the prediction goal in these papers. Secondly, Calvert et al. (2020); Shen et al. (2023) showed in their papers that defects can reduce the effectiveness of other components through transmission, this suggests that this feature is important for understanding how damage spreads in a bridge. Lastly, the information is already captured within the NEN 2767 standard and therefore would be simple to implement.

Structural Evaluation

the structural evaluation in the NBI standard is a comprehensive assessment of a bridge's ability to function safely, considering its physical condition, load-carrying capacity, and vulnerability to environmental factors. The final score is ordinal, similar to condition scores. The feature was applied 6 different times. Reasons for including the feature could be divided into 3 types. Firstly, three papers included the feature due to its occurrence in literature (Omar & Moselhi, 2022; Md. Ashiqur Rahman et al., 2023; M. A. Rahman et al., 2023). Secondly, three papers applied a form of preliminary feature selection, which identified that the feature was important (Abu Dabous, Alzghoul, et al., 2024; Abu Dabous, Ibrahim, et al., 2024). Lastly Yuan et al. (2020) aimed at evaluating the structural strength of concrete beams based on various factors over time.

4 papers compared structural evaluations impact to other features. These can be found in Table 53.

Table 53 Impact ranking of Structural Evaluation feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Omar & Moselhi, 2022)	2	7	Iowa, USA.	Deck	Prevalence in literature
(Abu Dabous, Alzghoul, et al., 2024)	3	11	10 coldest USA states	Deck	Author believes the feature impacts deterioration.
Average Impact					
(M. A. Rahman et al., 2023)	7	16	Florida, USA.	Steel Coating	Prevalence in literature
(Md. Ashiqur Rahman et al., 2023)	25	42	Florida, USA.	Steel Coating	Prevalence in literature

Abu Dabous, Alzghoul, et al. (2024) noted that structural evaluation was highly correlated with condition scores of both the superstructure and substructure; suggesting that if a bridge is not structurally sound its deck condition score will suffer as a result.

It is believed that the difference in impact ranking is due to the component which is being investigated. Decks are more prone to effects of structural health whereas a steel coating is most likely more affected by environmental factors. Similarly to the condition score results.

The frequency of inspection is identical for the NBI; every two years an evaluation is performed. However, these inspections could simply be performed at other intervals when a government agency sees fit. In addition, such structural evaluations could be performed only of bridges when Asset Managers believe it to be necessary.

Based on the results it can be concluded that this feature should be included in a bridge deterioration model for the Netherlands, however the way it is implemented will matter to this success. This is based on 2 reasons. Firstly, the impact table indicate that the feature has a strong impact on the deterioration modelling of bridges. Although this score is different for predicting the future state of steel coatings it could be argued that this is because this component is less effect by structural integrity. Secondly, however, the interval of these inspections will matter. In subsection 3.2.5 government bodies discussed their implementation of recalculation and were clear that this is not simply performed on every bridge. If these evaluations are only performed sporadically the feature should not be implemented into a bridge deterioration model as too little information will be gathered.

Sensors

One paper applied sensors for monitoring defects which had been spotted on bridges. Lai et al. (2024) implemented a strain sensor on a box girder which had a crack located on it. The study was able to determine the long-term forecasting of the deterioration rate based on the sensor.

Based on the limited findings in literature sensors for bridge deterioration modelling cannot be recommended. There is simply too little information to draw out a conclusion on whether sensor information could be beneficial for bridge deterioration modelling based on this literature study.

4.1.8 Environmental

This sub-section presents features related to environmental impacts on bridges. 6 different features are analysed: Temperature, Snowfall, Rainfall, Chloride, Other chemicals and influences and Wind conditions.

Temperature

Several forms of the temperature feature exist in literature. Temperature is expressed on the number of freezing and thawing cycles (Kale et al., 2021; Leiva-Maldonado et al., 2023; Liu et al., 2023; Liu & Zhang, 2020), Highest temperature (Miao & Yokota, 2024), Lowest temperature (Miao & Yokota, 2024) and just a general temperature measure (Md. Ashiqur Rahman et al., 2023; Shen et al., 2023; Yang et al., 2024). In this chapter it will simply be referred to as 'temperature'. The feature was used in 8 different papers. There were 3 reasons why the feature was included. Firstly, 3 papers added the feature due to its prevalence in literature (Kale et al., 2021; Leiva-Maldonado et al., 2023; Md. Ashiqur Rahman et al., 2023). Secondly, three authors believed that temperature could affect their components condition score (Miao & Yokota, 2024; Shen et al., 2023; Yang et al., 2024). Lastly, two papers provided no reasoning for including the feature (Liu et al., 2023; Liu & Zhang, 2020).

Only 2 papers assed temperatures impact on condition prediction in comparison to other features. These are presented in Table 54.

Table 54 Impact ranking of temperature feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion	Type
Average Impact						
(Kale et al., 2021)	6	9	The entire USA.	Superstructure	Prevalence in literature	Freeze-Thaw
(Md. Ashiqur Rahman et al., 2023)	21 AND 22 AND 27 AND 30	42	Florida, USA.	Steel Coating	Prevalence in literature	Temperature

Neither of these papers go into further depths on their findings. However, Md. Ashiqur Rahman et al. (2023) noted that in their literature review they found temperature had a large effect on steel coating deterioration. Their model included for temperatures at different levels: 60cm above ground, 2m above ground, 10m above ground and temperature at which water vapor condenses into liquid water.

Unfortunately no paper assessed its importance that was located in a colder climate; although the paper by Kale et al. (2021) includes cold states its results are diluted by the inclusion of warmer states. A similar situation is present when comparing the impact of the feature on different components; it is hard to know whether its impact differs.

Temperature data could be collected at different velocities from the KNMI in the Netherlands. Either on hourly basis, daily, weekly or even monthly. The volume of data related would change but additional resolution could be provided by considering to which detail level the temperature is measured; either on a local, provincial or nationwide basis.

Based on the gained insights the temperature feature could impact the deterioration of bridges in the Netherlands. This is based on 3 reasons. Firstly, the results of studies which assessed the features impact indicate that the feature has an average impact on both superstructures and steel coatings. Suggesting it could influence bridges. Secondly, the results are limited, and it is unclear what effects temperature has in colder locations where freeze and thaw cycles may be more commonplace. The study by Kale et al. (2021) includes bridges in the entire US but as it does not provide a focus on just colder states its impact could be limited. Lastly, the differences in temperature between studies could be relatively large. This could mean that the impact of the feature could be greater or lower dependant on the effect his difference has.

Snowfall

Snowfall is a feature which specifically measure how much snowfall falls around, and on a given bridge. The feature is measured in two forms in the literature: Snowfall in Centimetres (Kale et al., 2021; Miao & Yokota, 2024) and number of snowfalls in a year (Liu et al., 2023; Liu & Zhang, 2020). In total the feature was applied in 4 different papers. The feature will be referred to as snowfall from now on. There are 3 reasons for the inclusion of snowfall. Kale et al. (2021) implemented the feature due to its prevalence in literature, Miao and Yokota (2024) believed that the feature could affect deterioration and Liu et al. (2023); Liu and Zhang (2020) provided no reason for their inclusion of the feature.

Kale et al. (2021) was the only paper which ranked the feature in comparison to others. This is shown in Table 55.

Table 55 Impact ranking of snowfall feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Significant Impact					
(Kale et al., 2021)	2	9	The entire USA.	Superstructure	Prevalence in literature

2 further insights can be gained from papers which applied the feature. (Kale et al., 2021) noted that snowfall had a significant effect on the bridge deterioration rate; the author suggested that snowfall may be linked with a need for increased maintenance. Although Miao and Yokota (2024) did not investigate the impact of the feature in comparison to others they did find that snowfall affected the deterioration of bridges more over 2 years.

It remains unclear whether the feature specifically impacts certain components but what is apparent is that the feature will impact more in climates which have a higher chance of snowfall. It is the authors believe that snowfall could cause more accidents on bridges but also, particularly in the Netherlands, results in salting the roads, which can have a significant impact on deterioration through corrosion. It was not possible to find a number for comparing the amount of snowfall in the USA to the Netherlands so whether any changes are observed between these two should be studied.

Like temperature, snowfall data could be collected at different velocities from the KNMI in the Netherlands. Either on an hourly basis, daily, weekly or even monthly. The volume of data related would change but additional resolution could be provided by considering to which detail level the temperature is measured; either on a local, provincial or nationwide basis.

Although the results are limited in the insights, snowfall could be a feature which affects bridge deterioration in the Netherlands. This is based on 2 reasons. Firstly, the study by Kale indicated that the feature can significantly impact the deterioration of superstructures; however, because it is only one study it cannot be concluded that this will necessarily be the case in the Netherlands. Secondly, the relationship between snowfall and salt deposition on roads in the Netherlands could be worth tracking as this is known the cause corrosion.

Rainfall

Rainfall has been applied in 5 different papers and is measured through rainfall in centimetres (Kale et al., 2021; Miao & Yokota, 2024; Md. Ashiqur Rahman et al., 2023; Yang et al., 2024) and hour of wetness (Lai et al., 2024). The feature was included for 2 different reasons. Firstly, two papers applied it due to its prevalence in literature (Kale et al., 2021; Md. Ashiqur Rahman et al., 2023). Secondly, three papers believe rainfall effects deterioration (Lai et al., 2024; Miao & Yokota, 2024; Yang et al., 2024).

Two papers investigated the impact the feature had on their deterioration prediction. These can be found in Table 56.

Table 56 Impact ranking of rainfall feature

Paper	Impact ranking	Features used	Location study	Prediction goal	Reason for inclusion
Average Impact					
(Md. Ashiqur Rahman et al., 2023)	14	42	Florida, USA.	Steel Coating	Prevalence in literature
(Kale et al., 2021)	5	9	The entire USA.	Superstructure	Prevalence in literature

Kale et al. (2021) noted that in their results surprisingly, bridges in very high rainfall areas often perform better than those in low rainfall areas, even though this seems counterintuitive. Statistical tests confirmed this difference. Additional analysis showed that materials like prestressed concrete are more common in high-rainfall areas, while wood bridges are rare in such regions. This could explain why high-rainfall bridges perform better. Showing the importance of considering factors such as material when regarding environmental factors.

Based on the findings not much can be said about the features' effect on different components however the work by Kale et al. (2021) does suggest that rainfall affects different types of materials in different ways.

Table 57 presents the average rainfall of the different study locations. This indicates that on average the USA receives slightly less rain than the Netherlands with Florida receiving significantly more rain.

Table 57 Average rainfall per year research locations

Locations	Yearly rainfall (mm)	Source
Netherlands	850	(KNMI, 2023)
USA	762	(IbisWorld, 2024)
Florida	1371.6	(Florida Climate Center, 2024)

Just like temperature and snowfall data could be collected at different velocities from the KNMI in the Netherlands. Either on an hourly basis, daily, weekly or even monthly. The volume of data related would change but additional resolution could be provided by considering to which detail level the temperature is measured; either on a local, provincial or nationwide basis.

The literature findings suggest that this feature could have an impact on the deterioration of bridges for Dutch bridges. This is based on 2 reasons. Firstly, Impact assessment indicates that the feature has an average impact on both steel coatings and superstructures. Unfortunately, no studies looked at components which are more exposed to rain, such as decks to determine the impact of rainfall on their deterioration; this could enhance the impact of the feature. Secondly, the difference in rainfall between the studies suggests that if the feature were implemented its impact would fall between that of the study of Kale et al. (2021) and Md. Ashiqur Rahman et al. (2023) simply based on the amount of rainfall that is experienced. Suggesting that it could have a similar impact as these studies.

Chloride

Chloride is a commonly used feature being applied in 8 different papers with one paper considering the same feature in the form 'distance to seawater' (Anderson et al., 2021). The feature was applied for 2 different reasons. Firstly, two studies included the feature due to its frequency of use in literature (Md. Ashiqur Rahman et al., 2023; Yuan et al., 2020). Secondly, 6 papers suggested that the feature affected the deterioration of the component which they are trying to predict (Anderson et al., 2021; Choi et al., 2020; Miao & Yokota, 2024; Shen et al., 2023; Yang et al., 2024), Xu and Azhari (2021) even noted that Chloride induced corrosion is one of the most important factors to consider.

2 papers compared the features' importance to the other features used in their paper which can be seen in Table 58. Neither of these papers provided any further insights into their findings.

Table 58 Impact ranking of Chloride feature

Paper	Impact ranking	Features used	Location Study	Prediction goal	Reason for inclusion
Low Impact					
(Anderson et al., 2021)	1/3 phases of life	11	Oregon, USA.	Decks	The author believes the feature impacts the deterioration
(Md. Ashiqur Rahman et al., 2023)	38	42	Florida, USA.	Steel Coating	Prevalence in literature

The features information could be gathered in various ways. The Netherlands maintains data on where salt could be spread on the 'Strooitkaart' (Rijkswaterstaat, 2024); this information is updated daily and could provide insights into whether a bridge had been exposed to salt. Municipalities and provinces could also gather this information through their operations. In addition, the distance to the sea feature could be simply captured through a measurement and would be simple to collect as it is a constant value.

Based on the results from the literature the chloride feature could not be recommended to be included in a deterioration model. The results indicate that the feature has a low impact on both decks and steel coatings. Neither of these authors provides any insights about their opinion of these results. It makes it difficult to recommend the feature due to these findings.

Other chemicals and influences

The paper by Md. Ashiqur Rahman et al. (2023) included a large quantity of unique chemicals and influences as features for predicting the deterioration of steel coatings. The elements and compounds include sulphate (SO_4), potassium (K), sulphur dioxide, magnesium, calcium (Ca), ammonium (NH_4), pH, sodium (Na), nitrate (NO_3), nitrogen dioxide, solar radiation, promethium (PM10), ozone (O_3), and rhodium. The features were included based on findings in the literature. Their impact was also measured which is presented in Table 59.

Table 59 Impact ranking of other chemicals and influences feature

Feature	Impact ranking	Features used	Location Study	Prediction goal	Reason for inclusion
Significant Impact					
sulphate (SO_4)	10	42	Florida, USA.	Steel Coating	Prevalence in literature
potassium (K)	12	42	Florida, USA.	Steel Coating	Prevalence in literature
Average Impact					
sulphur dioxide	15	42	Florida, USA.	Steel Coating	Prevalence in literature
magnesium,	16	42	Florida, USA.	Steel Coating	Prevalence in literature
calcium (Ca)	19	42	Florida, USA.	Steel Coating	Prevalence in literature
ammonium (NH_4)	23	42	Florida, USA.	Steel Coating	Prevalence in literature

pH	28	42	Florida, USA.	Steel Coating	Prevalence in literature
Low Impact					
sodium (Na)	29	42	Florida, USA.	Steel Coating	Prevalence in literature
nitrate (NO_3)	31	42	Florida, USA.	Steel Coating	Prevalence in literature
nitrogen dioxide	34	42	Florida, USA.	Steel Coating	Prevalence in literature
solar radiation	32	42	Florida, USA.	Steel Coating	Prevalence in literature
promethium (PM10)	39	42	Florida, USA.	Steel Coating	Prevalence in literature
ozone (O_3)	40	42	Florida, USA.	Steel Coating	Prevalence in literature
rhodium	42	42	Florida, USA.	Steel Coating	Prevalence in literature

Md. Ashiqur Rahman et al. (2023) does not provide any further comments on their insights. The table above gives the impression that Sulphate and Potassium have a high impact when compared to other features, however, this is not really the case. The paper provides a SHAP (SHapley Additive exPlanations) score for the impact of each feature and compares this impact over 4 different condition scores of the bridge. Here the highest scores are given to Potassium with a score of 0.03, Sulphate with a score of 0.02 and Rhodium with a score of 0.02. These scores are only found for bridges with condition score 1 where their impact significantly drops after this scoring at its highest a score of 0.0005. These SHAP scores all represent a scoring of insignificant to low scores.

The data could be collected from the National Institute for Public Health and the Environment (RIVM), Royal Netherlands Meteorological Institute (KNMI), Netherlands Environmental Assessment Agency (PBL), Dutch Emissions Authority (NEA) and European Environment Agency (EEA). What frequency this data is collected will differ amongst the agencies and features but should be possible to collect on a yearly basis.

Although these results are only provided by one study Sulphate and Potassium could be features worth considering in a bridge deterioration model, though its impact on all components of a bridge may be limited. This is based on 2 reasons. Firstly, the evidence provided by Md. Ashiqur Rahman et al. (2023) shows that these features have the highest impact on steel coating deterioration from the chemicals considered. This impact quickly drops off after these features, making their impact significantly limited. Secondly, however, this study only assessed steel coating scores and this its impact on other components or materials cannot be confirmed.

Wind conditions

Wind conditions refer to the days where a lot of wind occurs. It was included in the paper by Yang et al. (2024), however its impact was never measured.

The Netherlands does have frequent days with higher winds, particularly near the coast; This information could be captured through services such as WindGuru, weather stations or the KNMI.

Wind condition, based on the limited results, cannot be recommended as there is no prove, within the literature study, of the feature being of significance.

4.2 Chapter conclusion

Sub-question c aims to investigate which bridge features are most important for predictive maintenance and which should be implemented to enable the predictive capabilities of the NEN 2767. To answer this sub-question 2 secondary questions were posed:

1. What features are used in bridge deterioration models?
2. Which of these features should be gathered to enable bridge deterioration modelling in the Netherlands?

In this section the secondary questions will be answered. These secondary questions serve as input for answering sub-question c in the conclusion of this report. This conclusion consists of 2 paragraphs, each which answer one of the secondary questions.

Based on the gathered information from 48 different literature sources, a 125 different features were collected. These were, based on their description, excluded or be classified into similar features which reduced the overall count to 37 different features. These features were further grouped into 8 different groups: Physical characteristics, Properties, Material, Traffic, Maintenance. Geographical, Inspection and Environmental. A list of all identified features is presented below in Table 60.

Table 60 Features identified in literature after filtering

Physical characteristics	Lanes on structure, lanes under structure, road width, approach roadway width, bridge total length, maximum span, maximum vertical clearance, number of spans, skew angle, total area, deck width, thickness overlay
Properties	Bridge age, operating rating, design load, functional class, type of service, component design type.
Material	Structural material, wearing surface, material characteristics, soil type.
Traffic	Average daily traffic, average daily truck traffic, national highway system.
Maintenance	Maintenance action, maintenance responsibilities, maintenance cost.
Geographical	Latitude/longitude, region/district.
Inspection	Historic condition scores, structural evaluation, sensor.
Environmental	Temperature, rainfall, chloride, other chemicals.

From these features a selection was made by collecting information on why authors included the feature, how its impact compared with other features used in their studies, any additional insights shared from these impact assessments, whether geography played a role in the features importance and how the data could be collected within the Dutch context. information gave an indication whether the feature should, could or shouldn't be included in a bridge deterioration model in the Netherlands. From these 7 features were identified which should be included, 18 which could be included and 13 which shouldn't or where inconclusive whether they could be important. These are presented in Table 61.

Table 61 Features categorised in should, could and shouldn't

Affect deterioration	Feature	Number of papers for each impact grouping		
		Low	Medium	High
Should	Bridge age		2	7
	Type of service over and under bridge	0.5	0.5	2
	Structural Material		3	2
	Wearing surface	2		2
	Maintenance actions			1
	Historic condition scores	1	1	2
	Structural evaluation		2	2
	Maximum span			2
	Average Daily Truck Traffic	1	2	3
	Maintenance responsibilities	1	1	3
Could	Total Bridge Length	1	2	1
	Total area	1	1	
	Deck width	2	2	1
	Operating rating	3	1	1
	Design Load	3	3	1
	Component design type	6	2	1
	Average Daily Traffic	3	3	3
	National Highway System			1
	Latitude/Longitude			1

	Region/District	1		1
	Temperature		2	
	Rainfall		2	
	Snowfall			1
	Sulphate and Potassium			1
Inconclusive	Other chemicals	1	1	
	Lanes on structure			1
	Lanes under structure			1
	Road width	1		
	Approach roadway width			
	Maximum vertical clearance			
	Skew angle	3	1	
	Thickness overlay			
	Functional class	2		1
	Material characteristics			
	Soil type			
	Sensor			
	Chloride	2		

5. Discussion

The aim of this study is to understand what capabilities the NEN 2767 data, gathered by government bodies, has for machine learning and how this could be improved. This aim was fulfilled by: investigating the data currently being collected by government bodies, through document analysis; understanding why there are differences in the ways in which data is stored and how data plays a role in maintenance decision making, through interviews with inspectors and government bodies; and identified which features should or could be gathered to enable the prediction of the future state of Dutch bridges through a comprehensive literature study. In this chapter the results of these investigations will be discussed by interpreting the findings, and their limitations.

5.1 Interpretation of findings

In this section what implications the findings indicate according to the author are presented. This section is divided into 5 paragraphs, each which discuss a different aspect of the findings.

Firstly, it is important to note that this research, is not meant as a scathing evaluation of Dutch government bodies; rather it is meant to inspire on what could be possible. Based on everyday experiences of traveling through the Netherlands and the relative absence of infrastructure-related incidents compared to neighbouring countries our infrastructure appears to be in good condition. However, the inconsistencies in collected data, reliance on PDF documents, and absence of a standardized data model for inspections suggest a broader issue: many Asset Managers may be unaware of the potential that could be unlocked by collecting more standardized data on infrastructure assets. Cultivating a data-conscious culture within government bodies is essential to realizing this potential, and this research aimed to be an early step toward achieving that goal.

Secondly, the results indicate that government bodies are currently operating in isolated islands, which significantly limits the potential for implementing Machine Learning for predictive maintenance. While the NEN 2767 and CUR 117 standards provide some consistency in terminology and establish clear expectations for inspectors, interview excerpts reveal that, although government bodies believe they are working uniformly, substantial variation persists. The collected data and inspector and government body interviews highlight differences in decision-making regarding data storage methods, types of data collected, choosing inspectors, and inspection frequencies.

