UNIVERSITY OF TWENTE.

Master thesis

Linking asset management and GIS: developing a spatial decision support tool that indicates and visualizes the functional performance of viaducts and roads for replacement decisions at Rijkswaterstaat

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Date: 14-08-2020

Version: 5.0 (Final)

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Course code: 195459999

Preface

This report marks the final part of my master's Civil Engineering and Management at the University of Twente. Several people played an important or supporting role in this research. First of all, I would like to thank my supervisors Andreas Hartmann and Marc van Buiten from the University. Their feedback allowed me to keep on the right track. From Rijkswaterstaat, I would like to acknowledge my supervisors Jaap Bakker, Mirjam Bakx-Leenheer, Tessa Eikelboom and Rob van der Schoot. Jaap and Mirjam helped me with the functional performance methodology and I always enjoyed our meetings. Tessa supported me the most in the starting phase of this research and introduced me to GIS, the CIV department of Rijkswaterstaat and a lot of colleagues. Rob stepped in at the end of this research.

Besides my supervisors, a lot of other employees of Rijkswaterstaat played a role in this research. I am grateful having Kaspar Sonnemans as a colleague. Not only in helping me when I had a question in GIS, but also on a more personal note, in our coffee or lunch breaks. The employees of Rijkswaterstaat (and sometimes outside Rijkswaterstaat) that helped me during the search for data played a crucial role in this research. When they provided me with a useful dataset, they also took the time to explain the data. Furthermore, I would like to thank the participants of the workshops and daily colleagues of the CIV and GPO department. During my time at Rijkswaterstaat, I have not only learned about GIS and asset management, but I also learned a lot about the tasks of Rijkswaterstaat as an organization. Previously, it was difficult to get an insight into the daily work practice of Rijkswaterstaat. I thank my supervisors in providing me the freedom to explore the organization. The IALCCE workshop at the SS Rotterdam and the Geodesign workshop at a regional office were quite fun and interesting. Lastly, I enjoyed having contact with the trainees at Rijkswaterstaat.

This report also marks the end of my life as a student. During my master's and pre-master program, I enjoyed working together with friends. During my internships, I was able to explore different organizations and see how civil engineering has been applied within these organizations. My time as a student also allowed me to meet a lot of interesting and nice people. Last, but certainly not least, I would like to thank my parents, sisters, brother and friends for supporting me.

Rob van Iddekinge

Executive summary

The functional performance of viaducts plays an important role in replacement decisions at Rijkswaterstaat. Previous research has established performance indicators, which are used to determine the functional performance. These are traffic flow, geometry, load-bearing capacity, safety and noise emissions. However, it is complex to determine the functional performance of viaducts and roads, because data sources are fragmented. Therefore, this research aims to develop a spatial decision support tool that integrates these data sources and visualizes the functional performance on a 4 point scale (perfect, good, fair or poor) for viaducts and road sections.

This research is design oriented and therefore, the methodological approach taken in this study is mainly a combination of systems engineering and the design cycle within design science. The main structure is divided into requirements, design and verification & validation. Based on a problem statement and research methods the requirements have been defined. This leads to a design solution which has been verified and validated. Additionally, some parts of the design need input from empirical research. The research is qualitative in nature and uses literature, workshops, unstructured interviews and a questionnaire as research methods.

The first results are the requirements for the design of the tool, which are divided into three categories: data, visualizations and interaction. Examples of requirements are:

- The tool should integrate the data.
- Data should be easy to interpret by decision-makers (visualizations).
- Users should be able to select a viaduct and see the data (interaction).

Subsequently, the existing performance indicators have been linked to sub-indicators. This is needed because the existing performance indicators from previous research are not always specific enough that they can be linked to data sources. The sub-indicators are shown in Table 0.1.

Table 0.1: Sub-indicators based on the existing performance indicators.

Performance indicator	Sub-indicator	Unit of measurement
Traffic flow	User delay costs (UDC)	€ / km[1]
Geometry	Height (lower side deck)	m
Load class	Design load class	Ordinal scale
Safety to users	Safety score based on the number of accidents with different consequences	Dimensionless quantity
Noise emissions	Exceedance of noise production limit	dB

The choice for a certain sub-indicator is also based on data availability, so that each sub-indicator is assessed based on a data source. These data sources have been linked to viaducts and road sections. This is a design step and has been executed based on a common attribute or spatial location of the data sources. The eventual dataset contains 3521 viaducts and 16591 road sections. However, it is not possible to link all data to all assets. Table 0.2 shows the percentages of assets with data for each sub-indicator. For viaducts, the height dataset has the highest amount of missing data.

Table 0.2: Percentages of available data, divided by sub-indicator and type of asset (viaducts and road sections).

	% of assets with data	
Sub-indicator	**Viaducts**	**Road sections**
UDC	58%	17%
Height	36%	not applicable
Load class	82%	not applicable
Accidents	100%	100%
Exceedance noise production limit	95%	99%

The next result is the division of data into score categories. The score categories are an ordinal scale and can either be perfect, good, fair or poor (see Table 0.3). This is also implemented in the tool, so for each sub-indicator the score has been defined based on the data. When data is missing, the score for that sub-indicator is set at ‘0’. The worst score is leading for the overall functional performance of a viaduct or road section.

Table 0.3: Overview of score categories per indicator.

Indicator / Score	**User delay costs (UDC) per km^1 (€/km^1)**	**Height (m)**	**Load class**	**Safety score**	**Exceedance of noise production limit (dB)**
1: Perfect	0 - 2.000	H ≥ 4,45	A, 60, NEN-EN-1991, NEN-6706	0 ≤ s < 5	Δ < -0,5
2: Good	2.000 - 36.000	4,05 ≤ H < 4,45	B, 45	5 ≤ s < 10	-0,5 < Δ < 0
3: Fair	36.000 - 347.000	3,85 ≤ H < 4,05	C, 30	10 ≤ s ≤ 15	0 ≤ Δ < 0,5
4: Poor	> 347.000	H < 3,85	D	s > 15	Δ ≥ 0,5

The final part of the design consists out of the visualizations, which lead to the design solution. This has been done using ArcGIS online. Used visualizations within the tool are colors, bar charts and pie charts. Figure 0.1 shows the spatial decision support tool, where a green color indicates a perfect score, yellow a good score, orange a fair score and red a poor score.