This fragmented approach results in data that cannot be effectively shared across government bodies for machine learning applications, as it varies widely in quality, resolution, and feature breadth. Consequently, each government body would need to gather its own data to train algorithms—an inefficient process given the low velocity of data generation, which would require significant time to accumulate a sufficient data volume. Additionally, bridges are part of an interconnected infrastructure, where maintenance needs or failures in one area can directly impact neighbouring regions. It is therefore essential that government bodies begin bridging these isolated workflows, working toward the standardization and sharing of data. Doing so would reduce the time needed to develop an effective predictive maintenance system, benefitting the entire Dutch infrastructure network.

Third, the results indicate that there exists no standard to which inspectors are held which could affect the Machine Learning potential. The results in chapter 2 indicated that there were large differences in the number of unique components and defects recorded by government bodies, it also showed that there were deviations in how many defects were found per inspection and what scores defects were given on average. Sub-section 2.3.4 further indicated the subjectivity of visual inspections and the different insights that inspectors may reveal. Further insights gained from interviews suggested that government bodies choose inspection bureaus based on different reasons which included price, quality and trust. Furthermore, the NEN 2767 standard does not provide a way in which assets should be inspected. These differences mean that the data gathered from inspector to inspector can vary greatly. For a machine learning algorithm, it is important that data is uniform as it may otherwise struggle to find patterns when training on it. There thus should be some way of ensuring that a base level of quality, in terms of an inspection protocol, is held by all inspectors.

Fourth, Inspectors capture the most data, their steps in converting their implicit information into documented data is a highly important part for enabling Machine Learning. Based on the results it indicates that all inspections are performed by external parties, this means that there is a distance between data gatherer and owner. More or less implicit information is gathered in these inspections, based on the experience of the inspector. These inspectors then formalize this information into NEN 2767 defect recording, Risk assessments, intervention suggestions, longevity assessments and other types of data. Between these steps there is a loss of information. This creates gaps in the data that hinder comprehensive analysis, making it difficult to fully leverage all observations for predictive maintenance. The resulting data is fragmented, lacking the contextual richness that inspectors originally observed, and this reduces the potential effectiveness of machine learning applications. This results emphasises the importance of also making inspectors aware of the position that they hold in enabling predictive maintenance for the Netherlands; how they document information, and particularly to what level of detail can make a big difference in the effectiveness of the machine learning model.

Fifth, although the NEN 2767 was originally intended solely for the uniform documentation of defects, the standard has expanded beyond this initial purpose. It's inclusion of a decomposition terminology standard in the form of the NEN 2767-4 has led to government bodies applying these two in combination to perform their asset management. Components are often linked with additional data outside the scope of the NEN, defects have additional contextual information added such as risk assessments, and intervention suggestions are linked with defects. It is therefore important that the NEN 2767 expands its scope outside of just providing guidelines on how defects should be recorded.

Sixth, the results indicate that the velocity and feature richness of data can be increased through the Schouw and features identified through the literature study as well as interviews. Based on the results of the interview excerpts in sub-section 3.2.1; it became apparent that apart from the low velocity inspections of the NEN 2767 other, more frequently performed inspections do occur in the form of the Schouw. It appears that these occur every year and could be a good way of increasing the velocity at which data is created in the NEN 2767. However, it is important to note that these Schouw inspectors are performed by internal employees and often do not have the technical expertise to perform a complete NEN 2767 inspection. In addition, the cost that would be incurred if such a technical inspection was performed yearly would be very high. Therefore, it is important to find a balance in how these inspections can serve as a way of increasing information stream. The literature study in chapter 4 has indicated that a lot more information plays a role in Bridge Deterioration Modelling than just condition scores based on defects. In addition to this, the interviews in section 3.3 indicated that more information, besides NEN 2767 inspections plays a role in maintenance decision making. Although not all the information from these interviews could be easily captured the risk assessment, which is linked to defects could be included in a Bridge Deterioration Model as it could be standardised method.

5.2 Reflection of findings against literature

This section investigates the findings of this paper and compares them to the literature discussed in section 1.1 and further in the report. There are 3 findings:

Firstly, the results regarding the subjectivity of defect documentation were found to be similar to those in the literature. The interview results showed that all inspectors and 3 government body representatives had exeperienced issues with quanitifying a defects damage; in particular the extent score. Similar challenges were noted regarding decomposition data. The work by Phares et al. (2004), which had a large impact, assessed inspector consistency for NBI inspections. Here large differences were found in the amount of defects that were identified as well as how they were scored. It suggests that these challenges are not only experienced in the Netherlands and provides validaty to the findings.

Secondly, the results from the Dutch literature study, as well as interviews indicate that the Netherlands is currently going towards standardisation. It suggests that the country could be open for further standardising aspects such as the way in which data is stored, how information is deliverd and exhanged. These steps have already been taken in the IMBOR (CROW, 2024b) and CUR 117 (CROW, 2020) has also standardized different aspects of inspections. It was shown in the interviews in section 3.1 that, especially the CUR 117 already played a major role in many government bodies on how they choose inspectors and what they are required to do. It is therefore believed that the resistance to additional changes will be minimal.

Lastly, it is believed that based on comparing the data used in other countries and the results from chapter 2 and 3 the Netherlands ccan make Deterioration Models work. The NEN 2767 inspection standard, although different, does share many commonalities with the NBI in America and the Chinese standard in terms of decomposition and condition scoring systems. The large differences in why it does currently work in these countries and not in the Netherlands is due to a big difference in the volume of data available as well as the number of features which are documented when performing inspection; as has been demonstrated in sub-section 1.1.3 and chapter 2; for example the NBI has information dating back from 1997. It is unclear why these standards were so much earlier in adapting such a inspection standard but it does show that the Netherlands can make such systems work.

5.3 Choise of features

The study has so for identified which features should and could affect deterioration for a Dutch bridge deterioration model. However, other aspects, such as data velocity and volume, but also the context of these features for the Netherlands, have not yet been discussed in terms of the importance for the Dutch Context. As these are two aspects which are severily limiting the ability of Machine Learning to be applicable for the NEN 2767 as was shown in chapter 2. Firstly the the velocity and volume of data generated from each feature is discussed followed by the discussion of the features and how they would be formed for the Dutch context.

5.3.1 Feature Volume and Velocity

The features estimated volume and velocity is presented in Table 62. Below it a discussion is held on the implications that these findings have on the Machine Learning Potential of these features; which will filter into the final recommendations. 3 findings were found.

The categories for volume are defined as follows, with the period set for 5 years, which is the average inspection interval currently for bridges as shown in sub-section 2.3.3 and 1.1.3:

- Minimal: 1 to 100 records per period
- Low: 101 to 10,000 records per period
- Moderate: 10,001 to 1 million records per period
- High: More than 1 million records per period

The categories for velocity are defined as follows

- Static: Data does not change
- Burst: Sudden spikes of data generation, often event-driven (Maintenance actions)
- Batch: Data collected and processed in chunks at scheduled intervals (weekly, daily)
- Periodic: Data generated at regular, predictable intervals (Hourly sensor data)
- Streaming: Real-time or near-real-time data (IoT devices)

Table 62 Feature velocity and volume

Grouping chapter 4	Feature	Volume by event count	Velocity	How data could be gathered
Should	Bridge age	Minimal	Static	Historic records
	Type of service over and under bridge	Minimal	Static	Google maps / Inspection
	Structural Material	Minimal	Static	Inspection
	Wearing surface	Minimal	Static	Inspection
	Maintenance actions	Low	Burst	From maintenance performer
	Historic condition scores	Low	Batch	Inspection
	Structural evaluation	Low	Batch	Inspection
	Maximum span	Minimal	Static	Inspection
	Average Daily Truck Traffic	Moderate	Periodic/Streaming	Sensor, CCTV, Manual count per lane
	Maintenance responsibilities	Minimal	Burst	Municipality contract data
Could	Total Bridge Length	Minimal	Static	Inspection or satellite images
	Total area	Minimal	Static	Inspection or satellite images
	Deck width	Minimal	Static	Inspection
	Operating rating	Minimal	Burst	Records or structural evaluation
	Design Load	Minimal	Burst	Records or structural evaluation
	Component design type	Minimal	Static	Inspection
	Average Daily Traffic	Moderate	Periodic/Streaming	Sensor, CCTV, Manual count per lane
	National Highway System	Minimal	Static	Asset owner
	Latitude/Longitude	Minimal	Static	Large-Scale Topography Basic Registry (BGT)
	Region/District	Minimal	Static	Large-Scale Topography Basic Registry (BGT)
	Temperature	Moderate	Periodic/Streaming	KNMI
	Rainfall	Moderate	Periodic/Streaming	KNMI
	Snowfall	Moderate	Periodic/Streaming	KNMI
	Sulphate and Potassium	Moderate	Periodic/Streaming	Sensors or KNMI

The results indicate that most features have a low velocity, with many being of a static nature. Only 12 of the 24 features are not static. This results in 2 points of attention. Firstly, the large amount of static features means that the model will have a lot of information at setup before including any time-related features. These are easier to collect as they do not require a systematic data collection method. Secondly, however, this means that ther additional data cannot be quickly be collected per bridge to create an effective Machine Learning algorithm. This could indicate that a horizontal approach to collecting data could be suitable rather than a verticle approach; this is where the focus is placed on collecting data from many bridges rather than a lot of hisotircal data on one bridge.

The additional features with high velocities can provide the volume of data required to make the model effective and should not be too difficult to collect. This is based on 2 reasons. Firstly, the historic maintenance actions and condition scores provide the insights into the changing state of bridges. With the other non static information providing insights into the deterioration, brought on by environmental factors. These features are thus highly important to collect to understand what a bridge is subjected too, once the static features of bridges, have been collected. Secondly, the infrastructure in the Netherlands already exists for most features to be simply collected. Many provincial bridges have cameras on their bridges and have open access traffic data; although this data may be less available for municaplities. Climate data can simply be collected from the KNMI with the exception of Sulphate and Potassium data.

The different, and sporadic data velocities of certain data may cause challenges for certain machine learning algorithms. This is due to 2 reasons. Firstly, Data like maintenance actions or structural evaluations are generated sporadically, often in response to specific triggers Their irregular availability can lead to data sparsity; which can be difficult for some algorithms to deal with. Secondly, having both static and dynamic data increases model complexity and might require time-series or machine learning models capable of handling temporal relationships. Time series models, such as LSTMs could possibly work with this.

5.3.2 Features in the context of the Netherlands

Although some features are straight forward in their implementation, others, based on the Dutch Context, should be further evaluated on how they could be implemented. These features are discussed below which are: National Highway System, Component Design Type, Location of bridge, Snowfall and Temprature and Operation Rating/Design Load.

National Highway System

The National Highway System feature is one which describes which part of a highway system a bridge is part of. Being National or local highway for example. The Netherlands also has these divisions. These being Rijks-roads, provincial-roads, municipal-roads and Waterboard-roads. This would change the naming of this feature too Road-systems. Which in place would take these different feature levels.

Component Design Type

The component design type does not currently have a standard in the Netherlands for defining, for example, what kind of bridge joint is installed. Therefore this feature will require a additional creation of a standard. This will be considered outside of the scope of this research but will be part of the recommendations for future works.

Location of bridge

The location of the bridge, in many of the other contexts, often can hold implict information about different environments. States in America such as Colorade, have very different environments within their boundaries do to different terrain, and therefore the feature played an important role in the study by Ghafoori et al. (2024). The Netherlands is a very small country with quiet similar terrain and almost no evelation change. However, the structures in the Netherlands are still often affected by different climate conditions. There are coastal areas, such as Zeeland, which have many more bridges influenced by salty seas and are often even placed within them; The east has much less salty environments and less water which may lessen deterioration; Friesland may experience more snow and cold; and the South of Holland has more river basins, which may affect a bridges deformation as the ground shifts below it. Therefore a exact location may not be the right way of implementing this feature, but rather taking the approach of considering the bridges geographic environment. One way in which this could be done is by considering the fysical-geographic regions; these consider the ground types in which a bridge would be located but it is believed implicitly also consider many of the features discussed above. How this looks for the Netherlands is presented in Figure 11.

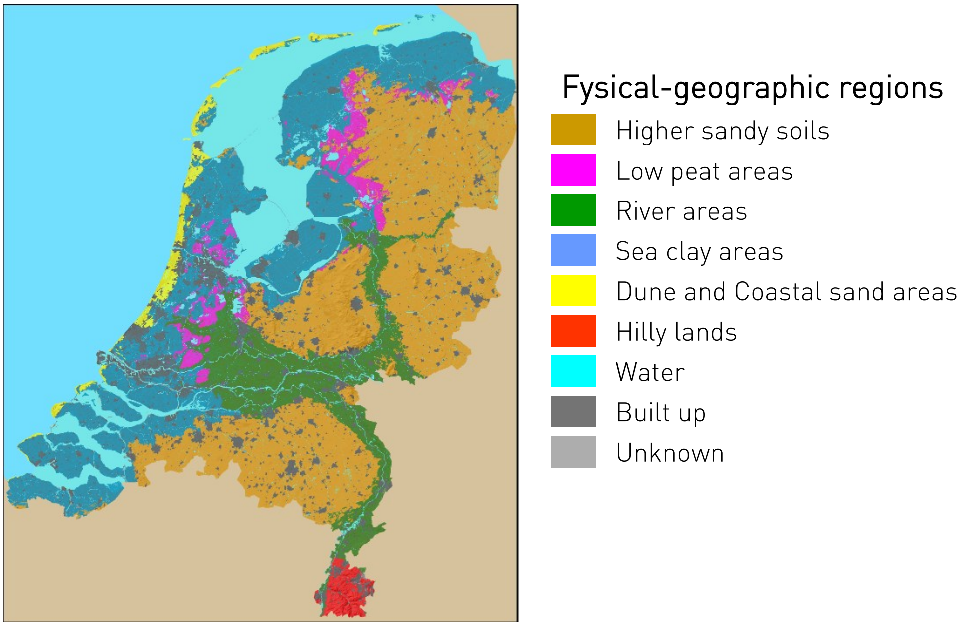


Figure 11 hysical-Geographical Regions in the Netherlands (Delft; et al., 2024)

Snowfall and Temprature

Snowfall and temprature came out as features which could affect the bridge deterioration rate. However, it is believed that this is even more the case in the Netherlands. Particularly because the country has a strong emphasis on throwing salt on roads and bridges when there is freezing temperatures or snow. This is known to destroy concrete and attack other corrosive affected materials. It is therefore believed that these features may carry this implicit information with them.

Operation rating/Design Load

Within the Netherlands these standards also exist but are documented in slightly different ways. Namely the 'Ultimate Limit'which is the Operation rating and the 'Servicability limit' which is the Design load. These terms will therefore be used in this estimation.

5.4 Limitations of the findings

In this section the limitations, based on the collected data are presented. This section consists of 5 paragraphs, each which discuss a specific limitation.

Firstly, apart from the data out of Obsurv, the data received from government bodies was often an extract from the data system in which the information is stored. This can result in the received information not being fully representative of what information is stored by government bodies. For example, additional information such as risk assessments could be stored in a different column in a database or IDs for specific components and elements could be stored within the system and not be exported when converting to a CSV. This could mean that the analysis in section 2.2 could be limited in its insights. However, it is believed that most data are extracted properly and that the results do still give a clear indication of the difference between government bodies.

Second, interviews were limited in the amount of government bodies and inspection bureaus interviews, this could result in bias towards certain outcomes. The Netherlands is divided into 342 municipalities across 12 provinces. While this research analysed a limited subset of the available data and included a small number of interviews, it provides a useful snapshot, particularly of municipal perspectives. Although the scope of these insights is limited, a clear pattern emerged from the interviews. However, these findings cannot be generalized to all government bodies. Nonetheless, because the interviews included representatives from large municipalities and provinces, it is reasonable to believe that these results may reflect broader patterns that could apply across different governmental entities.

Third, very small government bodies, in particular small municipalities, were not part of the research. This could mean that results are skewed to more organised government bodies. It could, for example, be the case that these smaller organisations are not even aware of the NEN 2767. Although it could be argued that the number of bridges these organisations deal with is very small, making the implementation of NEN inspections for a predictive maintenance system not worth it.

Fourth, the results of this study cannot proof how much data is needed and which features have the most impact on bridge deterioration in the Netherlands, only an indication can be provided. Due to the exploratory nature of the study, without any testing of the available data, it is unclear how well a provided algorithm would perform or how much additional data and features would be required to make it work. This makes the study limited in its insights for implementation, rather the studies aim it to provide an overview of the current challenges.

Fifth, there was a bias towards literature which applied data from the NBI in the USA. This could cause there to be a bias towards features which are presented in this dataset. It appears that there is a large body of literature on the Chinese standard 'JTG/T H21-2011', however, due to these papers being written in Chinese it was not possible to use their findings. The USA is, however, a varied country with many different climates, population densities and cultures. Because of this it is believed that the papers could provide a fair oversight of different features that are important.

Sixth, a severe lack of papers related to Structural Health Monitoring were captured when investigating bridge deterioration models. This absence of papers related to sensors data was quite surprising and could be a research gap which could be open where more static features are combined with real time sensor information to create an even more effective bridge deterioration model.

6. Recommendation

Based on the results in chapters 2, 3 and 4 as well as the discussion in chapter 5, various recommendations can be made to enable predictive maintenance of bridges in the Netherlands using Machine Learning. To ensure that these recommendations are sound and are suitable for the context of the netherlands preliminary recommendations, which can be found in Appendix F, were assessed through interviews. 5 Interviews were conducted with government bodies and inspectors. These are presented in Table 63. The interview excerpts were analysed, interpreted and mitigation measures were proposed which can be found in Appendix H. Based on these results the recommendations were adapted. The following sections present the final recommendation in two sections: Data storage standardisation and guidelines for inspectors as well as capture more information.

Table 63 Interviewees for validation of recommendations

ID	Years of experience in organisation	Organisation	Type of interview
Government representatives			
1	6	Province	Confirmatory
3	5	Province	Confirmatory
4	6	Municipality	Confirmatory
Inspectors			
4	13	Consulting Firm	Confirmatory
5	13	Consulting Firm	Confirmatory

6.1 data storage standardisation and Guidelines for inspectors

Based on discussion points 2, 3, 4 and 5 in section 5.2 it becomes apparent that there are large differences in how government bodies currently work; organisations work as isolated silos, there is no standard to which inspectors are held, however, these inspectors are the most vital as they are the link which converts implicit information to documented data and the NEN 2767 has grown outside of its boundaries of just documenting defects. Because of these insights there is a need to streamline data collection and storage to allow government bodies to share and train a machine learning model together; this way a predictive model can be trained faster, and maintenance could be organised as an interconnected web. This recommendation is divided into two sub-sections: standardising data storage and guidelines for inspections.

6.1.1 Standardising data storage

The results in chapter 2 indicate that there are large differences in how data is stored. The results from the interview excerpts in sub-section 1.1.2 show that different storage systems are used and in sub-section 3.4.3 data storage challenges clearly became apparent. Discussion points 2 also notes that government bodies are all working on islands, making training of machine learning data difficult and requiring a lot of time. To minimize these challenges the following solution is proposed.

An extension to the CUR 177 should be created where the ways in which information should be stored and delivered is outlined for inspectors. This way each government body documents information in the same way and inspectors' deliver data which can immediately be uploaded into such systems. This proposed standard would include three core components.

1. **A data model:** Specifies the structure and format for documenting assets within asset management systems, ensuring uniformity across all asset owners.
2. **A data delivery protocol:** Outlines standardized procedures for inspectors to deliver collected data, facilitating immediate integration with asset management systems.

3. **Data exchange framework:** Defines protocols for data sharing between government bodies, enhancing interoperability and supporting efficient machine learning model training.

An example of a data model is provided in Figure 15. This would have a few implications on current work: providers of asset management software would no longer compete on who can store the 'right' information or who has the best integration with data collection but rather who can provide the greatest insights or deliver the best user experience. In addition, frustrations and workload of government bodies as well as inspectors for integrating captured data into their systems could be reduced.

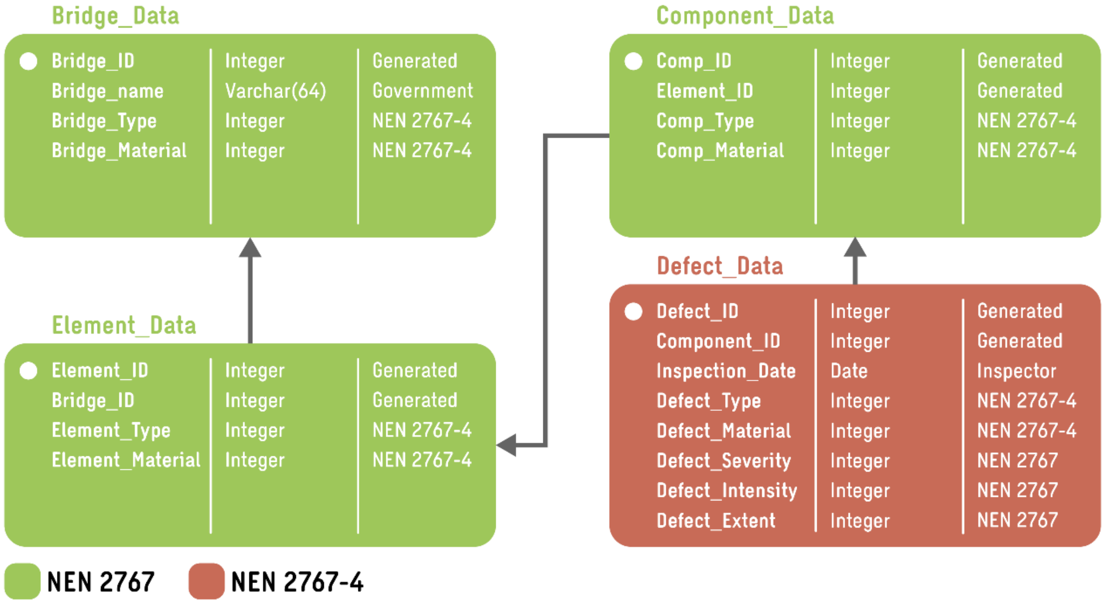


Figure 12 Data model example for the proposed CUR 117 extension

To ease the resistance to such a change a standardised tooling could be created for inspectors within the CUR 117; this would allow data to be captured using a digital tool, formatted for extraction in a simpel manner and be uploaded to government body systems in the correct way. It would therefore reduce the cost of individual inspection bureaus to adopt to this standard. This tooling should be created through an established working groups within CUR 117 committees which should include software providers, inspection bureaus, and government bodies to co-create compatible tools and processes. Part of their duties would also be to garuantee that once a government body decides to adopt this standard that they hold themselves to the required standard. This could, for example, be done by taking the proposed tool and collecting that information directly to a centralised system where its quality could be inspected.

6.1.2 Guidelines for inspections

An important part of training a Machine Learning model is knowing that the data that is input into the system is uniform; there for it is of importance that inspectors approach defect and decomposition documentation in the same way. As indicated in excerpts from the interviews in sub-sections 3.4.1 and 3.4.2 inspects, as well as government bodies note problems with defining extent scores of defects and to which level of detail a bridge should be decomposed. To minimize these differences the following solution is proposed.

A CUR 117 extension, which could be called a practice guideline, should be defined where a clear example is provided on how an inspection should be performed. It is important that this standard is not restrictive in allowing inspectors to capture the nuances of real life; therefore, it should be a guideline rather than a strict standard. However, it is imperative that government bodies can distinguish between inspectors who do and don't follow these guidelines; it can otherwise lead to the dilution of data for a machine learning algorithm. Therefore, it is recommended that inspectors are tested on the guideline to ensure captured data does not dilute a machine learning model.; this could, for example, be done by taking one bridge and performing a standardised test and comparing how decompositions are made and how defects are recorded. This could then ensure that only certified inspectors and their inspections are fed into the machine learning algorithms. The CUR 117 committee should include a public registry where it is made clear who is certified and who isn't.

The integration of this standard could be done in two stages to ease the resistance towards such a certification model. Firstly a voluntary phase could be created where inspectors can participate and the certification scheme could be improved upon. This would then be followed by a mandatory phase where the certification scheme is up to standard and data from only certified sources could be implemented into the Machine Learning model.

How this standard would exactly look in terms of guidelines for decomposition and defining defects cannot be recommended due to the researchers limited experience with the NEN 2767. Therefore, it should be created by a commitee which includes inspectors and government bodies. It is not necessary about choosing the 'right' way of documenting; rather ensuring that everyone does it in the same way. A particular important aspect of this standard will be to clarify why the level of detyail in terms of decomposition and defects is chosen: In this case it is for deterioration modelling; however the standard should still accommodate other types of inspectors such as electricians which may look for a higher level of detail on systems within their domain.

6.2 Capture more information

Based on the results of chapter 4 and the discussion point 6 it has become apparent that more contextual data is required to make a bridge deterioration model work but also that the frequency of data capture needs to be increased. This results in the following two recommendations: Capture more features and increase data capture through unplanned maintenance activities.

6.2.1 Capture more features

Based on the results from chapter 4 a list of features which can affect the deterioration rate of bridges in the Netherlands has been established. Many of these features are not related to the information currently being captured by the NEN 2767; this indicates that if a Machine Learning algorithm would currently be trained on just this data it would lack contextual information and could result in underfitting as the model doesn't have all the information to predict when maintenance will be required. From these identified features 10 should and 14 could affect the deterioration rate of bridges in the Netherlands.

Should affect deterioration: Bridge age, Type of service over and under bridge, Structural Material, Wearing surface, Maintenance actions, Historic condition scores, Structural evaluation, Maximum span, Average Daily Truck Traffic, Maintenance responsibilities.

Could affect deterioration: Total Bridge Length, Total area, Deck width, Operating rating, Design Load, Component design type, Average Daily Traffic, National Highway System, Latitude/Longitude, Region/District, Temperature, Rainfall, Snowfall, Sulphate and Potassium.

From these a discussion was held on how some of these features would be implemented within the Netherlands, which was presented in sub-section 5.3.2. From these the following changes, or adoptions to certain features was recommended:

- National Highway Systems: Name would be changed to Road-systems, and would include municipal, provincial or national roads.
- Component Design Type: Would require additional work to create a standardised list of components, as it is unclear whether such a detailed listing system currently exists.
- Location of bridge: The location of the bridge in terms of coordinates should be included but the region/district feature should be changed to fysical-geographic region, which are based on what type of ground the bridge finds itself in. This could capture a lot of additional implicit information.

- **Snowfall and temprature:** These two features will not change but rather a discussion was held that these features capture implicit information regarding salt spraying on roads. Which could be important.
- **Operation rating/Design load:** Their names change to consider correct Dutch terminology. 'Ultimate Limit'which is the Operation rating and 'Servicability limit' which is the Design load

Although some of these features could be captured in a NEN 2767 inspection it also becomes apparent that, if the Netherlands wants to enable predictive maintenance of bridges, more data, outside of the NEN 2767 scope will be required to make an effective model. In addition to this the challenges related to volume and velocity of data generation. Static information, for example can be more easily caputured as it does not require any infrastrucutre and once you have it will not change. However, not all static data can be captured by inspectors and some will require internal work. The higher velocity data such as traffic and weather data would have to be gathered from different teams within government bodies or external data. The recommendation is therefore to have three groups of data, collected in some sense by three different groups. Table 64 presents these. Risk assessments are also included.

Table 64 Feature capturing groups

Feature groups	Features to implement
Group 1: Government collection	Bridge age, Type of service over and under bridge, Maximum span, : Total Bridge Length, Total area, Deck width, Ultimate Limit, Servicability limit, Road-systems, Latitude/Longitude, Fysical-Geographic Region
Group 2: Inspector and maintenance workers	Maintenance responsibilities, Structural Material, Wearing surface, Maintenance actions, Historic condition scores, Structural Evaluation, Component Design Type, Risk assessments.
Group 3: External organisation data	Average Daily Truck Traffic, Average Daily Traffic, Temperature, Rainfall, Snowfall, Sulphate and Potassium.

As can be seen, some of this information, such as material types, are already recorded in the NEN 2767. This information should also be stored in a standard way as proposed by sub-section 6.1.1. Therefore, the standard should include this additional information. In addition, bridge age, will be substituted by an addition of component age, as this was found to possible contribute an even higher level of detail about the age of the structure. An example of how this could be done is presented in Figure 16.

This additional data should not become part of the NEN 2767 but rather could be a subliment for the CUR 117 data system proposed in the first recommendation. Firstly, govenrment bodies could streamline their basic data followed by including this information. To ease the difficulties of implementing this data it should be part of the the proposed tooling for recommendation 1 and a change management strategy should be implemented; which could involve things such as gamification which could aid employees of organisations to understand why these changes in data management must be performed. One noted absence of this information is that of SHM systems such a sensors. These could be added later but are for now considered outside the scope of this research.

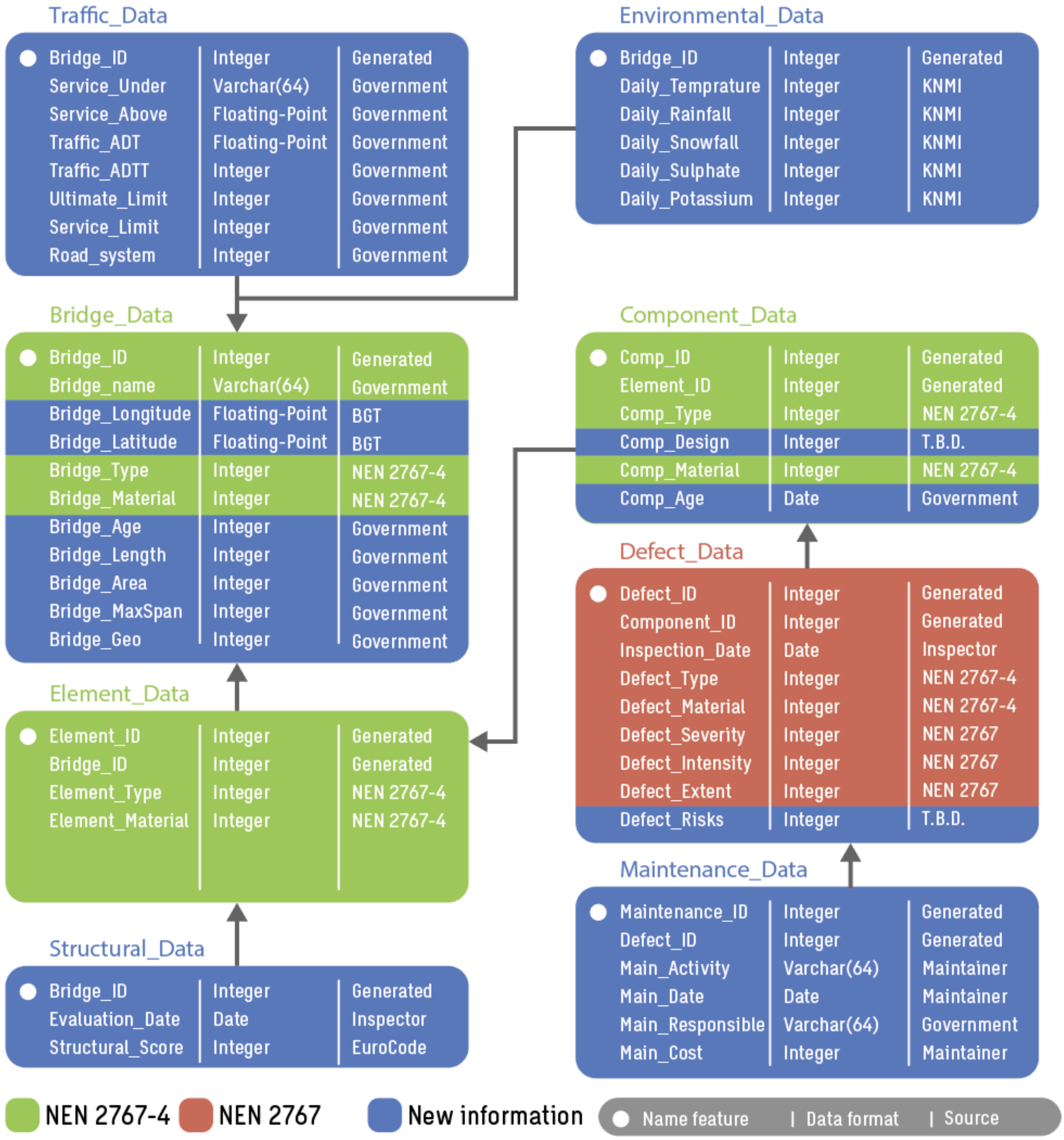


Figure 13 Example of additional features in proposed CUR 177 data standard

6.2.2 increase data capture through unplanned maintenance activities

The Schouw has been identified, in the discussion as point six, the Schouw is an annual inspection, usually performed by an internal employee of the government body. These employees often do not have a technical background and only check if something bad has not occurred. Based on interviews with stakeholders in the validaiton phase it became apparent that additional condition data could not be captured from them.

Despite this maintenance activities are planned based on the data gathered from schouw inspections. This information and the activities planned on a bridge from Schouw inspections could be valuable for a deterioration model and therefore, as part of the tool suggested to capture these maintenance activities to further train the model.

6.4 Further research

In this section further recommendations on what further research can be conducted based on the findings is discussed. 7 different directions are recommended for exploration.

Firstly, an investigation into the consistency of Dutch inspectors in the Netherlands could be performed. This pertains to taking a standard bridge and asking various inspection bureaus to investigate it on defects and decomposing it

Secondly, further research on how the recommendations can be implemented within government bodies and asset management software systems. The current recommendations are relatively simplistic in their presentation and although they do provide some initial ideas on how implementation should be performed, important details are still not worked out. To make these recommendations feasable to implement further work has to be conducted.

Third, the creation of an inspection guideline could be created and tested in real life for creating consistent data gathering. This could be done in combination with point 1. Where firstly the consistency of inspectors could be investigated, make them follow the guidelines and see how the consistency changes. This could indicate whether the guideline is effective or not.

Fourth, a case study could be conducted for gathering all the necessary information from a government body and seeing how efficiently and effectively this could be done. This study could indicate what the resistance is to gathering these features, how they could be accurately measured and whether it is realistic to implement these features for real life usage.

Fifth, once enough data and features have been gathered the first research can be conducted on which algorithms could be most suited within the context of the Netherlands. The same sources used in this study could be investigated for the usage of algorithms and comparing their performance. After this various of the algorithms could be tested in terms of accuracy for the Dutch context; which would be taking the first steps into enabling predictive maintenance in the Netherlands.

Sixth, including more features, which focus more on asset management, could be a next step once a deterioration model is working. This would include features such as price of maintenance activity, duration of maintenance, amount of required employees. These could make optimizing resource management more effective and change the way in which we work in the Netherlands even further.

Seventh, once features of bridges for a case study have been captured cross-data training could be attempted to see if the lack of data currently, could be compensated for. This would be done by taking NBI data and training an algorithm on modified features which could then be tested on Dutch bridge data for its predictive capabilities. This way the Netherlands could possibly be ready to implement predictive maintenance faster than currently is thought to be possible.

7. Conclusion

The aim of this research was to assess the potential of NEN 2767 data in enabling Predictive Maintenance through Machine Learning, and to identify any necessary modifications or additions to the data to enhance its predictive capabilities. To achieve this aim, a main research question was posed:

What potential does the NEN 2767 data hold for enabling Predictive Maintenance through Machine Learning, and what modifications or additions to this data could enable its predictive capabilities?

To answer this question three sub-questions were formed which each answer an aspect of this main question. This chapter consists of 4 paragraphs. The first three answer the three sub-questions after which a final concluding paragraphs ties the discussion points and recommendations together.

Based on the findings in Chapter 2, which analysed NEN 2767 data from 5 provinces and 7 municipalities, 4 key insights have been identified that hinder the potential for applying machine learning. Firstly, there are large differences in how information is stored by government bodies, requiring significant preprocessing. Secondly, there are variations in how many detailed decompositions are logged, the number of defects found per inspection and the number of unique defects and components recorded; indicating that there are different philosophies in how information is recorded. Third, only one government body has a system for assigning unique IDs to components, which limits the ability to track component degradation over time. Without consistent tracking, it is difficult for machine learning models to monitor changes and predict future deterioration patterns for specific components. Fourth, there is an insufficient amount of historical data to train a machine learning model, which would result in overfitting. Additionally, there are gaps in context-related information such as environmental factors, which are commonly used in bridge deterioration literature, which most likely this would result in underfitting. It can be concluded that there are large differences in how the NEN 2767 is implemented in government bodies and that it is currently not possible to apply machine learning on the NEN 2767 data as it stands due to a limited volume of data and a lack of contextual information which would be necessary to enable Predictive Maintenance through machine learning.

After analysing the results from interviews conducted with 5 government bodies and 4 inspectors with experience ranging between 3- and 14-years 4 different insights can be gained. Firstly, Different inspection intervals and subjective quality measures contribute to variations in data quality. Additionally, the experience and certification requirements for inspectors vary, affecting inspection quality. Secondly, Government bodies collect a plethora of additional information alongside NEN 2767 data, such as Schouw inspections which are performed yearly, risk data, intervention suggestions, pictures, recalculations, longevity assessments, and other relevant information like physical characteristics and potential failures. Third, NEN 2767 data serves as the starting point for maintenance decisions. Particularly risk assessments but also contextual factors such as traffic, the environment playing a role. Lastly, uncertainty in interpreting extent scores leads to inconsistencies amongst government bodies. The lack of a defined level of detail in the standard complicates decomposition documentation. Additionally, data management practices are insufficient, and software solutions do not meet government bodies' needs, limiting effective decision-making. In conclusion, there are several differences in inspection interval, quality standards and a lack of standardised certification of inspectors causes differences in data quality amongst government bodies. A wide range of different data is collected in inspection cycles. However, the NEN 2767 serves as the starting point for most maintenance decisions but particularly risk assessments also play a large role. Challenges are experienced with defining extent scores and creating the right decomposition of assets. The asset management systems used by government bodies also do not always fully satisfy asset managers.

The analysis of 48 papers related to bridge deterioration models published between 2020-2024 have revealed a 125 unique features, after grouping and excluding features not relevant for the Netherlands the following features were grouped in as should be included, could be included or shouldn't be included. 10 features should be included in a Dutch bridge deterioration model. Those are Bridge age, Type of service over and under bridge, Structural Material, Wearing surface, Maintenance actions, Historic condition scores, Structural evaluation, Maximum span, Average Daily Truck Traffic, Maintenance responsibilities. A further 14 features could be included in a Bridge deterioration model. Those are, Total Bridge Length, Total area, Deck width, Operating rating, Design Load, Component design type, Average Daily Traffic, National Highway System, Latitude/Longitude, Region/District, Temperature, Rainfall, Snowfall, Sulphate and Potassium. In addition Risk assessments should be included. Lastly 13 features shouldn't be included because of their low impact or because there were not enough insights to conclude that the feature was important. Those are Lanes on structure, Lanes under structure, Road width, Approach roadway width, Maximum vertical clearance, Skew angle, Thickness overlay, Functional class, Material characteristics, Soil type, Sensor and Chloride. Based on the findings it can be stated that 24 additional features could enable the predictive potential of the NEN 2767. 10 of these should be included in a Bridge Deterioration Model and 14 could be included.

Drawing from the discussion, which was written from the insights from the previous three sub-questions, a further 4 recommendations were synthesized on how the NEN 2767 predictive capabilities could be enabled. These were validated by 5 stakeholders and adapted based on the insights they provided. Firstly, a standardised data storage standard should be created which could become part of the CUR 117. This could ensure data is collected in a uniform manner to allow for the data exchange between government bodies, making the training of a collective machine learning model simpler. A tool, to ease the burden of implentation should be created to addition to this standardised storage. Secondly, a guideline should be created with a certification test to ensure that all government bodies receive inspections in a more uniform manner. The guideline could include suggestions on how extent scores should be measured as well as what level of detail a decomposition should be. Inspectors could be certified after performing a test. Third, the identified features in chapter 4 should be implemented to increase the contextual information a bridge deterioration model can train on. Three groups of features were created based on who would be responsible for gathering them. Lastly, the Schouw inspections should be utilized for increasing the velocity of data generation by caputuring data related to the maintenance activities which result from such inspections. The findings recommend 4 additions to the CUR 117 standard. Firstly the introduction of a standardised data storage, capture and exchange; Establish a certification scheme for inspectors to ensure their data is valid to include in a Machine Learning model; Increase the amount of features captured by collecting a additional 24 feartures; include maintenance activities captured through Schouw inspections.

To conclude, several avenues for future research could significantly enhance the implementation and effectiveness of predictive maintenance for Dutch infrastructure. Firstly, an investigation into the consistency of Dutch inspectors could be undertaken by evaluating how various inspection bureaus identify defects and decompose a standard bridge. Secondly, further research is needed to integrate the current recommendations into governmental operations and asset management systems, as the existing suggestions are too simplistic and lack detailed implementation strategies. Thirdly, the development and real-life testing of an inspection guideline could improve data collection consistency; this could be combined with the consistency investigation to assess the guideline's effectiveness. Fourthly, a case study could explore the process of collecting essential information from government bodies, examining the efficiency, resistance, and feasibility of such efforts. Fifthly, once sufficient data is collected, research could evaluate algorithms suited for predictive maintenance in the Dutch context, testing their accuracy and performance to initiate practical application. Sixthly, future work could include additional asset management features—such as cost, duration, and workforce requirements of maintenance—to optimize resource allocation and further transform maintenance practices. Finally, cross-data training could be explored by leveraging modified NBI data to compensate for the current lack of Dutch-specific data, accelerating the adoption of predictive maintenance in the Netherlands. These steps collectively represent a pathway toward a more efficient and data-driven infrastructure management system.

References

Abu Dabous, S., Alzghoul, A., & Ibrahim, F. (2024). Intelligent condition prediction model for bridge infrastructure based on evaluating machine learning algorithms [Article]. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-02-2024-0059

Abu Dabous, S., Ibrahim, F., & Alzghoul, A. (2024). Modelling bridge deterioration using long short-term memory neural networks: a deep learning-based approach [Article]. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-10-2023-0295

Agdas, D., Rice, J. A., Martinez, J. R., & Lasa, I. R. (2016). Comparison of Visual Inspection and Structural-Health Monitoring As Bridge Condition Assessment Methods. *Journal of Performance of Constructed Facilities*, *30*(3), 04015049. https://doi.org/doi:10.1061/(ASCE)CF.1943-5509.0000802

Aliferis, C., & Simon, G. (2024). Overfitting, Underfitting and General Model Overconfidence and Under-Performance Pitfalls and Best Practices in Machine Learning and AI. In G. J. Simon & C. Aliferis (Eds.), *Artificial Intelligence and Machine Learning in Health Care and Medical Sciences: Best Practices and Pitfalls* (pp. 477-524). Springer International Publishing. https://doi.org/10.1007/978-3-031-39355-6_10

Almarahlleh, N., Liu, H., Abudayyeh, O., & Almamlook, R. (2024). Predicting Concrete Bridge Deck Deterioration: A Hyperparameter Optimization Approach [Article]. *Journal of Performance of Constructed Facilities*, *38*(3), Article 04024009. https://doi.org/10.1061/JPCFEV.CFENG-4714

Alonso Medina, P., León González, F. J., & Todisco, L. (2022). Data-driven prediction of long-term deterioration of RC bridges [Article]. *Construction and Building Materials*, *317*, Article 125790. https://doi.org/10.1016/j.conbuildmat.2021.125790

Althaqafi, E., & Chou, E. (2022). Developing Bridge Deterioration Models Using an Artificial Neural Network [Article]. *Infrastructures*, *7*(8), Article 101. https://doi.org/10.3390/infrastructures7080101

Anderson, J. C., Unnikrishnan, A., & Schumacher, T. (2021). Heterogeneity-Based Survival Analysis of NBI Condition Ratings for Concrete Highway Bridge Decks in Oregon by Condition Group [Article]. *Journal of infrastructure systems*, *27*(4), Article 04021029. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000636

Asghari, V., & Hsu, S.-C. (2022). Upscaling Complex Project-Level Infrastructure Intervention Planning to Network Assets. *Journal of Construction Engineering and Management*, *148*, 04021188. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002221.