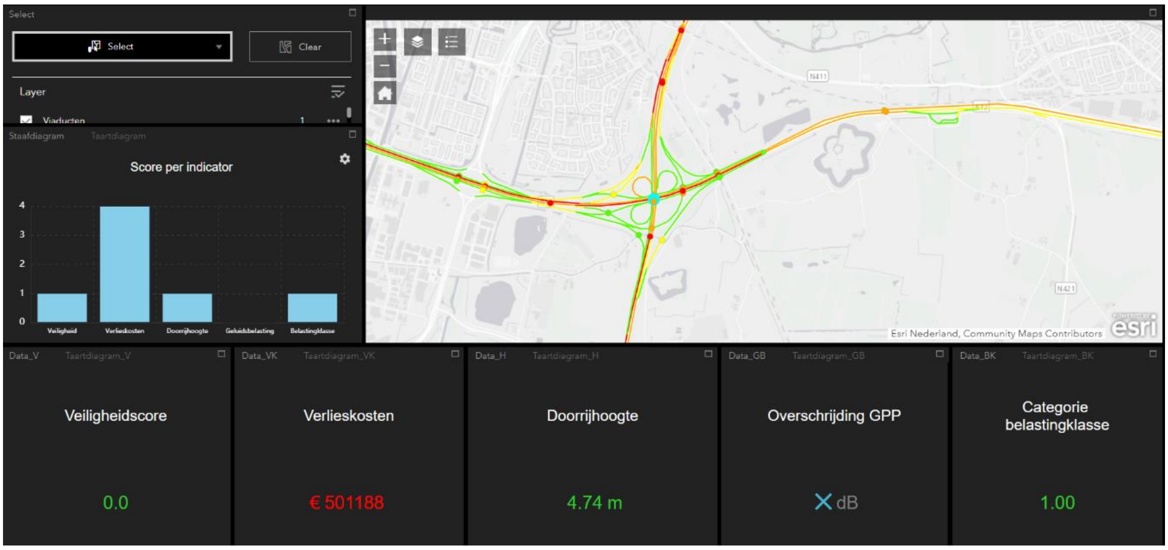


Figure 0.1: Screenshot of the tool. The dots indicate viaducts, the lines indicate road sections. The visualizations on the bottom and at the left side show the score of one selected viaduct.

During verification, the design solution has been compared with the requirements and explanations have been given how the design satisfies the requirements. Validation has been done in an online workshop, where the sub-indicators have been explained and the tool has been demonstrated. Respondents confirmed the relevance of the tool within replacement decisions and found the integration of data a valuable contribution. Most suggestions for improvements concern the used sub-indicators and the division into score categories. A few suggestions have been implemented in the tool, which leads to the final design solution. Further work is required to enhance data availability at Rijkswaterstaat which will enable that better sub-indicators can be used and will foster the coverage of the data. Another important issue for future research is how to move from the functional performance to a replacement decision. These suggestions will help Rijkswaterstaat to implement the functional performance earlier and more integral in the decision-making process of replacement of viaducts and road sections.

Managementsamenvatting

De functionele prestatie speelt een belangrijke rol in de keuze om viaducten te vervangen bij Rijkswaterstaat. Eerder onderzoek heeft hiervoor prestatie indicatoren in kaart gebracht, welke gebruikt worden om de functionele prestatie te bepalen van een viaduct. Dit zijn de verkeersdoorstroming, geometrie, belastingklasse, verkeersveiligheid en geluidsproductie. Echter is het bepalen van de functionele prestatie van viaducten en wegen nog complex, doordat data versnipperd is binnen de organisatie. Dit onderzoek stelt zich als doel om een beslissingsondersteunend systeem te ontwikkelen die:

- Deze databronnen integreert;
- De functionele prestatie op een 4 puntenschaal (perfect, goed, matig en slecht) van viaducten en wegvakken visualiseert.

Dit onderzoek is gefocust op het ontwerpen van een tool en daardoor is gekozen voor een methodologie op basis van zowel systems engineering als de design cycle volgens design science. Dit onderzoek is onderverdeeld in eisen, ontwerp en verificatie & validatie. De eisen zijn gebaseerd op een probleemstelling en onderzoeksmethodes. Dit resulteert in een ontwerp, welke geverifieerd en gevalideerd wordt. Voor enkele delen van het ontwerp is input benodigd van empirisch onderzoek. Dit onderzoek heeft een kwalitatief karakter en gebruikt literatuur, workshops, interviews (ongestructureerd) en een enquête als onderzoeksmethodes.

De eerste resultaten zijn de eisen voor het ontwerp van de tool, deze zijn verdeeld in drie categorieën: data, visualisaties en interactie. Voorbeelden van eisen zijn:

- De tool moet de data integreren.
- Het interpreteren van de data moet makkelijk zijn voor werknemers (visualisaties).
- Gebruikers moeten een viaduct kunnen selecteren en de data hiervan zien (interactie).

Vervolgens zijn de bestaande prestatie indicatoren gelinkt aan sub-indicatoren. Deze zijn benodigd omdat de bestaande prestatie indicatoren van eerder onderzoek niet altijd specifiek genoeg zijn. Hierdoor kunnen ze niet direct gelinkt worden aan databronnen. De sub-indicatoren zijn weergegeven in Tabel 0.1.

Tabel 0.1: Sub-indicatoren gebaseerd op de bestaande prestatie indicatoren.

Prestatie indicator	Sub-indicator	Eenheid
Verkeersdoorstroming	Verlieskosten	€ / km[1]
Geometrie	Doorrijhoogte	m
Belastingklasse	Ontwerpbelastingklasse	Ordinale schaal
Verkeersveiligheid	Veiligheid-score gebaseerd op het aantal ongelukken met verschillende gevolgen	Dimensie loos
Geluidsproductie	Overschrijding van het geluidsproductieplafond	dB

De keuze voor de sub-indicatoren is ook gebaseerd op data beschikbaarheid, zodat elke sub-indicator beoordeeld wordt op basis van een databron. Deze databronnen zijn gelinkt aan viaducten en wegvakken. Dit is een ontwerpstap en is gedaan op basis van een gemeenschappelijke attribuut of de locatie van de databron. De uiteindelijke dataset bevat 3521 viaducten en 16591 wegvakken. Het is echter niet mogelijk om elke databron te linken aan alle viaducten of wegvakken. Tabel 0.2 geeft het percentage van de viaducten en wegvakken met data voor elke sub-indicator. De dataset met de doorrijhoogtes heeft voor de viaducten de meeste missende data.

Tabel 0.2: Percentage van assets (viaducten en wegvakken) met data voor elke sub-indicator.

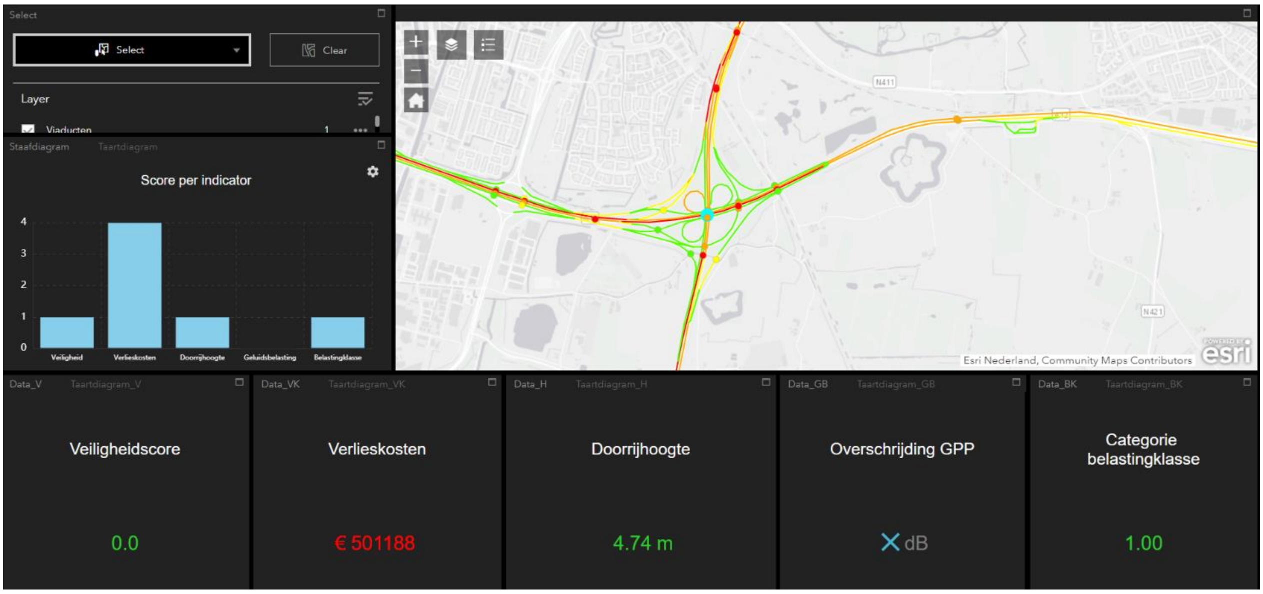
	% assets met data	
Sub-indicator	**Viaducten**	**Wegvakken**
Verlieskosten	58%	17%
Doorrijhoogte	36%	Nvt
Ontwerpbelastingklasse	82%	Nvt
Ongelukken	100%	100%
Overschrijding Geluidsproductieplafond	95%	99%

De volgende resultaten zijn de verdeling van de data in de vier score categorieën. Deze volgen een ordinale schaal, een viaduct kan een perfect, goede, matige of slechte score hebben voor elke sub-indicator (zie Tabel 0.3). De tool doet dit automatisch op basis van de data. Missende data voor een sub-indicator is gemarkeerd met een '0'. De slechtste score voor een sub-indicator is leidend voor de algemene functionele prestatie van een viaduct of wegvak.

Tabel 0.3: Score categorie voor elke sub-indicator.

Indicator / Score	**Verlieskosten per km^1 (€/km^1)**	**Height (m)**	**Load class**	**Safety score**	**Exceedance of noise production limit (dB)**
1: Perfect	0 - 2.000	$H \geq 4{,}45$	A, 60, NEN-EN-1991, NEN-6706	$0 \leq s < 5$	$\Delta < -0{,}5$
2: Goed	2.000 - 36.000	$4{,}05 \leq H < 4{,}45$	B, 45	$5 \leq s < 10$	$-0{,}5 < \Delta < 0$
3: Matig	36.000 - 347.000	$3{,}85 \leq H < 4{,}05$	C, 30	$10 \leq s \leq 15$	$0 \leq \Delta < 0{,}5$
4: Slecht	> 347.000	$H < 3{,}85$	D	$s > 15$	$\Delta \geq 0{,}5$

Het laatste resultaat van het ontwerp bestaat uit de visualisaties gemaakt in ArcGIS online. Voor de visualisaties zijn verschillende kleuren, staafdiagrammen en taartdiagrammen (weergegeven in Figuur 0.1) gebruikt. Een groene kleur geeft een perfecte score weer, een gele kleur een goede score, een oranje kleur een matige score en een rode kleur een slechte score.



Figuur 0.1: Screenshot van de tool. De punten in de kaart zijn viaducten en de lijnen zijn de wegvakken. De visualisaties in de onderste rand en aan de zijkant geven de scores van het geselecteerde viaduct weer.