Bektaş, B. A. (2017). Use of recursive partitioning to predict national bridge inventory condition ratings from national bridge elements condition data. *Transportation research record*, *2612*(1), 29-38.

Bektas, B. A., Carriquiry, A., & Smadi, O. (2013). Using classification trees for predicting national bridge inventory condition ratings. *Journal of infrastructure systems*, *19*(4), 425-433.

Bishop, C. M., & Nasrabadi, N. M. (2006). *Pattern recognition and machine learning* (Vol. 4). Springer.

Bloemheuvel, S., van den Hoogen, J., & Atzmueller, M. (2021). A computational framework for modeling complex sensor network data using graph signal processing and graph neural networks in structural health monitoring. *Applied Network Science*, *6*(1), 97. https://doi.org/10.1007/s41109-021-00438-8

Bolukbasi, M., Mohammadi, J., & Arditi, D. (2004). Estimating the future condition of highway bridge components using national bridge inventory data. *Practice Periodical on Structural Design and Construction*, *9*(1), 16-25.

Bu, G. P., Lee, J. H., Guan, H., Loo, Y. C., & Blumenstein, M. (2015). Prediction of Long-Term Bridge Performance: Integrated Deterioration Approach with Case Studies. *Journal of Performance of Constructed Facilities*, *29*(3), 04014089. https://doi.org/doi:10.1061/(ASCE)CF.1943-5509.0000591

Budach, L., Feuerpfeil, M., Ihde, N., Nathansen, A., Noack, N. S., Patzlaff, H., Harmouch, H., & Naumann, F. (2022). The Effects of Data Quality on Machine Learning Performance.

Bureau of Transportation Statistics. (2024). *National Bridge Inventory*. Bureau of Transportation Statistics. https://geodata.bts.gov/datasets/national-bridge-inventory/about

Calvert, G., Neves, L., Andrews, J., & Hamer, M. (2020). Modelling interactions between multiple bridge deterioration mechanisms [Article]. *Engineering Structures*, *221*, Article 111059. https://doi.org/10.1016/j.engstruct.2020.111059

Carvalho, T. P., Soares, F. A. A. M. N., Vita, R., Francisco, R. d. P., Basto, J. P., & Alcalá, S. G. S. (2019). A systematic literature review of machine learning methods applied to predictive maintenance. *Computers & Industrial Engineering*, *137*, 106024. https://doi.org/https://doi.org/10.1016/j.cie.2019.106024

Chang, M., & Maguire, M. (2020). Condition rating prediction using an interactive deterioration model development package [Article]. *Applied Sciences (Switzerland)*, *10*(24), 1-22, Article 8946. https://doi.org/10.3390/app10248946

Chen, H.-P. (2018). Structural health monitoring of large civil engineering structures.

Chen, L. (2009). Curse of Dimensionality. In L. Liu & M. T. ÖZsu (Eds.), *Encyclopedia of Database Systems* (pp. 545-546). Springer US. https://doi.org/10.1007/978-0-387-39940-9_133

Chen, Q., Cao, J., & Zhu, S. (2023). Data-Driven Monitoring and Predictive Maintenance for Engineering Structures: Technologies, Implementation Challenges, and Future Directions. *IEEE Internet of Things Journal*, *10*(16), 14527-14551. https://doi.org/10.1109/JIOT.2023.3272535

Choi, Y., Lee, J., & Kong, J. (2020). Performance Degradation Model for Concrete Deck of Bridge Using Pseudo-LSTM. *Sustainability*, *12*(9), 3848. https://www.mdpi.com/2071-1050/12/9/3848

Collins, J., & Weidner, J. (2023). Comparison of Markovian-based Bridge Deterioration Model Approaches [Article]. *Journal of Bridge Engineering*, *28*(8), Article 04023047. https://doi.org/10.1061/JBENF2.BEENG-5920

CROW. (2020). CROW-CUR 117:2020. In. www.crow.nl: CROW.

CROW. (2024a). *Het iAMPro model voor Assetmanagement*. CROW. Retrieved 27th of June from https://essit.nl/over-assetmanagement/wat-is-het-iampro-model-voor-assetmanagement

CROW. (2024b). *IMBOR 2022*. CROW. Retrieved 1st of July from https://www-crow-nl.tudelft.idm.oclc.org/imbor

CROW. (2024c). *Inhoud IMBOR*. CROW. Retrieved 1st of July from https://www.crow.nl/thema-s/management-openbare-ruimte/imbor/inhoud-imbor

CROW. (2024d). *Over CROW*. ***https://www-crow-nl.tudelft.idm.oclc.org/over-crow***

CROW. (2024e). *Wat is assetmanagement?* CROW. Retrieved 27th June from https://essit.nl/over-assetmanagement/wat-is-assetmanagement

De Verschil Makers. (2024). *Onderhoud en renoveren van bestaande bouwwerken*. https://www.deverschilmakers.nl/infrastructuur-bruggen

Dekelbab, W., Al-Wazeer, A., & Harris, B. (2008). History lessons from the national bridge inventory. *Public Roads*, *71*(6), 30.

Delft;, B. v., Maas;, G., & Waal, R. d. (2024). *De Landschapsleutel helpt landschap analyseren*. Wageningen University. Retrieved 26th of November from https://landschapsleutel.wur.nl/

Domingos, P. (2012). A few useful things to know about machine learning. *Commun. ACM*, *55*(10), 78–87. https://doi.org/10.1145/2347736.2347755

Endrenyi, J., Aboresheid, S., Allan, R. N., Anders, G. J., Asgarpoor, S., Billinton, R., Chowdhury, N., Dialynas, E. N., Fipper, M., Fletcher, R. H., Grigg, C., McCalley, J., Meliopoulos, S., Mielnik, T. C., Nitu, P., Rau, N., Reppen, N. D., Salvaderi, L., Schneider, A., & Singh, C. (2001). The present status of maintenance strategies and the impact of maintenance on reliability. *IEEE Transactions on Power Systems*, *16*(4), 638-646. https://doi.org/10.1109/59.962408

Fan, W., Chen, Y., Li, J., Sun, Y., Feng, J., Hassanin, H., & Sareh, P. (2021). Machine learning applied to the design and inspection of reinforced concrete bridges: Resilient methods and emerging applications. *Structures*, *33*, 3954-3963. https://doi.org/https://doi.org/10.1016/j.istruc.2021.06.110

Farrar, C. R., & Worden, K. (2007). An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1851), 303-315. https://doi.org/10.1098/rsta.2006.1928

Federal Highway Administration. (1995). Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. In: Federal Highway Administration.

FHWA. (2022). *State Motor-Vehicle Registrations*. https://www.fhwa.dot.gov/policyinformation/statistics/2022/pdf/mv1.pdf

Florida Climate Center. (2024). Precipitation. https://climatecenter.fsu.edu/products-services/data/statewide-averages/precipitation

Frolov, V., Ma, L., Sun, Y., & Bandara, W. (2010). Identifying Core Functions of Asset Management. In J. E. Amadi-Echendu, K. Brown, R. Willett, & J. Mathew (Eds.), *Definitions, Concepts and Scope of Engineering Asset Management* (pp. 19-30). Springer London. https://doi.org/10.1007/978-1-84996-178-3_2

Ghafoori, M., Abdallah, M., & Ozbek, M. E. (2024). Machine Learning-Based Bridge Maintenance Optimization Model for Maximizing Performance within Available Annual Budgets [Article]. *Journal of Bridge Engineering*, *29*(4), Article 04024011. https://doi.org/10.1061/JBENF2.BEENG-6436

Google. (2024). *Artificial intelligence (AI) vs. machine learning (ML)*. https://cloud.google.com/learn/artificial-intelligence-vs-machine-learning

Goyal, R., Whelan, M. J., & Cavalline, T. L. (2020). Multivariable Proportional Hazards-Based Probabilistic Model for Bridge Deterioration Forecasting [Article]. *Journal of infrastructure systems*, *26*(2), Article 04020007. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000534

Graybeal, B. A., Phares, B. M., Rolander, D. D., Moore, M., & Washer, G. (2002). Visual Inspection of Highway Bridges. *Journal of Nondestructive Evaluation*, *21*(3), 67-83. https://doi.org/10.1023/A:1022508121821

HADJI, S. (2020). Effective Network Level Optimization for Bridges Maintenance. *International Journal Of Engineering And Computer Science*, *9*(09).

Halevy, A., Norvig, P., & Pereira, F. (2009). The Unreasonable Effectiveness of Data. *IEEE Intelligent Systems*, *24*(2), 8-12. https://doi.org/10.1109/MIS.2009.36

Han, D. (2021). Heterogeneous deterioration process and risk of deficiencies of aging bridges for transportation asset management. *Sustainability*, *13*(13), 7094.

Huang, Y.-H. (2010). Artificial Neural Network Model of Bridge Deterioration. *Journal of Performance of Constructed Facilities*, *24*(6), 597-602. https://doi.org/doi:10.1061/(ASCE)CF.1943-5509.0000124

IbisWorld. (2024). *Average Annual Precipitation*. https://www.ibisworld.com/us/bed/average-annual-precipitation/489/#:~:text=Recent%20Trends%20%E2%80%93%20Average%20Annual%20Precipitation&text=Climate%20change%20has%20caused%20more,has%20averaged%20around%2030.0%20inches.

IBM. (2021). *What is dimensional data?* IBM. Retrieved 03/03 from https://www.ibm.com/docs/en/informix-servers/12.10?topic=databases-what-is-dimensional-data

IBM. (2024). *What is Strong AI?* IBM. Retrieved 14 Maart from https://www.ibm.com/topics/strong-ai#:~:text=Weak%20AI%2C%20also%20known%20as,to%20solve%20for%20new%20problems.

ISO. (2014). ISO 55000: 2014: Asset management—overview, principles and terminology. In: ISO Geneva, Switzerland.

Jain, A., Patel, H., Nagalapatti, L., Gupta, N., Mehta, S., Guttula, S., Mujumdar, S., Afzal, S., Mittal, R. S., & Munigala, V. (2020). *Overview and Importance of Data Quality for Machine Learning Tasks* Proceedings of the 26th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining, Virtual Event, CA, USA. https://doi-org.tudelft.idm.oclc.org/10.1145/3394486.3406477

Jeon, C.-H., Shim, C.-S., Lee, Y.-H., & Schooling, J. (2024). Prescriptive maintenance of prestressed concrete bridges considering digital twin and key performance indicator. *Engineering Structures*, *302*, 117383. https://doi.org/https://doi.org/10.1016/j.engstruct.2023.117383

Jia, J., & Li, Y. (2023). Deep Learning for Structural Health Monitoring: Data, Algorithms, Applications, Challenges, and Trends. *Sensors*, *23*(21), 8824. https://www.mdpi.com/1424-8220/23/21/8824

Jordan, M. I., & Mitchell, T. M. (2015). Machine learning: Trends, perspectives, and prospects. *Science*, *349*(6245), 255-260. https://doi.org/doi:10.1126/science.aaa8415

Kale, A., Ricks, B., & Gandhi, R. (2021). New Measure to Understand and Compare Bridge Conditions Based on Inspections Time-Series Data [Article]. *Journal of infrastructure systems*, *27*(4), Article e0000633. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000633

Klepper, W. (2024). Discussion on NEN-2767. In C. Thostrup (Ed.). Sweco.

KNMI. (2023). *2023 maakt een einde aan reeks droge jaren*. https://www.knmi.nl/over-het-knmi/nieuws/2023-maakt-een-einde-aan-reeks-droge-jaren#:~:text=Neerslag%20in%20Nederland%20is%20toegenomen&text=Tegenwoordig%20valt%20er%20gemiddeld%20rond,millimeter%20om%20precies%20te%20zijn.

Kompeer, J., & Schellevis, J. (2021). 'Babyboomerbruggen' toe aan groot onderhoud, files en kosten verwacht. *NOS*. https://nos.nl/artikel/2394865-babyboomerbruggen-toe-aan-groot-onderhoud-files-en-kosten-verwacht

Kossieris, P., Tsoukalas, I., Brocca, L., Mosaffa, H., Makropoulos, C., & Anghelea, A. (2024). Precipitation data merging via machine learning: Revisiting conceptual and technical aspects. *Journal of Hydrology*, *637*, 131424. https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.131424

Kuijper, C., Berkhout, M., Hesselmans, A., Bezemer, D., & Dicker, P. (2021). iAMPro, the Dutch approach for managing assets in public space. In *Life-Cycle Civil Engineering: Innovation, Theory and Practice* (pp. 1685-1689). CRC Press.

Lai, L., Dong, Y., & Smyl, D. (2024). SHM-informed life-cycle intelligent maintenance of fatigue-sensitive detail using Bayesian forecasting and Markov decision process [Article]. *Structural Health Monitoring*, *23*(1), 187-210. https://doi.org/10.1177/14759217231160412

Law, D. (2015). Forecasting Deterioration of Bridge Components from Visual Inspection Data. *International Journal of Engineering & Technology Sciences*, *7*, 40-44. https://doi.org/10.7763/IJET.2015.V7.763

Lei, X., Xia, Y., Dong, Y., & Sun, L. (2022). Multi-level time-variant vulnerability assessment of deteriorating bridge networks with structural condition records. *Engineering Structures*, *266*, 114581. https://doi.org/https://doi.org/10.1016/j.engstruct.2022.114581

Leiva-Maldonado, S., Bowman, M. D., & Gomez, D. (2023). Life-cycle cost profiles selection for different superstructure bridge types [Article]. *Structures*, *54*, 1-13. https://doi.org/10.1016/j.istruc.2023.04.105

Li, L., Sun, L., & Ning, G. (2014). Deterioration Prediction of Urban Bridges on Network Level Using Markov-Chain Model. *Mathematical Problems in Engineering*, *2014*(1), 728107. https://doi.org/https://doi.org/10.1155/2014/728107

Liu, H., Nehme, J., & Lu, P. (2023). An application of convolutional neural network for deterioration modeling of highway bridge components in the United States [Article]. *Structure and Infrastructure Engineering*, *19*(6), 731-744. https://doi.org/10.1080/15732479.2021.1979597

Liu, H., & Zhang, Y. (2020). Bridge condition rating data modeling using deep learning algorithm [Article]. *Structure and Infrastructure Engineering*, *16*(10), 1447-1460. https://doi.org/10.1080/15732479.2020.1712610

Liu, K., & El-Gohary, N. (2019, 2019//). Learning from Class-Imbalanced Bridge and Weather Data for Supporting Bridge Deterioration Prediction. Advances in Informatics and Computing in Civil and Construction Engineering, Cham.

Lu, M., Hydock, J., Radlińska, A., & Guler, S. I. (2022). Reliability analysis of a bridge deck utilizing generalized gamma distribution. *Journal of Bridge Engineering*, *27*(4), 04022006.

Mahesh, B. (2019). *Machine Learning Algorithms -A Review* (Vol. 9). https://doi.org/10.21275/ART20203995

McElroy, R. S. (1999). Update on national asset management initiatives: facilitating investment decision-making. Innovations in Urban Infrastructure Seminar of the APWA International Public Works Congress,

McRobbie, S. G., Wright, M. A., & Chan, A. (2015). Can technology improve routine visual bridge inspections? *Proceedings of the Institution of Civil Engineers - Bridge Engineering*, *168*(3), 197-207. https://doi.org/10.1680/jbren.12.00022

Mia, M. M., & Kameshwar, S. (2023). Machine learning approach for predicting bridge components' condition ratings [Original Research]. *Frontiers in Built Environment*, *9*. https://doi.org/10.3389/fbuil.2023.1254269

Miao, P., & Yokota, H. (2024). Comparison of Markov chain and recurrent neural network in predicting bridge deterioration considering various factors [Article]. *Structure and Infrastructure Engineering*, *20*(2), 250-262. https://doi.org/10.1080/15732479.2022.2087691

Miao, P., Yokota, H., & Zhang, Y. (2023). Deterioration prediction of existing concrete bridges using a LSTM recurrent neural network. *Structure and Infrastructure Engineering*, *19*(4), 475-489. https://doi.org/10.1080/15732479.2021.1951778

Microsoft. (2024). *Artificial intelligence (AI) vs. machine learning (ML)*. https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/artificial-intelligence-vs-machine-learning

Mishra, M., Lourenço, P. B., & Ramana, G. V. (2022). Structural health monitoring of civil engineering structures by using the internet of things: A review. *Journal of Building Engineering*, *48*, 103954. https://doi.org/https://doi.org/10.1016/j.jobe.2021.103954

Moscoso, Y. F. M., Rincón, L. F., Leiva-Maldonado, S. L., & A. S. C. Campos e Matos, J. (2024). Bridge deterioration models for different superstructure types using Markov chains and two-step cluster analysis [Article]. *Structure and Infrastructure Engineering*, *20*(6), 791-801. https://doi.org/10.1080/15732479.2022.2119583

Nasrollahi, M., & Washer, G. (2015). Estimating Inspection Intervals for Bridges Based on Statistical Analysis of National Bridge Inventory Data. *Journal of Bridge Engineering*, *20*(9), 04014104. https://doi.org/doi:10.1061/(ASCE)BE.1943-5592.0000710

NEN. (2019). Conditiemeting gebouwde omgeving - Deel 1: Methodiek. In (pp. 37). www.connect.nen.nl: NEN.

NEN. (2021). *Eerste stap eenduidige aansluiting tussen IMBOR en NEN 2767 gezet*. NEN. Retrieved 1st of July from https://www.nen.nl/nieuws/conditiemeting/eerste-stap-eenduidige-aansluiting-tussen-imbor-en-nen-2767-gezet/

NEN. (2023). *Informatie - Blijf op de hoogte*. NEN. Retrieved 21st May from https://www.nen2767-4.nl/informatie

NEN. (2024). *NEN 2767-4 webapplicatie*. NEN. Retrieved 9th of April from https://www.nen.nl/bouw/beheer-en-onderhoud/conditiemeting/nen-2767-4-webapplicatie

Niyirora, R., Ji, W., Masengesho, E., Munyaneza, J., Niyonyungu, F., & Nyirandayisabye, R. (2022). Intelligent damage diagnosis in bridges using vibration-based monitoring approaches and machine learning: A systematic review. *Results in Engineering*, *16*, 100761. https://doi.org/https://doi.org/10.1016/j.rineng.2022.100761

NOS. (2016). *'Bouwers Merwedebrug hadden zo veel verkeer niet voorzien'* https://nos.nl/artikel/2139101-bouwers-merwedebrug-hadden-zo-veel-verkeer-niet-voorzien

Nunes, P., Santos, J., & Rocha, E. (2023). Challenges in predictive maintenance – A review. *CIRP Journal of Manufacturing Science and Technology*, *40*, 53-67. https://doi.org/https://doi.org/10.1016/j.cirpj.2022.11.004

OECD. (2001). *Asset Management for the Roads Sector*. https://doi.org/doi:https://doi.org/10.1787/9789264193208-en

Omar, A., & Moselhi, O. (2022). HYBRID FEATURE SELECTION FRAMEWORK FOR PREDICTING BRIDGE DECK CONDITIONS [Article]. *Journal of Information Technology in Construction*, *27*, 1028-1041. https://doi.org/10.36680/j.itcon.2022.050

Oyegbile, O. B., Chorzepa, M. G., Durham, S. A., & Kim, S. S. (2021). Novel prioritization mechanism to enhance long-term performance predictions for bridge asset management [Article]. *Journal of Performance of Constructed Facilities*, *35*(1), Article 0001531. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001531

Phares, B. M., Washer, G. A., Rolander, D. D., Graybeal, B. A., & Moore, M. (2004). Routine Highway Bridge Inspection Condition Documentation Accuracy and Reliability. *Journal of Bridge Engineering*, *9*(4), 403-413. https://doi.org/doi:10.1061/(ASCE)1084-0702(2004)9:4(403)

Pintelon, L., Pinjala, S. K., & Vereecke, A. (2006). Evaluating the effectiveness of maintenance strategies. *Journal of Quality in Maintenance Engineering*, *12*(1), 7-20. https://doi.org/10.1108/13552510610654501

Poór, P., Ženíšek, D., & Basl, J. (2019). Historical overview of maintenance management strategies: Development from breakdown maintenance to predictive maintenance in accordance with four industrial revolutions. Proceedings of the international conference on industrial engineering and operations management,

Rahman, M. A., Zhang, L., Lau, K., & Lv, X. (2023). Leveraging Bridge and Environmental Features to Analyze Coating Conditions of Steel Bridges in Florida Using Neural Network Models. *Journal of Performance of Constructed Facilities*, *37*(6), 04023058. https://doi.org/doi:10.1061/JPCFEV.CFENG-4502

Rahman, M. A., Zhang, L., Lv, X., & Lau, K. (2023). Analyzing Coating Conditions of Steel Bridges at Florida: A Data-Driven Approach [Article]. *Journal of Performance of Constructed Facilities*, *37*(2), Article 04023010. https://doi.org/10.1061/JPCFEV.CFENG-4111

Rajkumar, M., Nagarajan, S., & Arockiasamy, M. (2023). Bridge Infrastructure Management System: Autoencoder Approach for Predicting Bridge Condition Ratings. *Journal of infrastructure systems*, *29*(1), 04022042. https://doi.org/doi:10.1061/JITSE4.ISENG-2123

Ranjith, S., Setunge, S., Gravina, R., & Venkatesan, S. (2013). Deterioration Prediction of Timber Bridge Elements Using the Markov Chain. *Journal of Performance of Constructed Facilities*, *27*(3), 319-325. https://doi.org/doi:10.1061/(ASCE)CF.1943-5509.0000311

Rasker, P., Bletsis, A., Brongers, B., Vervuurt, A., & Verweij, E. (2023). Vernieuwingsopgave infrastructuur.