Tijdens de verificatie is de tool is vergeleken met de eisen en is uitgelegd hoe het ontwerp voldoet aan de eisen. Validatie is gedaan tijdens een online workshop, waar de sub-indicatoren zijn uitgelegd en de tool gedemonstreerd. Medewerkers bevestigden de relevantie van de tool in het maken van vervangingskeuzes en de integratie van data vonden ze waardevol. De meeste suggesties voor verbeteringen slaan op de gebruikte sub-indicatoren en de verdeling van de score categorieën. Enkele suggesties zijn verwerkt in de tool, waarna het uiteindelijke ontwerp was voltooid. Het wordt geadviseerd om data beschikbaarheid bij Rijkswaterstaat te vergroten en te vergemakkelijken zodat betere sub-indicatoren gebruikt kunnen worden en om het percentage missende data in de tool te verminderen. Daarnaast is het belangrijk om verder te onderzoeken hoe vanuit een bepaalde functionele prestatie een beslissing gemaakt kan worden voor vervanging van een viaduct of wegvak. Deze aanbevelingen zullen Rijkswaterstaat helpen om de functionele prestatie eerder en meer integraal te implementeren in het besluitvormingsproces.

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1 Introduction

This chapter will start with some background concerning the research topic in section 1.1. This will provide input for the other sections in this chapter:

- Problem statement in section 1.2.
- Research objective in section 1.3.
- Research questions in section 1.4.

1.1 Background

The main topics in this section are infrastructure in general, asset management and geographical information systems.

Over the past decades, literature has addressed how infrastructure influences the social and economic well-being of countries and regions. The transportation or infrastructure network is widely regarded as one of the most crucial publicly owned goods in most countries (Sinha, Labi, & Agbelie, 2017). A reliable and safe infrastructure network is seen as a vital requirement for societies and economics (Hertogh, Bakker, van der Vlist, & Barneveld, 2018; Macdonald, 2008; Snieška & Šimkūnaitė, 2009).

There are a lot of aspects that make the preservation of a high-quality infrastructure network a complex task for infrastructure agencies. Current and future challenges influence this important responsibility of Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water Management. The second world war had a destructive impact on the Dutch infrastructure network (Geels, 2007). After the second world war, the economy and the population in the Netherlands grew significantly until 1975. The Marshall Plan created additional funding for investments in infrastructure (Geels, 2007). These developments resulted in a large upsweep of the number of viaducts and bridges, as shown in Figure 1.1.

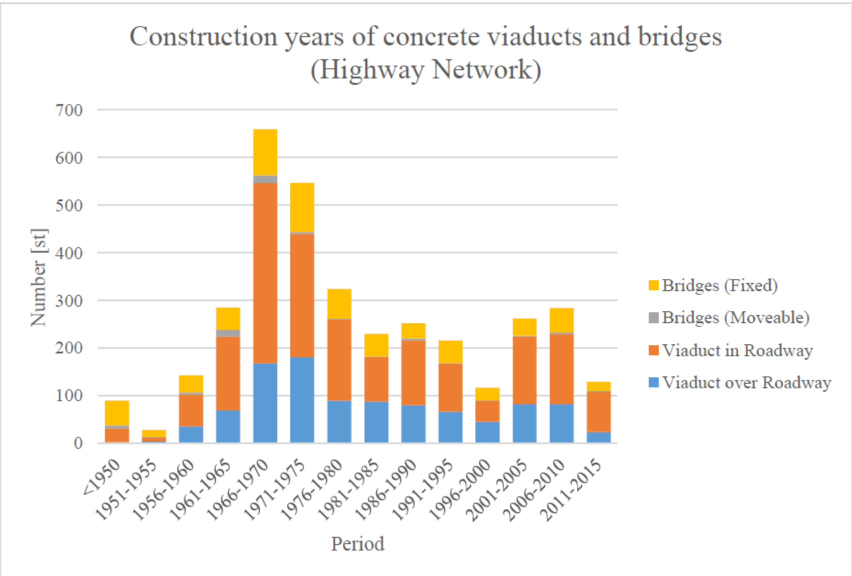

Figure 1.1: Histogram showing the construction year intervals of viaducts and bridges in the Dutch Highway network, derived from (Xie, 2017). In this figure, one could also notice a high proportion of viaducts.

The overall long lifespan of infrastructure (for viaducts and bridges 80 years) (Baldwin & Dixon, 2008; Klatter, 2019; Prud'Homme, 2005), causes that there are a lot of bridges and viaducts that reach the end of their life cycle in the coming decades. Standard maintenance budgets cannot cover these costs of replacement, therefore, Rijkswaterstaat has initiated the replacement and renovation program (in Dutch vervanging en renovatie or V&R). The aim of this program is to quantify, assess and substantiate budgetary needs for replacement, also directed towards the ministry (Bakker, Roebers, & Knoops, 2016). During the large investments in the Dutch infrastructure network after the second world war, the focus was on efficiency and therefore this approach can be characterized as a mono-functional approach (Hertogh et al., 2018). In other words, the focus was on large scale construction of the infrastructure as fast as possible, not on future functionalities. Nowadays, this results in limited functionalities for infrastructure assets which limits the functional lifespan. This is confirmed by the research of IV-infra (2016), which claims that 88,9% of a total of 216 bridges and viaducts are demolished based on functional aspects. Significant changes in the environment will drastically influence the functional performance (Cuendias González, 2018).

Other challenges are the limitations in terms of budgets (Schraven, 2011), coordination between national and regional public organizations (Sinha et al., 2017) and higher user needs such as availability, safety, reliability and comfort that arise from multiple stakeholders with sometimes conflicting needs (White, Too, & Too, 2010) (Arts, Dicke, & Hancher, 2008) (Hertogh et al., 2018). Additionally, political decision-makers play an important role when it comes to investments in public infrastructure (Sinha et al., 2017). However, the short-term focus of political procedures is also a challenge (White et al., 2010) and does not really match with the long lifespan of infrastructure assets. These challenges make the management of the infrastructure a complex task for roadway agencies. However, Rijkswaterstaat acknowledges that the extensive replacement and renovation of the infrastructure network can bring opportunities in terms of innovation and to align the network with future needs (Hertogh et al., 2018) (Blom, 2018).