Rijkswaterstaat. (2024). *Strooikaart*. https://rijkswaterstaatstrooit.nl/

Rubio, J. J., Kashiwa, T., Laiteerapong, T., Deng, W., Nagai, K., Escalera, S., Nakayama, K., Matsuo, Y., & Prendinger, H. (2019). Multi-class structural damage segmentation using fully convolutional networks. *Computers in Industry*, *112*, 103121. https://doi.org/https://doi.org/10.1016/j.compind.2019.08.002

Russell, S. J., & Norvig, P. (2021). *Artificial Intelligence: A Modern Approach*. Pearson.

Rustell, M. (2022). Artificial Intelligence and Data in Civil Engineering. In S. H. Ghaffar, P. Mullett, E. Pei, & J. Roberts (Eds.), *Innovation in Construction: A Practical Guide to Transforming the Construction Industry* (pp. 147-187). Springer International Publishing. https://doi.org/10.1007/978-3-030-95798-8_8

Rytter, A. (1993). Vibrational based inspection of civil engineering structures.

Schroeck, M., Shockley, R., Smart, J., Romero-Morales, D., & Tufano, P. (2012). Analytics: The real-world use of big data. *IBM Global Business Services*, *12*(2012), 1-20.

Setunge, S., & Hasan, M. S. (2011). Concrete bridge deterioration prediction using Markov chain approach.

Shen, Z., Liu, Y., Liu, J., Liu, Z., Han, S., & Lan, S. (2023). A Decision-Making Method for Bridge Network Maintenance Based on Disease Transmission and NSGA-II. *Sustainability*, *15*(6), 5007.

Singh, A., Thakur, N., & Sharma, A. (2016, 16-18 March 2016). A review of supervised machine learning algorithms. 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), Srikanth, I., & Arockiasamy, M. (2020). Deterioration models for prediction of remaining useful life of timber and concrete bridges: A review. *Journal of Traffic and Transportation Engineering (English Edition)*, *7*(2), 152-173. https://doi.org/https://doi.org/10.1016/j.jtte.2019.09.005

Sun, C., Shrivastava, A., Singh, S., & Gupta, A. (2017, 22-29 Oct. 2017). Revisiting Unreasonable Effectiveness of Data in Deep Learning Era. 2017 IEEE International Conference on Computer Vision (ICCV),

Sun, L., Shang, Z., Xia, Y., Bhowmick, S., & Nagarajaiah, S. (2020). Review of Bridge Structural Health Monitoring Aided by Big Data and Artificial Intelligence: From Condition Assessment to Damage Detection. *Journal of Structural Engineering*, *146*(5), 04020073. https://doi.org/doi:10.1061/(ASCE)ST.1943-541X.0002535

Sun, X., Zhang, Z., Wang, R., Wang, X., & Chapman, J. (2004). Analysis of past national bridge inventory ratings for predicting bridge system preservation needs. *Transportation research record*, *1866*(1), 36-43.

Szepesvári, C. (2010). *Algorithms for Reinforcement Learning* (Vol. 4). https://doi.org/10.2200/S00268ED1V01Y201005AIM009

Tinga, T., & Loendersloot, R. (2014). Aligning PHM, SHM and CBM by understanding the physical system failure behaviour. PHM Society European Conference,

TNO. (2023). *Forse renovatie-opgave infrastructuur vraagt inzicht en samenwerking van beheerders*. TNO. Retrieved 25th Febuari from https://www.tno.nl/nl/newsroom/insights/2023/11/renovatie-opgave-infrastructuur/

Treder-Tschechlov, D., Reimann, P., Schwarz, H., & Mitschang, B. (2023). Approach to Synthetic Data Generation for Imbalanced Multi-class Problems with Heterogeneous Groups. In B. König-Ries, S. Scherzinger, W. Lehner, & G. Vossen (Eds.), *BTW 2023*: Gesellschaft für Informatik e.V.

U.S. Department of Transportation. (2023). *National Bridge Inventory*. U.S. Department of Transportation. Retrieved 14th of Febuari from https://geodata.bts.gov/datasets/usdot::national-bridge-inventory/explore

VNG. (2024). *https://vng.nl/artikelen/aanpak-bgt-bor*. VNG. Retrieved 1st of July from https://vng.nl/artikelen/aanpak-bgt-bor

Vuren, R. v. (2014). *Kennisportaal iAMPro*. https://www-crow-nl.tudelft.idm.oclc.org/getattachment/bijeenkomsten-en-congressen/Hoe-assetmanagement-toe-te-passen-in-beheer/Terugblik/Kennisportaal-iAMPro-v9122014-Rianne-van-Vuren-(1).pdf.aspx

Wang, F., Lee, C.-C. B., & Gharaibeh, N. G. (2022). Network-Level Bridge Deterioration Prediction Models That Consider the Effect of Maintenance and Rehabilitation. *Journal of infrastructure systems*, *28*(1), 05021009. https://doi.org/doi:10.1061/(ASCE)IS.1943-555X.0000662

Webb, G. I. (2010). Overfitting. In C. Sammut & G. I. Webb (Eds.), *Encyclopedia of Machine Learning* (pp. 744-744). Springer US. https://doi.org/10.1007/978-0-387-30164-8_623

Wei, J., Chen, G., Huang, J., Shou, W., & Wang, J. (2024). Resource-constrained bridge maintenance optimization by harmonizing structural safety and maintenance duration [Article]. *Engineering Structures*, *308*, Article 118024. https://doi.org/10.1016/j.engstruct.2024.118024

Xia, Y., Lei, X., Wang, P., & Sun, L. (2022a). A data-driven approach for regional bridge condition assessment using inspection reports. *Structural Control and Health Monitoring*, *29*(4), e2915. https://doi.org/https://doi.org/10.1002/stc.2915

Xia, Y., Lei, X., Wang, P., & Sun, L. (2022b). A data-driven approach for regional bridge condition assessment using inspection reports. *Structural Control and Health Monitoring*, *29*(4), e2915.

Xu, G., & Azhari, F. (2021). Predicting the remaining useful life of corroding bridge girders using Bayesian updating. *Journal of Performance of Constructed Facilities*, *35*(5), 04021055.

Yang, G., Tian, L., Mao, J., Tang, G., & Du, Y. (2024). Bridge performance degradation model based on the multi-variate bayesian dynamic linear method [Article]. *Advances in Structural Engineering*. https://doi.org/10.1177/13694332241266541

Yosri, A., Elleathy, Y., Hassini, S., & El-Dakhakhni, W. (2021). Genetic algorithm-Markovian model for predictive bridge asset management. *Journal of Bridge Engineering*, *26*(8), 04021052.

Yuan, Y., Han, W., Guo, T., Chen, X., & Xie, Q. (2020). Establishment and Updating of Nonstationary Resistance Deterioration Model of Existing Concrete Bridge Component [Article]. *Journal of Performance of Constructed Facilities*, *34*(6), Article 04020104. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001517

Zhang, H., & Marsh, D. W. R. (2018). Generic Bayesian network models for making maintenance decisions from available data and expert knowledge. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *232*(5), 505-523.

Zhang, H., & Marsh, D. W. R. (2020). Multi-state deterioration prediction for infrastructure asset: Learning from uncertain data, knowledge and similar groups [Article]. *Information Sciences*, *529*, 197-213. https://doi.org/10.1016/j.ins.2019.11.017

Zhang, T., Chen, H., Cui, X., Li, P., & Zou, Y. (2024). Condition Rating Prediction for Highway Bridge Based on Elman Neural Networks and Markov Chains [Article]. *Applied Sciences (Switzerland)*, *14*(4), Article 1444. https://doi.org/10.3390/app14041444

Zhong, D., Xia, Z., Zhu, Y., & Duan, J. (2023). Overview of predictive maintenance based on digital twin technology. *Heliyon*.

Zhu, J., & Wang, Y. (2021). Feature Selection and Deep Learning for Deterioration Prediction of the Bridges. *Journal of Performance of Constructed Facilities*, *35*(6), 04021078. https://doi.org/doi:10.1061/(ASCE)CF.1943-5509.0001653

Appendix A: Interview questions

A.1 Descriptive/ Comfirmatory Asset Manager questions

Introductory Questions:

a. What prompted the implementation of the NEN 2767 standard?

b. What do you see as the purpose of the NEN 2767?

c. What are your organization's goals for implementing the NEN 2767 standard?

Implementation of the Standard:

a. How was the NEN 2767 standard implemented in your organization?

i. How do you ensure compliance with the NEN 2767?

b. How are NEN 2767 data stored?

Data Collection:

a. Are inspections conducted by internal staff or external parties?

i. What factors influence the decision to use an external party?

ii. What requirements are set for external parties conducting inspections?

iii. How are inspection reports delivered?

b. How is the inspection interval determined?

c. What data are collected during a NEN 2767 inspection?

d. Do inspectors sometimes provide additional information outside of the NEN reports?

i. How frequently does this occur?

ii. What type of information is shared?

Additional Data:

a. Do the NEN 2767 data include all the characteristics you have about your bridges?

i. If not, what other decomposition data do you have?

ii. Why are these data not currently stored within the NEN dataset?

b. Do the NEN 2767 data include all the inspection information you have about your bridges?

i. If not, what other inspection data do you have?

ii. Why are these data not currently stored within the NEN dataset?

c. Is a NEN 2767 inspection the only type of inspection conducted?

i. If not, what other types of inspections are there and what data are collected from them?

ii. In what situations is a NEN 2767 standard inspection insufficient?

Decision Making:

a. Is their other contextual information that plays a role in the maintenance decision-making process?

b. What types of data are most critical for making maintenance decisions?

i. How are data prioritized in the decision-making process?

c. What is the process for making maintenance decisions using the collected data?

i. How is it determined if a bridge is inacceptable condition?

ii. What constitutes a 'no-go' decision when a bridge is not in acceptable condition?

d. What data are collected after a maintenance decision is implemented?

Closing Questions:

a. What is your opinion on the NEN 2767?

i. Are there any changes you would like to see in the NEN 2767 standard?

A.2 Descriptive/ Comfirmatory Inspector questions

Introductory Questions:

a. When did your organization start conducting NEN 2767 inspections?

b. What do you see as the purpose of the NEN 2767 standard?

c. For how many and what types of clients do you conduct NEN 2767 inspections?

d. How flexible are you in adapting the inspection method to the client's needs?

Implementation of the Standard:

a. How is the NEN 2767 standard implemented in your organization?

i. How do you ensure compliance with the NEN 2767 standard?

ii. How are inspectors trained and certified?

b. How are NEN 2767 data stored?

c. How do you adapt the composition terms for each client or standard?

Data Collection:

a. Do you use different inspectors for different assets (e.g., bridges, houses)?

i. Is the same inspector usually sent to the same bridge?

b. How long does an inspection typically take?

c. How is the final report format determined?

i. Who decides what information needs to be included?

ii. How is the quality of the inspection assessed (e.g., level of decomposition, types of defects included)?

d. How is an inspection carried out in steps?

e. What data are collected during an inspection?

f. Do your inspectors ever communicate additional information to clients outside of the NEN reports?

i. How often does this occur?

ii. What type of information is shared?

g. What tools and technologies are used during the inspection?

h. Are their specific challenges or limitations you encounter during inspections?

Closing Questions:

a. Have you received any complaints or disputes about inspection results?

b. How do you differentiate yourselves from others in your field?

c. What is your opinion on the NEN 2767 standard?

i. Are there any changes you would make to the NEN

A.3 Exploratory Asset Manager questions

Introductory Questions

a. What led to the implementation of the NEN 2767 standard?

b. What are your organizational goals for implementing the NEN 2767 standard?

Implementation of the Standard

a. How has the NEN 2767 standard been implemented within your organization?

i. How do you ensure compliance with the NEN 2767 standard?

b. How is NEN 2767 data stored?

Data Collection

a. Are inspections conducted by internal staff or external parties?

i. What factors are considered when deciding to use an external party?

ii. How are requirements communicated to the external party for conducting inspections?

iii. How are inspection reports delivered?

b. How is the inspection interval determined?

c. What data is collected during an NEN 2767 inspection?

d. Do inspectors sometimes communicate additional information outside of the NEN reports?

i. How often does this occur?

ii. What kind of information is shared?

Additional Data

Show Table 10 with the decomposition information.

a. Do the NEN 2767 data include all the attributes you have about your bridges?

i. If not, what other decomposition data do you have?

ii. Why are these data not currently stored within the NEN dataset?

Show Table 11 with the parameter information.

b. Do the NEN 2767 data include all inspection information you have about your bridges?

i. If not, what other inspection data do you have?

ii. Why are these data not currently stored within the NEN dataset?

c. Is an NEN 2767 inspection the only type of inspection performed?

i. If not, what other types of inspections are conducted, and what data are collected during these?

ii. Under what circumstances is a standard NEN 2767 inspection insufficient?

Decision-Making

a. What types of data are most critical for making maintenance decisions?

i. How are data prioritized in the decision-making process?

b. What is the process for making maintenance decisions using the collected data?

i. How is it determined whether a bridge is in good condition?

ii. What constitutes a no-go when a bridge is not in good condition?

c. What data are collected after a maintenance decision is executed?

Concluding Questions

a. What is your opinion of the NEN 2767 standard?

i. Are there any changes you would like to see in the NEN 2767 standard?

A.4 Exploratory Inspector questions

Introductory Questions

a. When did your organization start conducting NEN 2767 inspections?

b. In your opinion, what is the purpose of the NEN 2767 standard?

c. For how many and what types of clients do you perform NEN 2767 inspections?

d. How flexible are you in adapting the inspection method to meet client needs?

Implementation of the Standard

a. How is the NEN 2767 standard implemented within your organization?

i. How do you ensure compliance with the NEN 2767 standard?

ii. How are inspectors trained and certified?

b. How are NEN 2767 data stored?

c. How do you adjust composition terms per client or standard?

Data Collection

a. Do you use different inspectors for different types of assets (e.g., bridges, houses)?

i. Is the same inspector typically assigned to the same bridge?

b. How long does an inspection usually take?

c. How is the final format of the report determined?

i. Who decides what information needs to be included?

ii. How is the quality of the inspection determined (e.g., level of decomposition, defects considered)?

d. How is an inspection carried out step by step?

e. What data are collected during an inspection?

f. Do your inspectors sometimes communicate additional information to clients outside the NEN reports?

i. How often does this happen?

ii. What type of information is shared?

g. What tools and technologies are used during inspections?

h. Are there specific challenges or limitations you encounter during inspections?

Concluding Questions

a. Have you received any complaints or disputes about inspection results?

b. How do you differentiate yourselves from competitors?

c. What is your opinion of the NEN 2767 standard?

i. Are there any changes you would make to the NEN 2767 standard?

Appendix B: NEN 2767 decomposition in practice

In this appendix how NEN 2767 decomposition, in different governmental organizations, is documented is presented. There are 6 sections. The coding of bridges, Elements and components, Inclusion of location, Bridge general dimensions, Main material of component and Type of asset. All these sections will have the same structure where the order of discussion is the provinces: Noord-Brabant, Utrecht, Limburg, Flevoland and Gelderland followed by the municipalities: Amsterdam, Tilburg, Utrecht, Maastricht, Gorinchem, Arnhem and Deventer.

B.1 Coding of bridges

Table 65 Coding of bridges found in data

Government bodies	Documentation style	Notes
	Provinces	
Noord-Brabant	43D 902	It is unclear from looking at the data what types of codification exactly mean.
Utrecht	VK202-50.911	It is unclear from looking at the data what types of codification exactly mean.
Limburg	GB02-397	It is unclear from looking at the data what types of codification exactly mean.
Flevoland	740d59c44f7dbe54ee6f0d72d61f1963	It is unclear from looking at the data what types of codification exactly mean.
Gelderland	402107	Incremental numbering system.
	Municipalities	
Amsterdam	BRU0002	The BRU identifies that the asset is a bridge. Code increases incrementally.
Tilburg	CKW_0096, 21784	The number incrementally increases; however, they apply a different ID to a bridge when investigating damages which are in the form of '20753'.
Utrecht	BAS03002-01	It is unclear from looking at the data what types of codification exactly mean.
Maastricht	BRB/06241/02	The BRB part refers to the type of asset, the second the location and the second which numbered asset it is at that location.
Gorinchem	3021000	The number incrementally increases
Arnhem	02002	The number incrementally increases.
Deventer	BGP3	The numbers and letters incrementally increase.

B.2 Elements and Components

Table 66 Documentation of elements and components

Government bodies	Documentation style	Notes
	Provinces	
Noord-Brabant	Written	has a comprehensive list of elements and components which follow the NEN 2767-4 terminology. An edition is made to certain elements and components where a '**' is added at the end. Spelling mistakes were also found for certain elements and components.

Utrecht	Written	The province of Utrecht has a comprehensive list of elements and components but does not have differing columns for these. So, elements and components are hard to distinguish.
Limburg	Written	NEN 2767 standard.
Flevoland	Code	All elements and components are in numbered form.
Gelderland	Written	Only sometimes elements and components are recorded; often missing. Elements and components appear to be interchanged confusingly.
Municipalities		
Amsterdam	Written.	NEN 2767 standard.
Tilburg	Written	NEN 2767 standard.
Utrecht	Written	NEN 2767 standard.
Maastricht		Has a comprehensive list of elements and components which follow the NEN 2767-4 terminology. An edition is made to certain elements and components where a '**' is added at the end. Spelling mistakes were also found for certain elements and components.
Gorinchem	Written	NEN 2767 standard.
Arnhem	Written	NEN 2767 standard for components, elements, and materials. There is, however, a lot of data missing on elements and materials.
Deventer	Written	NEN 2767 standard for components. There is, however, no data on elements or materials.

Table 67 documentation of elements and component duplicates

Government bodies	Dealt with duplicates	Method for dealing with duplicate elements and components
Provinces		
Noord-Brabant	Sometimes	Noord-Brabant has three elements where this is dealt with the 'frontwand', 'damwand' and 'afvoergoot'. These get an addition if two of the identical elements are present, as can be seen in Figure 14. These three elements fall within the 'duiker', which is a culvert. It is unclear why these elements did get unique numbering.
Utrecht	No	The province of Utrecht does not attempt to distinguish between multiple elements. There are bridges which state the component 'Deklaag, dicht' three types without making any distinctions.
Limburg	No	There does not seem to be any way in which duplicated elements or components are dealt with.
Flevoland	No	Multiple instances of identical element codes occur with no way of identifying if they are the same or different elements. The same occurs for the components.
Gelderland	No	There does not seem to be any way in which duplicated elements or components are dealt with.
Municipalities		
Amsterdam	No	There does not seem to be any way in which duplicated elements or components are dealt with.
Tilburg	Yes	The province of Tilburg does make distinctions between elements and building components by providing a unique ID.
Utrecht	No	There does not seem to be any way in which duplicated elements or components are dealt with.
Maastricht	No	There does not seem to be any way in which duplicated elements or components are dealt with.
Gorinchem	No	There does not seem to be any way in which duplicated elements or components are dealt with.
Arnhem	No	There does not seem to be any way in which duplicated elements or components are dealt with.
Deventer	No	There does not seem to be any way in which duplicated elements or components are dealt with.

Frontwand

Frontwand (2)

Figure 14 Example from Noord-Brabant on how they deal with multiple elements

B.3 Inclusion of location

Table 68 documentation of the location of bridges

Government bodies	Documentation style	Notes
		Provinces
Noord-Brabant	Street and GIS location	Adds both the location on the map in code form as well as the specific street that the bridge or viaduct is located near.
Utrecht	-	-
Limburg	Street and GIS location	Adds both the location on the map in code form as well as the specific street that the bridge or viaduct is located near
Flevoland	-	-
Gelderland	-	-
		Municipalities
Amsterdam	-	-
Tilburg	Street, neighbourhood, and GIS location	Adds both the location on the map in code form as well as the specific street and neighbourhood that the bridge or viaduct is located near.
Utrecht	Street and GIS location	Adds both the location on the map in code form and sometimes the specific street that the bridge or viaduct is located near.
Maastricht	Street and GIS location	Adds both the location on the map in code form as well as the specific street that the bridge or viaduct is located near.
Gorinchem	Street and GIS location	Adds both the location on the map in code form as well as the specific street that the bridge or viaduct is located near.
Arnhem	Street and GIS location	Adds both the location on the map in code form as well as the specific street that the bridge or viaduct is located near.
Deventer	Street and GIS location	The street is only occasionally added.

B.5 Bridge general dimensions

Table 69 Documentation of bridge dimensions

Government bodies	Documentation style	Notes
		Provinces
Noord-Brabant	-	-
Utrecht	-	-
Limburg	-	-
Flevoland	Component unit.	Differ in units such as mm, m, m^2 etc. Often not included.
Gelderland	Width (m), length (m), height (m).	Height is not always included. Length and width sporadically missing.
		Municipalities
Amsterdam	-	-
Tilburg	Surface area (m^2), width (m), length (m), height (m).	Sometimes the height, length and width are included, but not always. The surface area is always included.
Utrecht	-	-
Maastricht	-	-
Gorinchem	-	-
Arnhem	-	-
Deventer	-	-

B.6 Main material of components

Table 70 Documentation of material types

Government bodies	Documentation style	Notes
		Provinces
Noord-Brabant	Written	Includes the general type of material of the bridge but also the element and component materials.
Utrecht	-	-
Limburg	Written	Includes the material of components and general material of the bridge.
Flevoland	Number	Includes the material type in number form for components.
Gelderland	Written	Includes material type for damages but not for specific components or elements. When damage occurs, they know which material damage is done to.
		Municipalities
Amsterdam	Written	Includes the material of components.
Tilburg	Written	Includes the material of components.
Utrecht	Written	Includes the material of components and general material of the bridge.
Maastricht	Written	Includes the material of components.
Gorinchem	Written	Includes the material of components.
Arnhem	Written	Sometimes includes the material of components.
Deventer	-	-

B.7 Type of Asset

Table 71 documentation of type of asset

Government bodies	Documentation style	Notes
		Provinces
Noord-Brabant	Written	Not included in the form of the NEN 2767. The name of the object often includes what type of asset it is.
Utrecht	Written	NEN 2767 standard.
Limburg	Written	NEN 2767 standard.
Flevoland	Written	Not included in the form of the NEN 2767. The name of the object often includes what type of asset it is.
Gelderland	Written	Not included in the form of the NEN 2767 and is often missing.
		Municipalities
Amsterdam	-	-
Tilburg	Written	NEN 2767 standard.
Utrecht	Written	NEN 2767 standard.
Maastricht	Written	NEN 2767 standard.
Gorinchem	Written.	NEN 2767 standard.
Arnhem	Written	NEN 2767 standard.
Deventer	Written	NEN 2767 standard.