The relevance of infrastructure and the challenges that are indicated in the previous section stresses the importance of efficient management of the infrastructure. This is often called infrastructure asset management or asset management. Infrastructure asset management is a trade-off between cost, risk and performance (Brown & Humphrey, 2005). The concepts of asset management produce substantial savings for transportation agencies (Frangopol, Gharaibeh, Kong, & Miyake, 2000; Sinha & Fwa, 1989). Or, to put differently, asset management yields the highest value from the budget available (Brown & Humphrey, 2005). Besides savings, it can help with improving the safety of the infrastructure (Frangopol et al., 2000). Within asset management, there are multiple roles with each of their own responsibilities. The asset owner is responsible for determining technical, financial and risk criteria. The owner is mostly concerned with the corporate strategy. The asset manager translates these in an asset plan by planning and budgeting. Lastly, the service provider executes these decisions and provides feedback on actual cost and performance (Brown & Humphrey, 2005). The company responsible for this executes the actual interventions and is focused on operational excellence. Asset management can also be divided into three pillars, representing competencies: management, engineering and information. These competencies are often located at different people within or outside an organization (Brown & Humphrey, 2005). This is confirmed by the work of Amadi-Echendu et al. (2010), by stating that within the management different people have different interests (e.g. engineer focuses on condition monitoring, information manager is interested in providing data). This is also true within Rijkswaterstaat as an organization with multiple national departments. The department Major Projects and Maintenance (MPM or GPO in Dutch) is mainly concerned with condition monitoring, while the Central Information Services (CIS or CIV in Dutch) has a major task in the management of data within asset management. In total, most national departments (five in total) are involved within asset management. Furthermore, regional departments are also involved at Rijkswaterstaat. In the end, asset management is in charge of spending decisions (Brown & Humphrey, 2005). Literature has shown that infrastructure assets cannot be analyzed solely, but that there is a need to consider them as networks (Frangopol et al., 2000). This can be linked to a central attribute of infrastructure: a viaduct, for example, is part of a road network. Too (2010) argues that the majority of asset management frameworks focus on individual assets and not on the whole system.

Asset management is also often linked to life cycle management (Sarfi & Tao, 2004) and life cycle costs (Brown & Humphrey, 2005). Within life cycle costs, a differentiation can be made between agency costs and user costs (Frangopol et al., 2000). Rijkswaterstaat also uses cost-benefit analysis, wherein agency costs are linked to the costs and the reduced user costs as benefits. Within Rijkswaterstaat and the V&R program, the following life cycles can be distinguished for infrastructural assets:

- Technical life cycle.
- Economic life cycle.
- Functional life cycle.

These life cycles can be used to decide upon replacement decisions. These life cycles cannot be seen completely independently. They will be explained in the next sections.

Technical life cycle
The technical life span of assets and how it develops over time-based on deterioration curves is often a popular topic in literature. However, these are often object-specific, so a generalization to a large group of assets is difficult. To forecast the replacement needs in the future, Rijkswaterstaat has roughly three time horizons: a long term prognosis based on a statistical approach, a medium-term prognosis for groups of objects with known technical issues and a short term approach, which is object-specific and often based on inspections (Bakker et al., 2016). As previously mentioned, the decision to replace assets is often based on functional aspects and not on technical reasons. This is because there exist many opportunities to repair assets and to extend the technical life, even for aging assets (Bakker et al., 2016). The end of the technical life can be defined as the moment that the asset becomes unrepairable, or that the performance or accepted risk level can no longer be restored without replacing the asset (Bakker et al., 2016). However, in practice, this does not occur that often.

Economic life cycle
The economic life cycle is closely related to the technical life cycle. The starting point behind the consideration of the economic life cycle is that in general, maintenance of an old asset is more frequent and more expensive than the maintenance of a relatively new asset. The economic life cycle can be defined as the period that the asset is the lowest cost alternative to provide the required service or to have an acceptable risk level. Rijkswaterstaat has developed an economic end of life indicator (EELI): this is a ratio between the life cycle costs of (1) maintaining a specific asset and replacing it in a specified replacement year and (2) replacing the specific asset immediately and maintaining it afterward. Life cycle costs are obtained by calculating the present value of future costs. This is done by discounting the future costs to the present value, for the EELI, the discount rate is assumed to be 3% and the time horizon 100 years (Bakker et al., 2016).

The input needed for the EELI calculation are the following:

- Costs of maintenance of an existing asset, based on the maintenance plan.
- Costs of maintenance of a new asset.
- Costs of replacement.
- Replacement year.

The costs for replacing an asset are significantly higher than yearly maintenance costs. Thereby, the replacement year of an asset will influence the calculation significantly. In general, the EELI will increase when the replacement year is shifted earlier in time. However, this replacement year is often based on a rough estimate (long/medium time horizon). This estimation becomes more reliable during the life cycle of an asset (Bakker et al., 2016). Lastly, the EELI cannot be calculated when the maintenance plan is missing or the outcome will not be realistic when the maintenance plan is not up-to-date.

Functional life cycle

There was a lack of standardized and objective decision-making within Rijkswaterstaat when a viaduct was being replaced based on functional aspects. Therefore, the research of Cuendias González (2018) uses the performance age principles of Xie (2017) in order to develop a standard methodology that supports the decision to replace viaducts based on functional aspects. Ten performance indicators are mapped in order to determine the remaining functional life of viaducts (Cuendias González, 2018), these performance indicators are shown in Table 1.1.