Appendix C: NEN 2767 parameters in practice

In this appendix, how parameter data of the NEN 2767 are documented in different governmental organizations, is presented. There are 6 sections. Connection with Asset, Elements and Components, Defects, Materials, Parameters and Data of inspection. All these sections will have the same structure where the order of discussion is the provinces: Noord-Brabant, Utrecht, Limburg, Flevoland and Gelderland followed by the municipalities: Amsterdam, Tilburg, Utrecht, Maastricht, Gorinchem, Arnhem and Deventer.

C.1 Connection with Asset

Table 72 parameter connection to asset

Government bodies	Documentation style	Notes
	Provinces	
Noord-Brabant	Written.	The names include the location of the asset also.
Utrecht	Code.	Includes a code in the following form 'VK229-17.323'
Limburg	Written.	The names include the location of the asset also.
Flevoland	Code.	Includes a code in the following form '74ad8b9e2c9ed36956057c531cd8b942'
Gelderland	Code	Includes a code in the following form '325064'
	Municipalities	
Amsterdam	Code.	Includes a code in the following form 'BRU0113'
Tilburg	Code.	Includes a code in the following form '20753'
Utrecht	Written.	The names include the location of the asset also.
Maastricht	Code and Written.	The name is included as well as a code in the form of 'GS/13685/05'
Gorinchem	Written.	Just the name, sometimes includes the location.
Arnhem	-	-
Deventer	-	-

C.2 Elements and Components

Table 73 Inclusion of Elements and Components

Government bodies	Documentation style	Notes
	Provinces	
Noord-Brabant	Component written. No Elements.	Includes the strange ** symbols which were present in the decomposition data. Elements are not included.
Utrecht	Element/Component present.	Includes both Elements and Components but these are mixed through each other. There are thus also condition scores provided for elements which are not possible within the standard.
Limburg	Component written. No Elements.	-
Flevoland	-	Not included.
Gelderland	Written	Only sometimes elements and components are recorded; often missing. Elements and

		components appear to be interchanged confusingly.
Municipalities		
Amsterdam	Component and elements.	In NEN 2767 form.
Tilburg	Written and ID.	Element and component are included.
Utrecht	Component written. No Elements.	In NEN 2767 form.
Maastricht	-	Not included.
Gorinchem	Component written. No Elements.	In NEN 2767 form.
Arnhem	-	-
Deventer	-	-

C.3 Defects

Table 74 Defect documentation

Government bodies	Documentation style	Notes
Provinces		
Noord-Brabant	Code as well as written.	Both the damage as well as its code are included in the data. Which does not add additional data.
Utrecht	-	Not included.
Limburg	Code as well as written.	Both the damage as well as its code are included in the data. Which does not add additional data.
Flevoland	Coded.	There is an inclusion of additional information about the damage in a separate column.
Gelderland	Written.	In NEN form.
Municipalities		
Amsterdam	Written.	In NEN form.
Tilburg	Written and ID.	In NEN form.
Utrecht	Written.	In NEN form.
Maastricht	Number	Only a number representing how many defects there are, is available.
Gorinchem	Written.	In NEN form.
Arnhem	-	-
Deventer	-	-

C.4 Materials

Table 75 Material documentation

Government bodies	Documentation style	Notes
Provinces		
Noord-Brabant	-	Not included.
Utrecht	-	Not included.
Limburg	-	Not included.
Flevoland	-	Not included.
Gelderland	Written.	Material is always present even if there is no specific damage.
Municipalities		
Amsterdam	Written.	Material is always present even if there is no specific damage.
Tilburg	Written.	Material is always present even if there is no specific damage.

Utrecht	-	Not included.
Maastricht	-	Not included.
Gorinchem	Code.	Is included with material number.
Arnhem	-	-
Deventer	-	-

C.5 Parameters

Table 76 parameter documentation

Government bodies	Documentation style	Notes
Provinces		
Noord-Brabant	Written.	Includes Severity, Extent, and Intensity.
Utrecht	-	No parameters included. Only the final condition score is presented.
Limburg	Written.	Includes Severity, Extent, and Intensity.
Flevoland	Number.	Includes only Intensity and Extent.
Gelderland	Written.	A condition score is included for each component. The Extent is very extensively written down with its full description.
Municipalities		
Amsterdam	Written.	Includes Severity, Extent, and Intensity. Different terminology is applied for Extent and Intensity.
Tilburg	Written and numbered.	All the parameters are not located in columns next to each other but are spread out across the table. Severity and Intensity are written, and Extent is numbered. Different terminology is applied for Intensity and Extent.
Utrecht	Written.	Includes Severity, Extent, and Intensity.
Maastricht	-	No parameters included. Only some defects are presented.
Gorinchem	Written.	Includes Severity, Extent, and Intensity.
Arnhem	-	-
Deventer	-	-

C.6 Date of inspection

Table 77 date documentation

Government bodies	Documentation style	Notes
Provinces		
Noord-Brabant	Day-Month-Year. Numbered.	Each inspection has its own date.
Utrecht	-	Not included. But all inspections were from the year 2020.
Limburg	Day/Month/Year. Numbered.	Each inspection has its own date.
Flevoland	Year-Month-Day. Numbered.	Each inspection has its own date.
Gelderland	Day-Month-Year. Numbered.	Each inspection has its own date.
Municipalities		
Amsterdam	-	-
Tilburg	Year-Month-Day. Numbered.	Each inspection has its own date.

Utrecht	Day/Month/Year. Numbered.	Each inspection has its own date.
Maastricht	Day/Month/Year. Numbered.	Each inspection has its own date.
Gorinchem	Day/Month/Year. Numbered.	Each inspection has its own date.
Arnhem	-	-
Deventer	-	-

Appendix D: NEN 2767 method for multiple defects

If multiple defects occur on one component the following methodology should be applied according to the NEN 2767. Firstly, an adjustment factor is applied to all scored defects which are presented in Table 78. These adjustment factors, in essence, change the extent of the damage by changing its proportions. An example calculation is presented in Table 80, the foundation beam with 4 defects has a recalculated condition score. This score ends up being a 4, had the worst damage been taken as default the condition score would have been a 6. A similar example is given for multiple components compromising a foundation element in Table 81. Here the costs of replacement are applied to determine the condition score. There is no methodology for estimating the condition score of a complete asset.

Table 78 Condition adjustment

Condition Score	Adjustment factor
1	1
2	1.02
3	1.1
4	1.3
5	1.7
6	2

Table 79 Condition conversion

Outcome calculation	Condition score
Outcome ↖ 1.01	1
1.01 ← Outcome ↖ 1.04	2
1.04 ← Outcome ↖ 1.15	3
1.15 ← Outcome ↖ 1.40	4
1.40 ← Outcome ↖ 1.78	5
Outcome → 1.78	6

Table 80 example of calculating the total damage of building component flat roof finish

Component: (133) Foundation (1051) beam Material: (3) Concrete						
Defect	Severity	Intensity	Extent	Condition with ext. 100%	Adjustment factor	Calculated extent
(G-028) Crumbling	Severe	Final	20%	6	2	40.00%
(G-072) Scratches	Serious	Advanced	8%	4	1.3	10.40%
(G-074) Onkruidgroei	Minor	Final	5%	4	1.3	6.50%
(G-100) Graffiti	Minor	Initial	25%	2	1.02	25.50%
No defect			42%		1	42%
			100%			124.40%

The resultant calculated extent: 1.244 which based on Table 79 results in a condition score of 4.

Table 81 calculation of foundation element based on several components

Element: (133) Foundation				
Component	Condition score	Replacement value	Adjustment factor	Adjusted value
(1051) beam	4	2000	1.244	2000 × 1.244 = 2488
(1236) H-palen	5	4000	1.7	4000 × 1.7 = 6800
(1110) Caisson	2	5000	1.02	5000 × 1.02 = 5100
		∑ = 11000		∑ = 14388

Resultant condition: 14 388/11000 = 1.308 which based on Table 79 results in a condition score of 4.

Appendix E: Features used in papers

Grouping	Feature	# of times used in papers	Included/ Excluded	Reason for exclusion or whether combined
physical characteristics	Road Level	1	Excluded	Unclear what this feature is as no explanation is provided. Thus, making it hard to know how to implement it in the Netherlands.
	Lanes on structure	5	Included	
	Lanes under structure	2	Included	
	Road width	5	Included	
	Approach roadway width	1	Included	
	Bridge side	1	Included	
	Bridge Total Length	12	Included	
	Maximum span	8	Included	
	Min. vertical clearance	3	Included	
	Horizontal clearance	1	Included	
	Number of spans	12	Included	
	Skew angle	9	Included	
	Total area	3	Included	
	Deck width	8	Included	
	Thickness overlay	2	Included	
	Deck Geometry	3	Included	Combined into type of component
	Type of bridge	3	Included	Combined into type of component
	Type of girder	1	Included	Combined into type of component
	Type of support	2	Included	Combined into type of component
	Type of overlay	1	Included	Combined into type of component
	Type of Deck structure	6	Included	Combined into type of component
	Type of membrane	5	Included	Combined into type of component
	Type of Deck protection	4	Included	Combined into type of component
	Main span physical makeup	1	Included	Combined into type of component
	Span interaction	1	Included	Combined into type of component
	Structural configuration main span	1	Included	Combined into type of component
	Type of Deck rebar	1	Included	Combined into type of component
Properties	Bridge age	21	Included	
	Bridge built year	3	Included	Combined with bridge age
	Operating rating	8	Included	
	Type of Service	4	Included	
	Approach roadway alignment	3	Included	
	Mile	1	Excluded	Unclear what this feature is as no explanation is provided. Thus, making it hard to know how to implement it in the Netherlands.
	Functional Class	6	Included	
	Toll	2	Excluded	Tolls are not applied in the Netherlands. Thus, cannot be used.
Design Aspects	Design Load	4	Included	
	Design speed	1	Included	

	Type of design	8	Included	
	Deck strength	1	Included	
	Continuity	1	Included	
	Design period	1	Excluded	Was related to design consideration and not maintenance.
	Reconstruction duration	1	Excluded	Was related to cost benefit analysis. Outside of the scope of this research.
Material	Structural Material	12	Included	
	Wearing surface	8	Included	
	Material characteristics	1	Included	
	Soil type	1	Included	
	Chloride related properties	1	Included	
	Concrete strength	2	Included	
Traffic	Average Daily Traffic	21	Included	
	Annual Average Daily Traffic	2	Included	
	Year of future average daily traffic	1	Included	
	Future average daily traffic	2	Included	
	Average Daily Truck Traffic	17	Included	
	National Highway System	4	Included	
	Direction of traffic	1	Included	
	Travel speed before project	1	Excluded	This feature was concerned with cost benefit analysis of performing maintenance. Which is outside the scope of this paper.
	Travel speed during project	1	Excluded	This feature was concerned with cost benefit analysis of performing maintenance. Which is outside the scope of this paper.
	Overloading rate	1	Included	Combined with average daily truck traffic.
Maintenance	Maintenance actions	8	Included	
	Level of service	1	Included	
	Maintenance responsibilities	7	Included	
	Maintenance duration	2	Excluded?	This feature was concerned with cost benefit analysis of performing maintenance. Which is outside the scope of this paper.
	Rehabilitation duration	1	Included	
	Reconstruction duration	1	Included	
	Maintenance improvement	2	Included	
	Economic benefit maintenace	1	Excluded	This is too much related to cost-benefit and societal impact. We are looking at predicting deterioration.
	Maintenance cost	3	Included	
Geographic	Latitude degrees	3	Included	
	Longitude degrees	3	Included	
	Elevation	1	Excluded	The Netherlands elevation changes is very limited.
	Region/District	5	Included	
	Climate group	1	Included	
Inspection	Condition score	21	Included	
	Structural evaluation	6	Included	

	Inventory rating	4	Included	
	Year of inspection	2	Included	
	Defect score	1	Included	
	Risk management	1	Included	
Environmental	Number of Freezing Thaw cycles	4	Included	
	Snowfall (cm)	2	Included	
	Number of snowfalls	2	Included	
	Carbon Dioxide concentrations	2	Included	
	Rainfall (cm)	4	Included	
	Time of wetness (h/year)	1	Included	
	Humidity	1	Included	
	Highest temp	1	Included	
	Tempature	3	Included	
	Lowest temp	1	Included	
	Chloride	7	Included	
	Distance to sea water	1	Included	
	Sulfate (SO4)	1	Included	
	Potassium (K)	1	Included	
	Sulfur dioxide	1	Included	
	Magnesium	1	Included	
	Calcium (Ca)	1	Included	
	Ammonium (NH4)	1	Included	
	pH	1	Included	
	Sodium (Na)	1	Included	
	Nitrate (NO3)	1	Included	
	Nitrogen dioxide	1	Included	
	Solar radiation	1	Included	
	Promethium (PM10)	1	Included	
	Ozone (O3)	1	Included	
	Rhodium	1	Included	
	Wind condition	1	Included	
Earthquake	Earthquake magnitude (SD/mean)	1	Excluded	Earthquakes are not a (serious) problem in the Netherlands.
	Earthquake magnitude rate	1	Excluded	Earthquakes are not a (serious) problem in the Netherlands.
	HAZUS class	1	Excluded	Earthquakes are not a (serious) problem in the Netherlands.
Defect	Structural component failure	1	Included	
	Defect type	1	Included	
	Defect significance	1	Included	
	Defect intensity/severity	2	Included	
	Corrosion potential	2	Included	Included in material characteristics
	Carbonation of concrete	1	Included	Included in material characteristics
	Defect extent	2	Included	
Pile stuff	Nr of hammer blows required	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their

				deterioration cannot be measured through the standard.
	Percetage energy from hammer to gage location	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
	Pile depth	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
	Angle of pile and verticle soil	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
	Pile circumference * length	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
	Cross sectional area pile	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
	Max compressive strength guages	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
	Max compressive strength pile	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
	Ram weight	1	Excluded	Piles are not included in the NEN 2767 as they cannot be monitored visually. Therefore, their deterioration cannot be measured through the standard.
Sensor data	Strain sensor	1	Included	

Appendix F: Preliminary recommendations

This appendix presents the preliminary recommendations which were presented to government bodies and inspectors from which feedback was requested. These recommendations are divided into 2 sections: Guidelines for inspections and standardisation for data storage and capture more data. Each will be discussed on why it is important, how it could be implemented and what the implications are of the recommendation.

6.1 Guidelines for inspections and standardisation of data storage

Based on discussion points 2, 3, 4 and 5 in section 5.2 it becomes apparent that there are large differences in how government bodies currently work; organisations work as isolated silos, there is no standard to which inspectors are held, however, these inspectors are the most vital as they are the link which converts implicit information to documented data and the NEN 2767 has grown outside of its boundaries of just documenting defects. Because of these insights there is a need to streamline data collection and storage to allow government bodies to share and train a machine learning model together; this way a predictive model can be trained faster, and maintenance could be organised as an interconnected web. This recommendation is divided into two sub-sections: guidelines for inspections and standardising data storage.

6.1.1 Standardising data storage

The results in chapter 2 indicate that there are large differences in how data is stored. The results from the interview excerpts in sub-section 1.1.2 show that different storage systems are used and in sub-section 3.4.3 data storage challenges clearly became apparent. Discussion points 2 also notes that government bodies are all working on islands, making training of machine learning data difficult and requiring a lot of time. To minimize these challenges the following solution is proposed.

A NEN 2767-1 should be created where the ways in which information should be stored and delivered is outlined. This way each government body documents information in the same way and inspectors' deliver data which can immediately be uploaded into such systems. This proposed standard would include three core components.

4. A data model: Specifies the structure and format for documenting assets within asset management systems, ensuring uniformity across all asset owners.
5. A data delivery protocol: Outlines standardized procedures for inspectors to deliver collected data, facilitating immediate integration with asset management systems.
6. Data exchange framework: Defines protocols for data sharing between government bodies, enhancing interoperability and supporting efficient machine learning model training.

An example of a data model is provided in Figure 15. This would have a few implications on current work: providers of asset management software would no longer compete on who can store the 'right' information or who has the best integration with data collection but rather who can provide the greatest insights or deliver the best user experience. In addition, frustrations and workload of government bodies as well as inspectors for integrating captured data into their systems could be reduced.

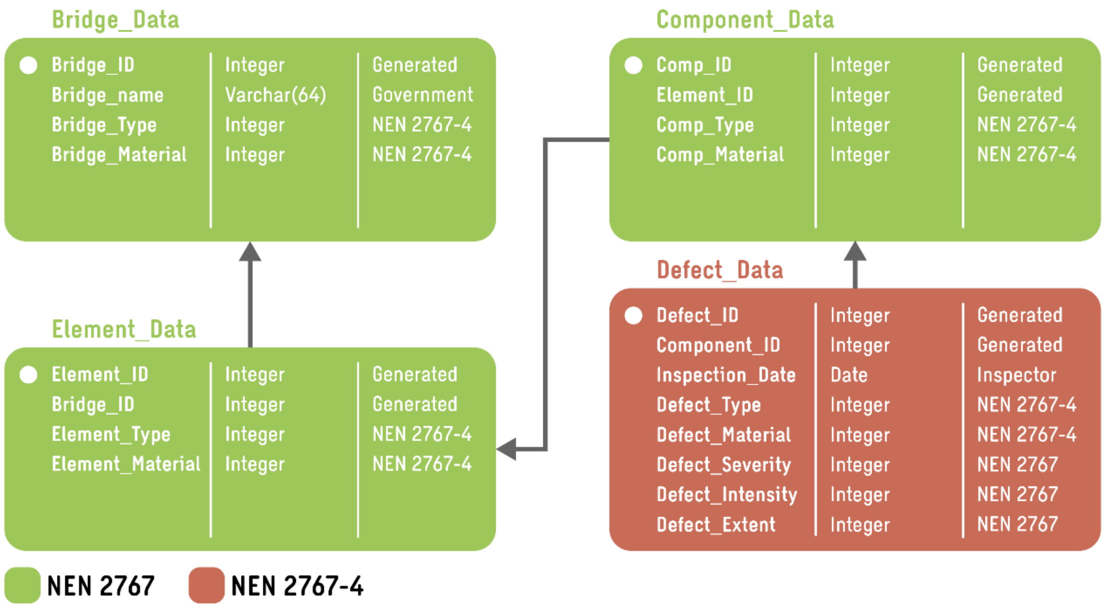


Figure 15 Data model example for the proposed NEN 2767-1

6.1.2 Guidelines for inspections

An important part of training a Machine Learning model is knowing that the data that is input into the system is uniform; there for it is of importance that inspectors approach defect and decomposition documentation in the same way. As indicated in excerpts from the interviews in sub-sections 3.4.1 and 3.4.2 inspects, as well as government bodies note problems with defining extent scores of defects and to which level of detail a bridge should be decomposed. To minimize these differences the following solution is proposed.

A NEN 2767-3 guideline should be defined where a clear example is provided on how an inspection should be performed. It is important that this standard is not restrictive in allowing inspectors to capture the nuances of real life; therefore, it should be a guideline rather than a strict standard. However, it is important that government bodies can distinguish between inspectors who do and don't follow these guidelines; it can otherwise lead to the dilution of data for a machine learning algorithm. Therefore, it is recommended that inspectors are tested on the guideline to ensure captured data does not dilute a machine learning model.; this could, for example, be done by taking one bridge and performing a standardised test and comparing how decompositions are made and how defects are recorded. How this standard would exactly look in terms of guidelines for decomposition and defining defects cannot be recommended due to the researchers limited experience with the NEN 2767. Therefore, it should be created by the NEN committee which includes inspectors and government bodies. It is not necessary about choosing the 'right' way of documenting; rather ensuring that everyone does it in the same way.

6.2 Capture more information

Based on the results of chapter 4 and the discussion point 6 it has become apparent that more contextual data is required to make a bridge deterioration model work but also that the frequency of data capture needs to be increased. This results in the following two recommendations: Capture more features and increase data capture through the Schouw.

6.2.1 Capture more features

Based on the results from chapter 4 a list of features which can affect the deterioration rate of bridges in the Netherlands has been established. Many of these features are not related to the information currently being captured by the NEN 2767; this indicates that if a Machine Learning algorithm would currently be trained on just this data it would lack contextual information and could result in underfitting as the model doesn't have all the information to predict when maintenance will be required. From these identified features 7 should and 13 could affect the deterioration rate of bridges in the Netherlands.

Should affect deterioration: Bridge age, Type of service over and under a bridge, Structural Material, Wearing surface, Maintenance actions, Historic condition scores, Structural evaluation dependant on its implementation.

Could affect deterioration: Total Bridge Length, Maximum span, Total area, Deck width, Operating rating/Design Load, Component design type, Average Daily Traffic, Average Daily Truck Traffic, National Highway System, Maintenance responsibilities, Maintenance cost, Latitude/Longitude, Region/District, Temperature, Rainfall, Snowfall, Other chemicals (Sulphate and Potassium).

Although some of these features could be captured in a NEN 2767 inspection it also becomes apparent that, if the Netherlands wants to enable predictive maintenance of bridges, more data, outside of the NEN 2767 will most likely be required to make an effective model. The recommendation is to immediately implement the features which should influence deterioration. After this features which could have an effect and are easy to implement within the NEN 2767 methodology should be added, after which the remaining 'could' features can follow. In addition, the risk assessment, which is applied by all government bodies and plays a key role in maintenance decision making should be included in a bridge deterioration model. This results in the following phases:

Phases	Features to implement
Phase I	Bridge age, Type of service over and under a bridge, Structural Material, Wearing surface, Maintenance actions, Historic condition scores, Structural evaluation dependant on its implementation. As well as the risk assessment.
Phase II	Total Bridge Length, Maximum span, Total area, Deck width and Component design type.
Phase III	Operating rating, Design Load, Component design type, Average Daily Traffic, Average Daily Truck Traffic, National Highway System, Maintenance responsibilities, Maintenance cost, Latitude/Longitude, Temperature, Rainfall, Snowfall, Other chemicals (Sulphate and Potassium).

As can be seen, some of this information, such as material types, are already recorded. This information should also be stored in a standard way as proposed by sub-section 6.1.1. Therefore, the standard should include this additional information. In addition, bridge age, will be substituted by an addition of component age, as this was found to possible contribute an even higher level of detail about the age of the structure. An example of how this could be done is presented in Figure 16.

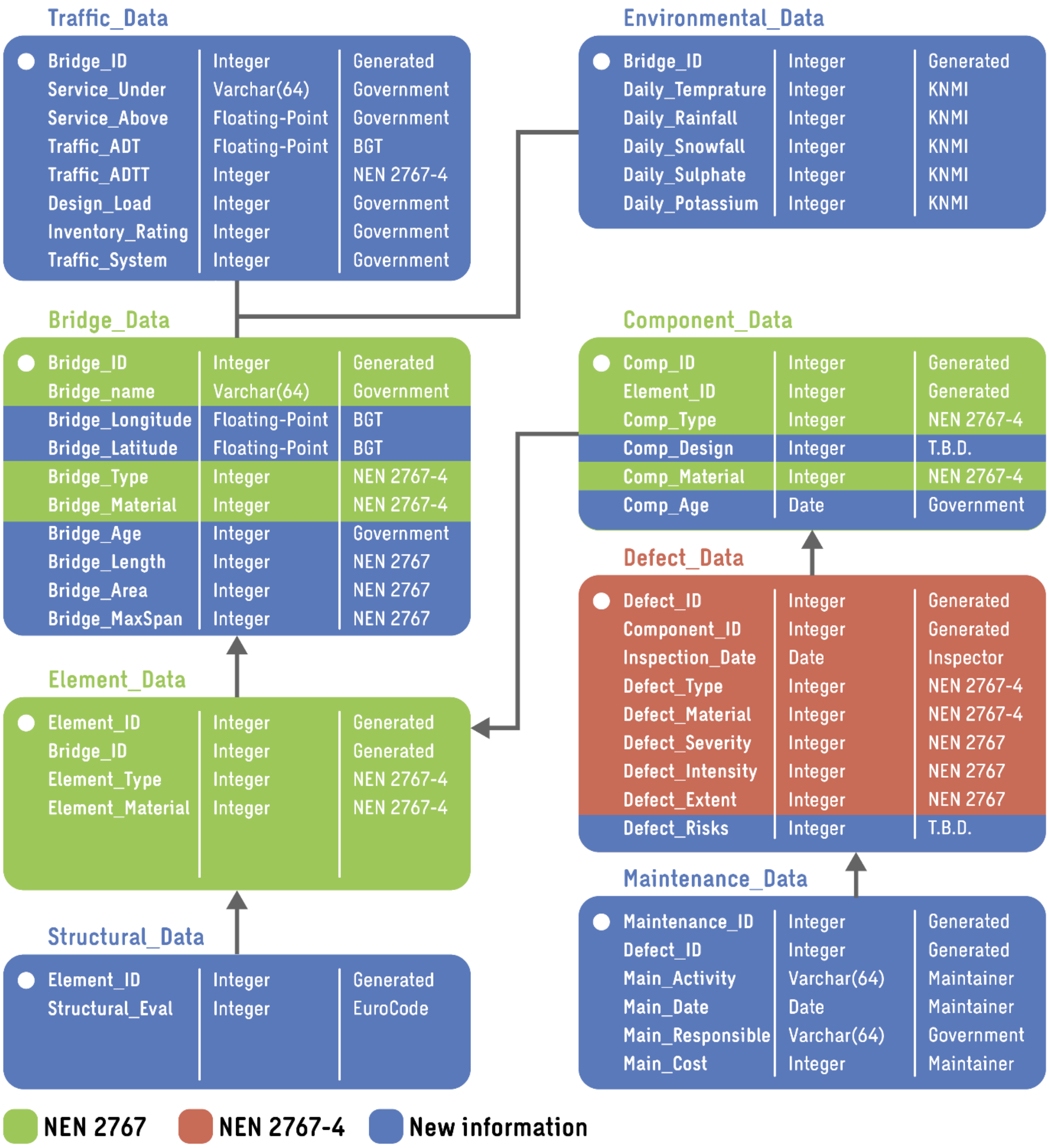


Figure 16 Example of additional features in proposed NEN 2767-1 data standard

6.2.2 Capture more data

The Schouw has been identified, in the discussion as point six, the Schouw is an annual inspection, usually performed by an internal employee of the government body. These employees often do not have a technical background and only check if something bad has not occurred. Despite their technical knowledge being limited and inspections often being quick this moment could be a great opportunity to capture additional information. Therefore, the following is recommended.

Schouw inspections can serve as a moment where already existing defects are reevaluated and if new defects are spotted, they could be scored. This could be done by letting these internal inspectors take pictures of the existing and found defects and letting an inspection bureau do a quick check up by comparing the old and new pictures to each other. This way more data is captured to train the model.

Appendix G: Recommendation validation

In this appendix the questions posed about each recommendation are presented.

Questions recommendation 1

Can your existing practices or tools be integrated with this extended standard?

What challenges might arise when implementing this extension in terms of technology, personnel or resources?

What do you estimate the time and cost implications of implementing this extension would be for your organization?

What potential effects, both positive and negative, could this extension have on your organization?

Questions recommendation 2

Can your existing practices or tools be integrated with this Practice Document?

What challenges might arise when implementing this Practice document in terms of technology, personnel or resources?

What do you estimate the time and cost implications of implementing this Practice Document would be for your organization?

What potential effects, both positive and negative, could this Practice Document have on your organization?

Questions recommendation 3

Can your existing practices or tools be integrated with capturing these additional features?

What challenges might arise when capturing these additional features in terms of technology, personnel or resources?

What do you estimate the time and cost implications of capturing these additional features would be for your organization?

What potential effects, both positive and negative, could capturing these additional features have on your organization?

Questions recommendations 4

Can your existing practices or tools be integrated when applying the Schouw for additional data capture?

What challenges might arise when applying the Schouw for additional data capture in terms of technology, personnel or resources?

What do you estimate the time and cost implications of applying the Schouw for additional data capture would be for your organization?

What potential effects, both positive and negative, could applying the Schouw for additional data capture have on your organization?

Appendix H: Excerpts for validation

Here the excerpts applied for validating the recommendations are presented. Which is followed by their analysis.

Table 82 Validation excerpts recommendation 1

ID	Data standard recommendation
Government representatives	
1	Government Body 1 - 3:20 "Well, what they have started with through the CUR is more or less standardizing, right? But yes, my concern is that when you look across the Netherlands, everyone ends up interpreting it in their own way. And yes, that's where I miss a national approach. What you're proposing now—I fully embrace it. I think, 'This is it.' If you do this, then any inspector can proceed in the same way and deliver the results back into your system." Government Body 1 - 4:03 "Well, you also need to make sure that the companies providing these management systems conform to this standard. They shouldn't be doing their own thing. You see this in other countries too. If, for example, you work at a bureau, you might think, 'This is what I find important,' and incorporate it into your system. But a colleague at another bureau might think differently and approach it another way." Government Body 1 - 4:54 "I think this is perfect. I am definitely in favor of doing this. But again, how do you get everyone on the same page? Every bureau—whether it's Sweco, Antea Group, or, who else is there, Witteveen+Bos—they all need to adopt these changes." Government Body 1 - 5:36 "Arcadis is the largest engineering firm in the Netherlands. They should collaborate to establish something like this. Then you're set, right? But as a province, we have here a weak point: in two years, Arcadis will conduct inspections for us. And they'll do it in their own way again. That means I'll get data in different formats, and that's exactly what you want to avoid."
3	Government Body 3 representative 1 - 6:01 "Yes, I find that very logical. There are already several projects in the Netherlands that work this way. Take the IMBOR standard as an example. It's also about how you can deliver information in a data-driven way, transferring it from point A to point B. I see this recommendation as fitting within the same context: that data is delivered in this way, either from an inspection or by the inspector." Researcher - 6:54 "Yes, I have another question about this. This was one of the suggestions I received. I already showed this presentation to an inspector, and they said, 'Hey, maybe this isn't for the NEN, but rather for the CUR 117, as part of its framework.' What do you think of that idea?" Government Body 3 representative 1 - 7:07 "Yes, I completely agree."
4	Government Body 4 Representative - 6:26 "No, what you're saying is absolutely correct. And now I'm thinking about what your goal should be. Would you want everyone—since you've seen differences, which might come up again later—would you want to get everyone on board and working the same way? Or would you aim, for example, at integrating with an IS management system, saying, 'Here, I've got this framework, attach it to your management system, and everyone will want to use yours.' I think that approach has a better chance of success than trying to convince various other parties to agree to work in the same way." Government Body 4 Representative - 8:32 "Yes, I think the data itself is already standardized, also for storing inspection data. And, of course, the standard prescribes how you should create a decomposition. But you always have the risk of the human factor, right? An inspector goes into the field and needs to follow the guidelines, but they can easily make mistakes. That's a significant risk here. But essentially, the data is standardized. However, then you have municipalities, for example, that sometimes receive a report, a PDF, or an Excel sheet describing their plans for the coming years, while larger organizations use management systems. And that's where the big difference lies." Government Body 4 Representative - 9:19

	"We've also moved from package X to management system Y. Sure, you can transfer the data using some tool or other method, but it always involves manual work and customization to align those systems. One system might offer more features than the other, leading to missing or lost data when switching systems. Yes, that's correct; you need to normalize it."
	Inspectors
4	Inspector 4 - 10:35 "Yes, I'm still looking at it, indeed, that's a good point. This standard, it's really about standardization, right? And I'm looking at where—there's still a piece of personal interpretation, right? And I'm trying to figure out what kind of human interpretation you might run into in this case. What goes wrong when the inspector is actually working it out? Do you understand what I mean? Look, in the end, you have your PDF, which is basically useless, but the data, the attributes in that PDF, as long as you have them in a database, you can do anything with them, right?" Inspector 4 - 12:51 "You also see preferences, both from the NEN and, for example, from Rijkswaterstaat, that say, 'Well, they are even working on this now.' I hear that if I ask 10 people within Rijkswaterstaat to decompose a viaduct, about 95% of the time, they will really follow the same standard. So, there is a certain level of standardization. I always think you should ask, 'Is there a problem? Is there a situation, a challenge, and what can be done about it?' But then you always have to look at what already exists and how well it's being rolled out." Inspector 4 - 13:31 "Yeah, you often see that with policy, right? They say, 'If something goes wrong, people always say, 'No, there needs to be stricter policy.' Well, the first step is: what policy is in place, and is it being executed? Before we change policy, we should first look at whether it was done well in the first place and if it wasn't executed well. And that's a bit the same story here. If you look at Rijkswaterstaat, they have, for example, a decomposition framework." Inspector 4 - 14:00 "In it, they also set requirements, such as an object should never exceed network boundaries. So if you have a concrete object where two networks intersect, that can never be considered a single object. It's just an example, but there are a lot of agreements like that. And I think what could be good is—maybe not for now, but as a recommendation—to look at leading institutions, such as Rijkswaterstaat and some water boards. What policy is there, and can that be made more publicly available without having to reinvent the wheel?" Inspector 4 - 16:36 "There are parties that do more of the pull-down inspection, as I call it. You come to a guardrail, for example, and you pull down the corrosion, the extent of the corrosion, and the stage of the corrosion. And that's how the inspection is done. I think the key part of the implementation is how you write that in the text. At [organisation], we emphasize that you have to guide someone on what they see and also what they don't see, and how you determine the extent, right? As we mentioned earlier, the extent is very crucial for your score, and that's where you'll see the greatest variation."
5	Inspector 5 - 00:09:21 "I think it's a good idea. I just think it doesn't belong in NEN 2767, because it's essentially a standard that describes a particular TYPE of inspection, and it's not meant to introduce how data should be stored. That's where it's not a good fit. A good idea would be to put it under CROW, which has developed the CUR 117. I think that's a better approach. Of course, you can still implement it if you perform a NEN 2767 inspection. But then, it would just be an outcome sheet next to the condition report." Inspector 5 - 00:10:16 "Well, no, it shouldn't touch 2767. It could be a separate standard, but making it a standard means something quite significant. I think that's going too far, because that would actually mean imposing a certain method on inspection agencies. The CUR 117 essentially says, 'As the market, we believe this is the way it should be done.' And that intent is necessary to get this through because people need to see the need and invest in it. That won't work through a model like that, but it can work with CUR 117, where all agreements are defined. It might be that it references a new standard, and then it's a choice. You can say, look, if you create a standard, then you must adhere to it because it's Dutch legislation. But if you say it's through CUR, then it's a guideline you can conform to, and in such a CROW environment, the committee can make this easier to implement, and the people involved can recognize its usefulness and necessity. Look, the people in the 2767 Committee only care about what they need to do to get the condition measurement as accurate and complete as possible. That's already been hashed out; the development of it is over. You don't really need anything else." Inspector 5 - 00:12:54 "I think it's a good idea, and I can also imagine that other parties will quickly agree. Yes, that's indeed the case." Inspector 5 - 00:13:22 "The hardest part in this is actually enforcement. Look, if everyone agrees to do it this way, then they have to do it that way. Because anything that deviates from that, any individual interpretations and so on, is a threat."

	Inspector 5 - 00:13:41 "You can do two things here: either you make it as simple as possible, keep it simple, or you say, there has to be something in place to control that. But that takes more energy, more money. Someone has to do that. So yes, I suggest keeping it as simple as possible. But the simpler it is, the less efficient it will be, and machine learning will suffer. So, there's a transition period in that, and yes, there needs to be oversight." Inspector 5 - 00:14:59 "It's tricky because I'm trying to practically translate it in my head. I'm doing a condition measurement, or whatever, and I have a second sheet with me. Oh, you also have to fill this in, all these boxes. Am I going to fill that in? This might work with an online tool, maybe, where you just fill in a sheet, or 117.nl/filloutform." Inspector 5 - 00:15:31 "So the system must be able to handle gaps, blank cells, so to speak, which is quite challenging. What we haven't discussed yet is how reliable it is."

Table 83 Validation excerpts recommendation 2

ID	Inspector qualification recommendation
	Government representatives
1	Government Body 1 (6:41) "Yes. Standard best. Yes, yes, we also think so, yes, well, fine, yes, definitely, yes." Government Body 1 (7:15) "Well, if you look at the example you're showing here, it's a serious defect, intensity, last stage, yes, scope. Yes, no, yes, perfect, I mean, yes, that's fine, yes, no, I can agree with that." Government Body 1 (7:37) "So, it's unfortunate, I think that's what you need for road inspections, right? The COA, they have something similar for road inspectors. Let me check, hold on. Then you also need, say, a certificate to inspect according to the CRW, right? So they also have standards for that, yes. But that's road inspection, but well, you could do the same for this."
3	Government Body 3 representative 1 (9:23) "I believe that if you have inspections carried out, they should be done by a certified party. That should actually be the minimum baseline, knowing that in practice, other forms of inspections and standards also exist. Ultimately, it's about the intervention values, right? The ones you then assign here, and based on the photos as I see them now, you might even want the photo to be a bit larger, more of an image to properly assess that crack, because this picture as it is here actually says nothing about how severe this really is. So it mainly comes down to the interpretation of that, and you can even see that a Monday morning report and a Friday afternoon report can look different from a regular report. You see that there's simply a difference, and that's the most difficult part, I think. How do you translate that arbitrary part of the inspector's assessment in a good way? Because when he says, 'Hey, it's 30%, yes, that's really the system.' Yes, it's also 30%. But that assessment, that human estimation that goes with it, is what makes it difficult. And then you create a kind of threshold to establish, for example, such a crack, and those thresholds apply to everyone. A threshold is measurable, either from a 3D model or a photo. And from that, you can then always see if it falls within or outside the threshold, and that should be the input for the standardization." Government Body 3 representative 1 (11:14) "Exactly, right?" Government Body 3 representative 1 (11:49) "Well, we already see changes in the world of inspectors. There are agencies that no longer go outside with ropes, ladders, and hammers, but initially go outside with drones, and only then do they carry out additional research. So you see that the working methods are changing in the countries. More and more parties are offering that. It is, however, a very costly affair, because I've calculated the difference, and right now, for a typical structure, you're easily spending €10,000 on a drone inspection."
4	Government Body 4 Representative (12:55) "This works. The idea is good, but in practice, it's going to be very difficult." Government Body 4 Representative (13:03) "I've given an example before. If you have a baker or a mason who just started working, one has seen a lot of bread being made, the other has seen a lot of real construction work and has more experience with it, and they will think about it differently. And this

	is also, to a certain extent, open to interpretation, right? Here, 10 to 30%, yes, that's... Yes, it's 11% sometimes, as much as 29%, while that's a huge difference. And intensity, last stage, yes, that also depends a bit on the inspector and how they handle it. How they measure it, and how they interpret it. And a crack that runs, perhaps through... It may get thinner at some point, and how far do you measure it then? I once heard someone give an example of the length of the coastline of the Netherlands." Government Body 4 Representative (14:18) "So, if you want to collect everything in the same way, yes, keep it at the main points and not so much at the detail level where you depend on human work." Government Body 4 Representative (15:24) "So, that can be, that's inflexible, but determining the extent here, that becomes difficult. Risks can be, well, I've also done that myself, down to the component level. I think I've mentioned that before, right? You can have more risks in one area than in another. Sometimes it also depends on the object, right? A busy road or somewhere deep in the forest makes a big difference, of course."
	Inspectors
4	Inspector 4 (22:46) "Actually, you now have a nice detailed photo. Would you, in principle, want to include a little card showing the actual crack, but you're actually missing an overview photo as well? Just take a few steps back, what am I looking at here? Is it a paving stone? Is it a really important foundation element? You can't see that. Also, in terms of intensity, you have a beginning stage, an advanced stage, and an end stage. I would then check those terms for you, so if there's someone in the room you know who might recognize it, they'd understand." Inspector 4 (23:36) "Yes, what I can say about that is the decomposition. Yes, yes. You need to make sure that all of this decomposition is purposeful, and that also means you need to have the right decomposition for the right person at the right time. And that means you should have a clear decomposition on a rough level. I've mentioned this before, but if, for example, you look at a mechanic..." Inspector 4 (27:06) "Look, you can do it quickly, and then we come to the next point, where you get high scores in your findings because you make smaller decomposition pieces. But does that give you the right picture? Can you actually act on that information? So you also need to check, is that the information you want to act on? So, if you get a report where everything is decomposed down to the wall and that wing, and you go outside with that, then you get much higher scores. But if you have merged things together, the question is, what information is better to act on? Well, briefly, there's also an element of risk assessment in that, which I think is super important and hasn't been taken into account. I've also mentioned this before, for example, with cracks in bearing supports and such, you also..." Inspector 4 (29:55) "Then we describe all the spacers that are corroded. We see the spacers as 1/4, meaning 25% of the guardrail is corroded. Then you also have 1/5, actually, and that's the sliding construction above the early transition. Well, we see that, we say that, so it's correct to quantify." Inspector 4 (31:46) "Having your own ideas about it, and I think you could standardize that pretty well. What you would need to do, however, is if you want to standardize this, you would actually need it in the tooling provided for that. And it's, I'm going to say it again, something where you simultaneously see a limitation because everyone has their own tools. But then, you would need help from AI, so all those arrangements about widths, seeing the guardrail in pieces of four, and so on, you can go on with many things. If you want to standardize it, it should actually be supported by your software, so that your software helps with this."
5	Inspector 5 (00:19:58) "The burden, yes, the burden here is that there is a certification." Researcher (00:20:04) "Well, I heard there's no certification, then okay." Inspector 5 (00:20:06) "Certainly, they have series. I have the certificate, people in 67. I received training to participate in the condition measurement from the standardization committee." Inspector 5 (00:20:28)

	"We Dutch are not really fans of certificates. No, and diplomas, and 'I'm good enough and you're not.' Yes, there's something Dutch about that. Other countries don't have this. If you don't have a diploma, you're out. You have this season. I would actually advocate for it, but that's beyond the scope of the standards in 67. I would really like to see a quality mark for inspectors in the Netherlands. And not just for condition measurement, no, but in general, so that you have 1, 6 points and a number of products, just like the registry. More about designing a registry, I would really like to see a register of inspectors who comply with certain guidelines and also have certifications in that regard." Inspector 5 (00:21:25) "So, but going back to the practice guideline. Yes, there certainly is certification, but you know, as a client, if you and I are not going to name names because that's not allowed to say, if you have a low-cost provider who for €150 per object sends an inspector with a tablet to quickly produce a report." Inspector 5 (00:22:33) "Yes, you want to know how often, but you don't want to know how often it's filled out incorrectly, like with a gap. If you're standing in the last stage in this example, but it's written as 'advanced' and not 'final stage,' well, God, it's the final stage, guys, when a gap is indicated, this is not a gap. And that's very often explained incorrectly. The consequence of that is..." Inspector 5 (00:24:02) "He said he doesn't know that, but training is simply given, and that doesn't mean you're certified. But a certificate, I think, is already something, indeed." Inspector 5 (00:25:17) "So, I advocate making that mandatory, but that can only be enforced with agreements in the industry, CUR 117."