*Table 1.1: Performance indicators identified by Cuendias González (2018). Performance indicators highlighted in **bold** are part of the pre-evaluation.*

Goal category	Subcategory	Performance indicator
Safety	Users	**Safety to users**
Accessibility	Traffic Flow	**Traffic volume carried**
	Bridge physical features	**Load bearing capacity**
		Bridge geometry
	Intervention	Maintenance hindrance
	Resilience to climate change	Resilience to extreme weather events
Society	Social hindrance	Aesthetics
Environment	Sustainability	**Noise emissions**
		Presence of polluting substances
		Landscape fragmentation

The assessment of the remaining functional life is divided into two steps: a pre-evaluation and the (normal) evaluation. The objective of the pre-evaluation is to ensure that the viaduct has a certain minimum level of performance for the performance indicators that are considered to be essential for the functioning of the viaduct. The performance indicators that are used within this pre-evaluation are highlighted in bold in Table 1.1 (safety to users, traffic volume carried, load-bearing capacity, bridge geometry and noise emissions). When one of these indicators scores below a certain threshold, the methodology prescribes that the viaduct should be directly replaced. When the viaduct succeeds in the pre-evaluation, the remainder of the performance indicators are also scored on an ordinal scale between 1 (perfect) and 4 (poor). Based on the weighting of the performance indicators, the global bridge functional performance can be determined. This can be a number between 1 and 4, where also non-integer values are possible. However, when a performance indicator from the pre-evaluation has a worse score than the global bridge functional performance, the score for the specific performance indicator will be leading for the global bridge functional performance. In order to determine the remaining functional life, the functional evolution with time is related to the global bridge functional performance.

Unfortunately, the application of the methodology proved to be difficult. Data sources to assess the functional performance indicators are fragmented within the organization. Additionally, sometimes performance indicators have multiple sub-indicators or data sources. An example is the performance indicator ‘safety’, which is based on the number of accidents with different consequences (fatal accidents, accidents causing injuries and accidents limited to material damage). This complexity causes that a large scale validation of the methodology is currently missing, the remaining functional life methodology has only been applied on one viaduct. The complexity to use the methodology also complicates an expansion to a network level. Lastly, the complexity causes that decisions are still mostly based on subjective expert opinions. Decisions would be more objective, and thus better to substantiate when they are based on data. Continuing on this topic, Rijkswaterstaat has accepted the relevance of data and information as an underlying concept in the challenges that are facing the Dutch infrastructure, also within asset management. Therefore, Rijkswaterstaat aims to become a data-driven organization. However, the accessibility of data is limited and hindered by fragmentation across the organization (Allewijn, 2019). This is confirmed by the research of Cuendias González (2018), which additionally indicated quality problems of data.

Within Rijkswaterstaat, a large proportion of data is geographical or spatial in nature: every asset has a particular location. Furthermore, the spatial dependencies of assets are important, because every asset is part of a network. Geographical information systems (GIS) are commonly used to manage this kind of data or information. In their book, Burrough, McDonnell, McDonnell, and Lloyd (2015) describe GIS as a powerful set of tools for collecting, storing, retrieving, transforming and displaying spatial data. Dickinson and Calkins (1988) argue that GIS consist of three elements: technology (e.g. hardware and software), database (e.g. geographical and related data) and infrastructure (e.g. supporting elements, staff and facilities). Maguire (1991) presents three views about GIS, which are compatible with each other. In the map view, GIS are seen as map processing or display systems with layers. The database view perceives database management systems as the integral parts of GIS. Lastly, the spatial analysis view places GIS more in spatial information science. When working with geographical data, three phases can be distinguished: data preparation and entry, data analysis and data presentation (By, 2001). Crain and MacDonald (1984) identify three phases for developing GIS: in the initial phase, called the inventory phase, the system contains basic common information. Based on minor manipulations of the data, such as summations and counts basic questions are answered. The second phase, the analysis phase, explores data relationships to confirm for example hypotheses. The third phase creates a management information system which directly aids the decision-making process. Forecasting and planning facilities are added to the system in this phase to answer questions such as “What if … ?” (Crain & MacDonald, 1984). Similar to asset management, GIS can then be seen as decision support tools. GIS are also often used as a platform for interactive spatial tools, which can be divided among drawing, simulation and evaluation tools (Eikelboom & Janssen, 2013). Within Rijkswaterstaat, GIS are mainly used to present and visualize data.

1.2 Problem statement

The problem statement is based on the broad management problem and the preliminary literature review (Bougie et al., 2017). The broad management problem can be defined as follows: "There is limited standardization and objectivity in the decision to replace viaducts and roads based on functional performance". In this chapter, this broad management problem will be transformed into a feasible research topic for a master thesis. This will be done by making it more specific and defining the scope of the research. The problem statement is defined as followed and illustrated in Figure 1.2:

It is complex for Rijkswaterstaat to determine the current functional performance of viaducts and roads, because:

a. *Data sources for the functional performance indicators are fragmented across the organization which makes them less accessible.*
b. *Individual performance indicators can have multiple data sources.*