Table 84 Validation excerpts recommendation 3

ID	Additional feature collection recommendation
	Government representatives
1	Government Body 1, 9:50 "Yes, what you see is that what is very important to assess risks is indeed the age of the structure. The load class for which it was designed must be clear. And the increase in the percentage of freight traffic?" Government Body 1, 10:17 "Look, those three elements... At some point, we must be able to predict relative to what it was ultimately designed for, right? What is it again? We now use the Eurocode, but before that, there was, let's say, the VOCB 63 or others. Those are the elements you need to be clear about to anticipate changes. The intensity, right? That is a very important factor. The percentage of freight traffic has increased so much." Government Body 1, 10:57 "Yes, but now it may be that this bridge, given its age and load class, will no longer meet the requirements." Government Body 1, 11:08 "That is a crucial parameter to monitor to determine when we need to take a closer look and see if things will hold up." Government Body 1, 11:25 "Where we face issues in [government location], for example, is that we don't have a clear view. For instance, we have a bridge, and we know its construction year. But why is it even standing there? What load class was it designed for? Those calculations are no longer available. So now, what we do is remove small pieces of concrete to determine the concrete restoration class. We take a small piece of steel to find out the steel quality used at the time to estimate the load class for which this bridge was designed." Government Body 1, 12:05 "Well, and then we say, okay, the new parameters are, well, we have the intensity data, and then you can redo the calculations to see if this bridge meets the requirements or not. And if there is an increase in freight traffic, then at some point, we realize it no longer meets the requirements." Government Body 1, 12:29 "And that's the issue we are currently facing—at least, that's my perception. Many road authorities are saying, 'Yes, all bridges, or many bridges, no longer meet the requirements.' But that's because we simply don't know." Government Body 1, 15:37

	"Sometimes you lack consistency, and it would be very beneficial to adhere to your recommendation to systematically document fixed characteristics. I support that."
3	Government Body 3 Representative 1, 15:38 "Some aspects are already organized at a national level. As you mentioned, weather data from the KNMI can still be retrieved years later. They have organized and made it accessible. Traffic data is also quite readily available, at least for larger authorities. I'm not sure if smaller authorities always have visibility into the number of vehicle movements per lane or object on municipal roads. As a province, we do have this data, and we even publish it as open-source data. So weather data and traffic data can already be linked to this system. The challenge lies in obtaining information about the objects themselves, especially older ones. Data collection on objects has only really taken off in the last five years. Before that, we have the data, but it is buried in documents. If you want to analyze patterns going back decades, it requires a very intensive archive effort." Government Body 3 Representative 1, 17:27 "That's certainly true. To give you an example, over the past three years, we've invested more than half a million euros solely to retrieve information from our physical inventory. So we are making those investments, and we do see the added value in these kinds of projects." Government Body 3 Representative 1, 17:50 "This often boils down to what we're also seeing with IMBOR. IMBOR was launched two to three years ago nationally and is still developing. But very few authorities have embraced it so far. The reason is operational management and the culture of those parties aren't ready yet. Internally, we also face the challenge of our organization not adapting as quickly as such systems require. That presents a major risk—launching a 'rocket to the moon' without having the launchpad ready." Government Body 3 Representative 1, 18:38 "While the organization isn't fully prepared yet, the biggest transition paths involve cultural and organizational changes to enable these projects." Government Body 3 Representative 1, 18:57 "I understand that, and that's where the main challenge lies—it's a cultural shift. To put it simply, it's like moving from the standard Windows Explorer to SharePoint."
4	Government Body 4 Representative, 18:47 "A lot can be done. A large part involves collecting new passport data. Let me grab an example of a passport." Government Body 4 Representative, 19:01 "You know, something like age—so the construction year would be included. We also indicate whether it's a monument, as that significantly affects your maintenance strategy. Traffic intensity, and what would also be good, is the design load class." Government Body 4 Representative, 20:14 "Additionally, there are many passport details that the owner/manager must fill in. That's possible, but I wonder whether extending the NEN standard would help. You could make it a requirement for NEN inspections: using the model is only possible if the passport data is in order." Government Body 4 Representative, 20:38 "You can't reasonably ask an inspector to gather this passport data during an inspection. That involves a lot of archival work, and they can't estimate the time and cost beforehand." Government Body 4 Representative, 22:34 "So actually, you're not collecting extra data, but verifying existing data. That's how I see it."
	Inspectors
4	Inspector 4, 34:30 "I think inspectors shouldn't be burdened with gathering more data during inspections." Inspector 4, 34:43 "They are often so focused on inspecting the object that they almost 'dance' with it, understanding it deeply by the end. Beforehand, you don't always conduct a desk study, but during the inspection, you learn about the object." Inspector 4, 35:49 "There is a lot of data that could be gathered centrally. As long as you know where the object is located, you can use online resources to gather information, like traffic intensities." Inspector 4, 36:59

	"You could even incorporate incidents, like how often vehicles crash in a certain spot. If you notice repeated damage to guardrails in a curve, you could investigate further." Inspector 4, 37:32 "We already have sensor data and weather data. These connections can help prioritize maintenance more effectively."
5	00:29:05 Inspector 5 "Exactly, I was just about to suggest, perhaps even with traffic, right? Maybe we should categorize this under something like 'sensor in' or similar. This provides the most information, so it's about continuously transmitting data or maybe at a specific interval—taking measurements every day or at certain times." 00:29:50 Inspector 5 "Yes, you could potentially connect more to it, for example, how often a bridge opens. That also says something about wear and tear, right? You could also measure deformations in the bridge itself. For instance, if you see how much longer the bridge becomes, especially steel components in the sun combined with temperature fluctuations, you could predict at what temperature the bridge might seize up. That's really fascinating, don't you think?" 00:31:06 Inspector 5 "No, but it doesn't provide that yet, but you can combine a lot of data. Yes, otherwise errors might seem random, but we don't yet know what data we can use. By combining different datasets, new insights could emerge—even when paired with something as basic as temperature." 00:31:30 Inspector 5 "Suddenly, you have a lot of information we weren't even aware of before. For example, fatigue earlier than expected. Now we know the number of movements, the bridge, and the temperature—all of these influence the fatigue progression of the bridge. You could even install a sensor that occasionally sends an electromagnetic pulse through a bridge component. And when it detects a change in the pulse, you know that somewhere, the atomic lattice has been disrupted by fatigue." 00:32:00 Inspector 5 "That's amazing, of course. So, I would also recommend—even though this may not fully align with the current research—to think about what kinds of sensors exist and what we should install in these bridges. It will help us at some point in the future. Wouldn't you agree?" 00:32:12 Inspector 5 "Yes, a very good point. It doesn't even cost that much anymore. Sensors, sure, they have their costs, and I don't know everyone's budget, but if we all contribute a little, we could make significant strides."

Table 85 Validation excerpts recommendation 4

ID	Additional feature collection recommendation
	Government representatives
1	Government Body 1 18:34 "Because I, I would have liked it, and I also tried to get this, so to speak, into the heads of the people. We then said, let's do it twice a year, that the caretaker, so to speak, takes a walk around a work of art, right? They call it an archive, where you see all the parts of a work of art, right? If you walk around an archive? Well, in practice, there were all sorts of stories. Yes, but I had this service, and I had yes, that was a big maintenance project and I had to be there. And well, all sorts of 5s and 6s to indicate that, yes, I didn't have time to walk around the school, but well, at some point, we said, let's have an external agency do this. Let's carry out a maintenance inspection once every 6 years, or every 5 years, because then we could follow a financial cycle. Okay, so at least during that maintenance inspection, once every 5 years, the structure would be thoroughly checked. And yes, what happens in between, well, I really wanted it, and I still believe it should be possible. But in practice, I found that people had all kinds of stories, which meant, well, this didn't happen. A persistent nice app was made, right? They could tap on their mobile phones and register various parts they inspected, right? It made it really easy for them. Only, well, it just didn't happen." Government Body 1 20:40 "They don't see the importance of it, the underlying ideas, and the level of people is also very different. One person, well, they're more involved with the artworks and thinks, well, I'll just check if it's clean and if there's graffiti. And well, like I just said, at Rijks, I now face the problem that the drains aren't well maintained, and the drainage isn't secured properly. I think, well, when I walk there and I see that, I think, hey guys, this is important to have in order. If you drive by at 80 km/h and think, oh, it all looks neat, yeah, that's what you think, but that's not how it is. So, at that level, you need to assess it a bit. Yes, this is the fourth recommendation."

	Government Body 1 21:41 "Hi, that would be nice. No, so this could be a recommendation. But then, in practice, well, the implementation of that, yes, has some difficulties. People are busy, and well, they don't see the importance of it, because they are further removed from it. They also have to inspect the roads and mow the berms. And so, yes, this is just a small part, right? But when you're responsible for ceilings, yes, and one person takes that seriously, and well, the other person finds it all..."
3	Government Body 3 Representative 1 23:25 "Well, in the Nen 27 67, of course, part of it is included in daily maintenance. And from that part, the survey would be very appropriate, right? If you look at things like graffiti, pollution, moss growth, rust, and that kind of thing, it fits very well into that survey. But often, these are just the parts that don't always say anything about the lifespan and progression of an object." Government Body 3 Representative 1 21:26 "Yes, yes. What I know for sure is that our surveyors have a different level of education, a different level of knowledge than the inspectors of an object. And that the judgment of the surveyor is still arbitrary, while the judgment of an inspector is more certain. Therefore, a survey inspection for daily maintenance fits very well, right? Small-scale maintenance and things that are visible at a glance on the surface. But to really make a technical statement about the lifespan, I don't think a survey is a suitable method for that. From the survey, damages only show up once they are so severe that you can no longer reverse it because the damage is so visible that it can be seen with the naked eye from the road, so to speak. Yes, we want to intervene much earlier when you're still just at the very beginning, like with a tiny crack. So, when the object starts to show signs of wear, as we call it, right? When it starts showing small flaws." Government Body 3 Representative 1 22:47 "We want to be there at that point, and those things don't come up from the survey."
4	Government Body 4 Representative 22:34 "Yes, I'm actually not gathering extra data, but verifying data. That's how I see it, I think." Government Body 4 Representative 22:52 "Yes, that's of course always good. What we do is also conduct a visual inspection every quarter. But we never use the Nen inspection alongside that, right? We just look and say, hey, something is wrong here. Then we immediately raise the alarm, and that's what it's really for. It's different from confirming an inspection, so to speak. I assume you want to see something like damage or issues, so you can monitor that." Government Body 4 Representative 23:36 "Because that kind of data can be collected, but that data becomes very valuable, we have one concrete damage, but we see it and schedule it. We're not going to check again next year if it's 1 square meter, and the following year it's 1.1 square meters. You want to see growth, so you can predict how it will develop. But you have to be careful. I have concrete damage here, maybe some concrete cover issue or traffic intensity." Government Body 4 Representative 24:17 "Yes. In the Netherlands, it's not very difficult, but it can happen at any time of day, and then you need to process it right away. And managers need to let things happen and keep things going, right? Because in the short term, everyone can do it. It's all success, but you need to look into the future, because that's what it's all about. In the short term, such things are always very difficult. I give an example, collecting data is easy, right? We give an agency or whatever. We give them a budget. We get lots of data, stuff it into a system, and it's all nice and pretty, but then you need to process it, you need to edit it, and that's where it always goes wrong. And I think..." Government Body 4 Representative 25:25 "Also, you shouldn't leave that to the manager because then it won't succeed. My advice is really to contact a reputable inspection agency, and I'll help you with that if you want. You can also say that I referred you, and I really think you should look for help there. Because such an agency can use it as a business model. We have this as an extra in the inspection, but for example, we do inspections every 5 years or 4 years, and every two years we can do a quick survey."
	Inspectors
4	Inspector 4 44:46 "On Dutch roads, you often have the manager driving around with the wipers, right? Those road inspectors, right? And they check, for example, if there's a dangerous situation, like if there's a truck tire on the road, but they don't have a specific checklist for objects. Actually, it should..." Inspector 4 45:30 "He knows where to look, but it really needs to stand out. He won't notice tiny cracks from a scraping accident, and then you have the road inspector, and then there's also a kind of legal scale from the performance contract where the contractor is required to

	drive once a week over the area to remove animals from the road, really. Because if you have a dead animal on the asphalt, the proteins from such an animal break down the bitumen, so aside from the fact that it's unpleasant to drive over, and if it's a deer, you could have an accident, it's also unsustainable." Inspector 4 46:21 "If you leave that for too long, you'll get a sort of nest in there. So those stones will loosen up, and the contractor has technically met his obligation, according to the performance contract. The manager then really puts the responsibility with the performance contractor, and policy is set up that says you will drive there every week. You'll have a number that people can call in case of emergencies, like the 0800 002 number from Rijkswaterstaat, for example, and that's how it's managed. But we don't need to send someone to carry out survey inspections with decomposing objects outside. Casper."
5	00:39:00 Inspector 5 "Traditional measurement, in my opinion, is insufficient for programming maintenance, because then you're actually looking at the future, right? Condition measurement is actually a bit of a 'backward' approach. Not entirely how I put it, but you're a bit behind the facts. Yes. The predictive nature, where perhaps learning is used, there it sits, right? Or multiple inspections, which reduces the interval, allowing for a more reliable prediction of the future." 00:39:32 Inspector 5 "So, you need to do it every two years, or, yeah, two years. Or, I don't know if you'll still perform that other heavier inspection? Also, yes, that can be stopped in the system. But only once every 5 years, condition measurement, that's really insufficient. That's not good." 00:40:05 Inspector 5 "It's already established in the CUR 117. Yes. In my opinion, the 'schouw' is a mid-term evaluation of the last performed inspection: has something changed? No, and it's precisely that, and sometimes you see, for example, an impact from a pressure of 4, or something, then you have to deal with that. So, essentially, you're addressing problems with the 'schouw' scale." 00:40:31 Inspector 5 "Furthermore, the 'schouw' is often carried out in a very low-threshold way, often by in-house personnel. Yes. Untrained personnel. That's not necessarily bad. You can be a layperson with the cold, because, yes, you only need to look for a moment. The reasons for me have been written down. Does it still hold true?" 00:41:38 Inspector 5 "Because it predicts something. It only deals with predictions based on aging. And yes, it doesn't know that we crashed a tractor into a wall or that the railing was hit. Maybe that's not something it can learn. That's what the 'schouw' is for. With the 'schouw', you can say, 'the best machine'. We have new inspection data, which means your prediction, yes..." 00:42:00 Inspector 5 "...can be adjusted, because we already had to repair the railing, and the new railings are up. So exactly. I think that's what you mean. Yes. Yes, then I would explain what I would advise. What I would advise here is, document the results of the 'schouw' better. Not as extensively as the app inspection, but still put it in the system in that one block."

6.3 Validation of recommendations

In this section, the findings from performed validation interviews with government bodies and inspectors are presented. The aim is to understand what weaknesses the recommendations have and thus change them. This section is divided into 4 sub-sections, each which investigate one of the recommendations, their weaknesses which is then followed by changes which will be made to the preliminary recommendations.

6.3.1 Standardising data storage validation

From the excerpts presented in Table 82 six different insights can be identified. Firstly, Government body 1, 3 and inspector 5 encourages the data storage uniformity for NEN 2767 data. Government body one noted the importance of getting large organisations such as Sweco, Wittenveen+Bos and Antea to join in on this standardisation. Government Body 3 suggested that standards such as the IMBOR provide a similar level of standardisation amongst organisations; although they do note that this has taken a long time to implement. Inspector 5 suggests that such a standard should not be part of the NEN 2767 but rather could become part of the CUR 117 where a market wide standard could be generated. Secondly, inspector 4, 5 and government body 4 note the importance of practical applicability. Inspector

4 noted that they apply a pull-down system where a inspector is led through the steps of defect quantification. Inspector 5 emphesised the importance of consistency and limiting the interprability by creating simple formats. Government body 4 stressed that such a system could be possible, however its practical implementation could cause complications when dealing with manual processes. Third, regulation and monitoring must be implemented carefully according to inspector 5 and government body 1. Inspector 5 mentioned that ensuring that all involved parties are compliant with the standard is an important step for making ML a success. Government Body 1 noted that they believe it should be enforced for provinces, municipalities and inspection bureaus. Fourth, the collaboration with data managers is hightly important according to Government body 1, 4 and inspector 5. Inspector 5 again notes that the CUR 117 is the right tool to make this compliance a reality. Fifth, the usage of existing standards is an important part of making these changes work occurding to government body 3, 4 and inspector 4 and 5.These interviewees all noted that applying existing standards, whether the CUR 117, practices by Rijkswaterstaat or other government bodies, could improve the implementation. Specifically not using the NEN platform for these changes but rather the CUR 117 was mentioned by 2 interviewees.

4 different changes to the recommendations can be found based on these findings. Firstly, a Shift focus from incorporating data standardisation into NEN 2767 and instead adopt CUR 117 as the basis for a unified approach should be pursued. This should all be done whilst encourage large organisations, such as Sweco, Witteveen+Bos, to actively collaborate on developing this standard under CUR 117. Secondly, the improve the adaptability of this standardisation the development of user-friendly digital tools that guide inspectors through defect quantification and data entry would be desirable. Third, is the establishment of a central body to oversee compliance and provide technical support to ensure consistent implementation across provinces, municipalities, and inspection bureaus. Fourth, would be to establish working groups within CUR 117 committees to include software providers, inspection bureaus, and municipalities to co-create compatible tools and processes; this could in turn also leverage existing standards and protocols applied in the Netherlands.

6.3.2 Guidelines for inspections validation

From the excerpts presented in Table 83 two different insights can be gained. Firstly, inspector 4, 5 and government body 1, 3 noted that certfication are important to implement. Inspector 5 even noted that a register of certified inspectors should be created but also indicated that Dutch culture is often opposed to formal certification; this could mean that there may be resistance. In addition inspector 4 notes that is important that when implementing such as standard it is important to ask: for who is this standard made? The level of decomposition is highly dependant on that. Secondly, technology could be a big part of making this inspection guideline work occurding the inspector 4 and government body 3. They both note different forms of AI usage which could ease the subjectivity of inspections and make them more streamlined.

Based on these findings, 3 key changes can be made to the recommendation. Firstly, the certification protocol should be adjusted to ensure that cultural resistance is limited; this could be done by implementing a certification which is only mandatory if the data will be used for Machine Learning. In addition this mandatory certification could firstly be introduced by having a voluntary phase. Secondly, the creation of a register for certified inspectors, which would be managed by the certifying body, could be a way of increasing transparency. Third, the level of detail required in terms of decomposition and defect documentation should be tailored for the target audience. In essense you may want a more detailed decomposition for one task rather than another. The qualification should allow for this flexibility.

6.3.3 Capturing more features validation

From the quotes presented in Table 84 five separate insights are gathered. Firstly, Government body 1 and 4 note the importance of gathering additional passport data with government bodies 3 and inspector 4 and 5 nothing that this information could provide new insights. Secondly, government body 3 and inspectors 4 and 5 noted that the inclusion of publicly available or centralised data could be of great benefit and even mentioned different data sources not currently considered such as traffic incidents. Third, new technologies such as sensor data, were mentioned by inspector 4, 5 and government body 4 as a potential interesting source to include. This indicates that there is a growing interest in including SHM data in these systems. Fourth, Government body 3 ,4 and inspector 4 note that there may be challenges in terms of cultural change for gathering this information. Government body 3 noted that they had experienced challenges with adapting their organisation to IMBOR, suggesting similar challenges may occur with this. Government Body 4 noted that clear standardisation and responsibilities are an important aspect of getting this all working. Inspector 4 notes that keeping it simple and having a centralised system to reduce the friction of intergration. Lastly, government body 3, 4 and inspector 4 had some practical advise related who should gather information. It is advised by all of them that historic and passport information should be gathered by the asset owners as to limit the burdon on inspectors. Government Body 3 notes that it is advised to ensure that the digital system can link with IMBOR information.

Based on the analysed excerpts the following 3 changes to the recommendation should be made. Firstly, the recommendation should emphasize that the responsibility for gathering and maintaining historical and passport data should lie with the asset owners. This could be done by developing standardized protocols for asset owners to update passport data, potentially making it a compliance requirement for the expanded CUR 117. Secondly, incorporate Structural Health Monitoring (SHM) Data Using New Technologies. Although the read papers did not apply SHM sensor systems it was already discussed that this could be a potential interesting inclusion for future works; the validation interviews indicate that stakeholders are also interested in this data. Lastly, addressing the organisational resistance in the recommendation is an important aspect which is currently not considered strongly. Therefore a change management strategy should be implemented. In addition the steps of intergrating should be explained simply and user-friendly. In addition it should be centralised.

6.3.4 Capturing more data validation

Based on the interview results and utilised paragraphs presented in Table 85 the following insight was gained. It became apparent that the desire to capture more data through the schouw was an unrealistic desire. This was due to 3 reasons. Firstly, The knowledge level of shouw inspectors varies greatly, which can lead to arbitrary assessments. Some staff focus only on superficial aspects, such as graffiti, while others take a more detailed look at technical elements such as drains and drainage systems. Secondly, Inspection and survey results often only detect severe damage that is already visible, while early signs of aging or defects, such as hairline cracks, are missed. This leads to a reactive rather than a proactive maintenance approach. Lastly, although tools (such as a mobile app) are available to facilitate inspections, they are not consistently used. Government bodies indicate that other priorities hinder the execution of detailed surveys. The results did indicate that maintenance actions, specifically corrective maintenance is performed from these inspections which could provide insights for a ML model in terms of whether it can predict such maintenance requirements accurately.

This result suggests that the schouw is not suited due to the reasons provided above. However, it did indicate that corrective maintenance is performed and this data could be collected by maintenance perfomers. This way data, in between NEN 2767 inspections could still be captured which pertains to the deterioration of bridges.