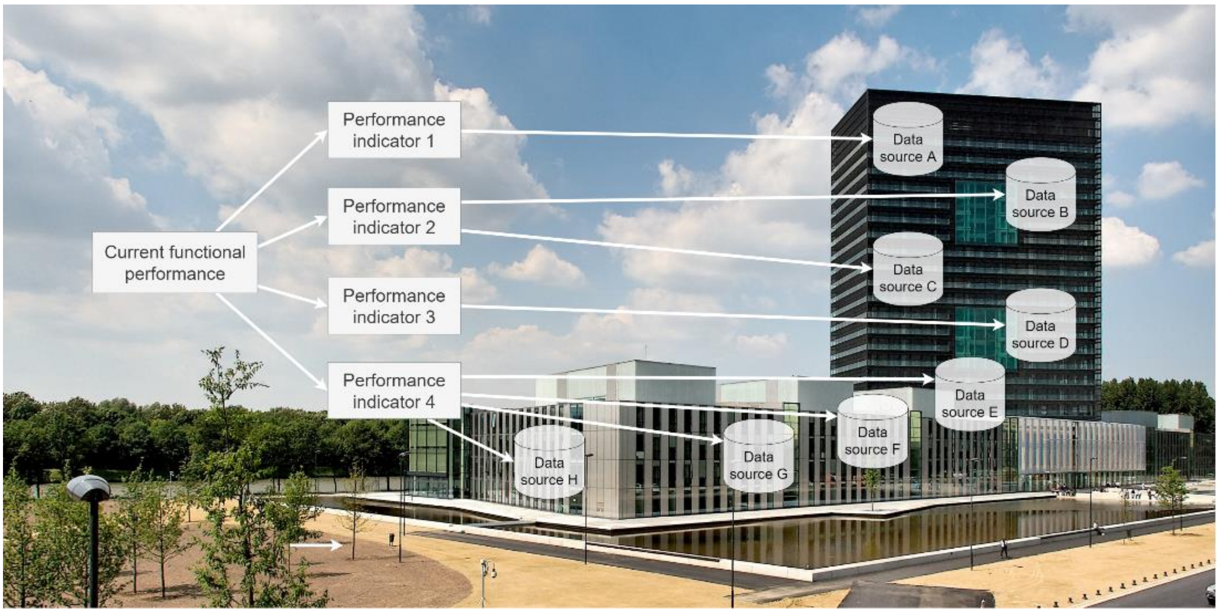

Figure 1.2: Illustration of the problem statement, in the background, the main office of Rijkswaterstaat in Utrecht is shown.

1.3 Research objective

Based on the problem statement, the research objective can be defined:

> *To develop and evaluate a spatial decision support tool that integrates performance indicators and visualizes (1) performance indicators and (2) the current functional performance of viaducts and roads for replacement decisions at Rijkswaterstaat.*

Based on this main objective and the problem statement, several sub-objectives can be differentiated:

- To identify sub-indicators and data sources which can be used to indicate the performance of the performance indicators identified by Cuendias González (2018) in the pre-evaluation.
- To integrate these data sources into a spatial decision support tool.
- To visualize the data in the spatial decision support tool.
- To verify and validate the spatial decision support tool in its intended problem context: replacement decisions at Rijkswaterstaat.

1.4 Research questions

The main research question is based on the research objectives and the problem context.

> *How can a spatial decision support tool be developed and evaluated that integrates performance indicators and visualizes (1) performance indicators and (2) the current functional performance of viaducts and roads for replacement decisions at Rijkswaterstaat?*

This main research question can be divided into sub-questions that provide, together with the sub-objectives, the first structure to this research:

- Which sub-indicators and data sources can be used to indicate the performance of the performance indicators?
- How can these data sources be integrated into a spatial decision support tool?
- How can the data be visualized in the spatial decision support tool?
- To what extent is the tool useful within replacement decisions at Rijkswaterstaat and what improvements can be made?

The first question is seen as a knowledge question, while the other three questions are seen as design problems within design science (Wieringa, 2014). This combination will come back more frequently in the next chapter, which describes the research methodology. The remaining part of this report proceeds as follows:

- Chapter 2: Research methodology.
- Chapter 3: Results.
- Chapter 4: Discussion.
- Chapter 5: Conclusion and recommendations.

2 Research methodology

The objective of this research is to design a decision support tool. In order to do so, this research follows a structure comparable with systems engineering (Alsem et al., 2013; de Graaf, Voordijk, & van den Heuvel, 2016; De Graaf, Vromen, & Boes, 2017; Press, 2001) and the design cycle within design science (Wieringa, 2014). Requirements have been defined, which are used to design the tool and after that, the tool will be verified and validated. The overall structure of this research is shown in Figure 2.1.

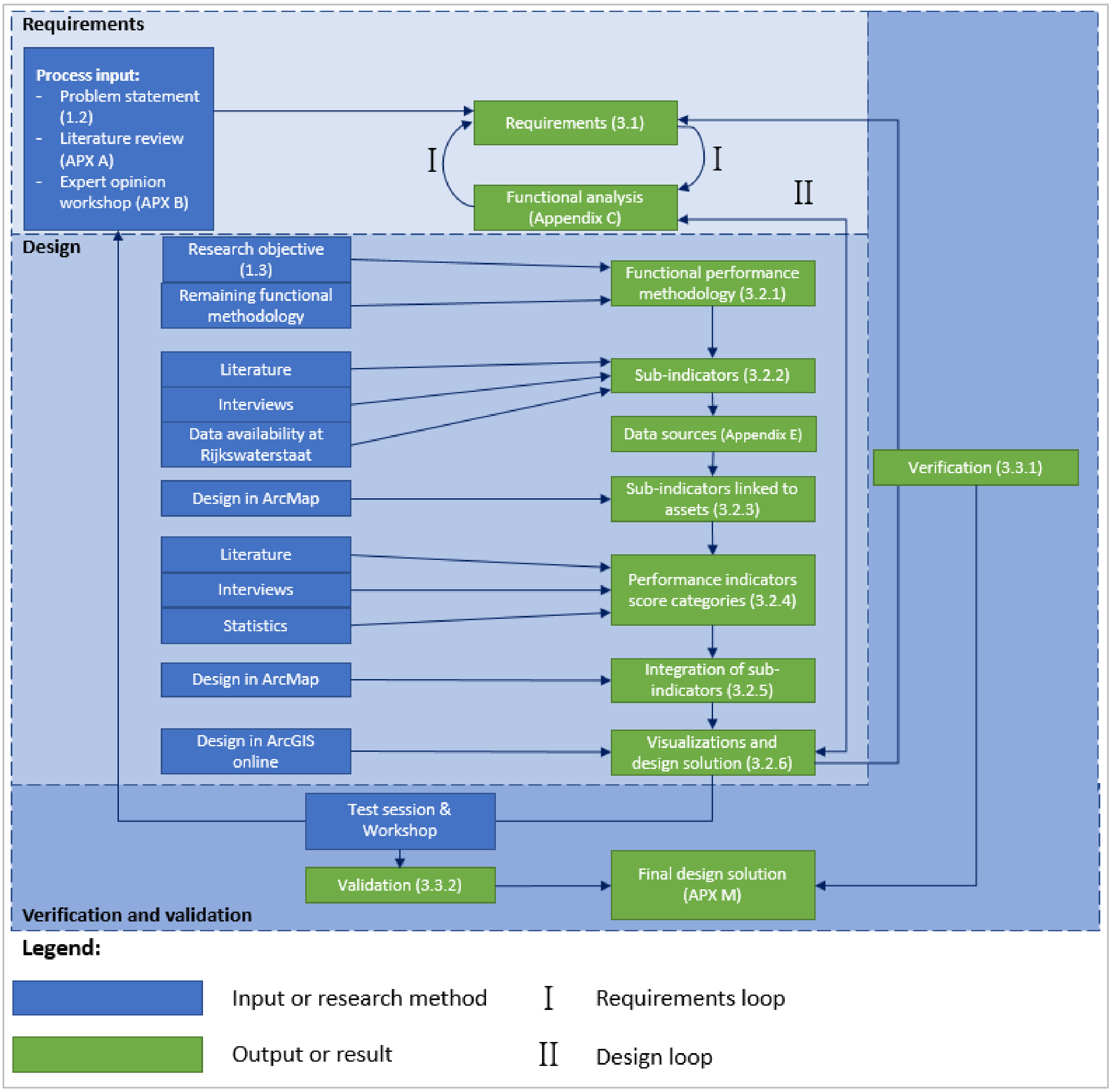

Figure 2.1: Structure of the research. The research methods or input on the left will lead to results or outputs, shown at the right side. Vertically, the elements of the research are divided among the requirements, design and verification and validation phase.

The main focus of this research is design oriented. However, to solve the design problems in this research, knowledge questions need to be answered by empirical research. Examples are the choice for the sub-indicators and the division of sub-indicators in score categories.

As indicated in Figure 2.1, the research starts with the process input, which is based on the problem statement, a literature review about visualizations and an expert opinion workshop. The literature review describes different types of data, what visualizations should do and provides some examples of visualizations. In the expert opinion workshop, a group of employees of Rijkswaterstaat have been asked to generate ideas about the requirements and functionalities of the tool, based on the problem context. The requirements from the workshop have been compared with the literature review. The requirements are based on the process input and describe what the tool should do. Based on the requirements, the functions and objects of the tool are composed and specified in the functional analysis. The functions are described with a combination of a verb and a noun and are solution neutral. The objects are the elements in the tool. During the functional analysis, new functions and objects can arise, which can lead to new requirements. The requirements loop ensures that the requirements, functions and objects are in line.

The design commences with an alteration of the remaining functional life methodology, that is based on the scope and objective of this research. The existing performance indicators in the methodology of Cuendias González (2018) are not always specific enough that allow them to be directly linked to data sources, so for this research, sub-indicators are introduced. These are based on literature, interviews and data availability at Rijkswaterstaat. The description of data sources is given in Appendix E – Description data sources. In the next design step within ArcMap, the data sources will be linked to viaducts and road sections (assets). After this, the sub-indicators will be divided into four score categories (perfect, good, fair and poor). This is based on literature, interviews with employees and statistics. Subsequently, the last two design steps will be performed: the integration of the sub-indicators and the visualizations in ArcGIS online. This leads to the design solution in section 3.2.6. The design solution may lead to new functions and objects. The design loop will ensure that the functional analysis and the design solution are in line.

Verification has been executed by comparing the design solution and the requirements. This will be done by the interpretation of the author. For every requirement it will be explained how the tool satisfies the specific requirement. Validation has been done in two sessions: a test session and a workshop. In the test session, the tool has been presented to a small group of employees at Rijkswaterstaat and asked if and how it solves the problem context. During the workshop, the tool has been presented to a large group of employees, where after they could give their opinions and feedback about the tool within the problem context: replacement decisions. The feedback has been collected with a questionnaire, email, chat function within skype and a discussion session at the end of the workshop. After verification and validation some changes are made within the tool, which leads to the final design solution in Appendix M.

The research methods within this research are qualitative in nature. Literature used within this research are academic research, guidelines and documents within Rijkswaterstaat. Interviews are unstructured, and are mostly used to have a deeper understanding about a certain sub-indicator or data source. The workshops have been used to collect feedback from employees after presenting the tool. During validation, a questionnaire has been used, but the collected data is mostly qualitative in nature. The questions in the questionnaire are mostly used to keep feedback of respondents within the scope of this research.

3 Results

This chapter presents the results and is divided into three main sections: requirements, design and the verification and validation results.

3.1 Requirements

The requirements are based on the problem statement from the first chapter, a short literature review about data visualizations and an expert opinion workshop. The literature review and the description of the expert opinion workshop are given in the following Appendices:

- Appendix A – Literature review visualizations.
- Appendix B – Expert opinion workshop.

Table 3.1 shows the requirements specification of the tool, which is divided into the categories 'data', 'visualizations' and 'interaction'. The requirements describe what the tool should do.

Table 3.1: Requirements specification.

Nr	Name	Requirement
1.	Data	
1.1.	Data integration	The tool should integrate data sources of multiple performance indicators
1.2.	Data sources	The tool should contain data that indicate the overall performance of performance indicators and that are specific enough
1.3.	Completeness	The tool should at least contain data that indicate the current performance of all used performance indicators
1.4.	Data quality	The tool should contain data with the desired quality to assess the functional performance
2.	Visualizations	
2.1.	Interpretation	The data in the tool should be easy to interpret by decision-makers and users
2.2.	Validity	The visualization should lead to valid conclusions about the data
2.3.	Level of detail	The visualization should show the data on different levels of detail
3.	Interaction	
3.1.	Selection	Users should be able to see, select and explore data of specific viaducts and road sections
3.2.	Selection	Users should be able to select certain parts of the data

Based on these requirements, functions and objects can also be defined, this is the functional analysis within systems engineering. An overview of the requirements, functions and objects are shown in Appendix C – Tables requirements specification and functional analysis.

3.2 Design

This chapter will present the results from the design phase of this research. Both design aspects as empirical aspects are treated in this section, because sometimes empirical results are first needed in order to design the tool. The design is also based on the results from the requirements phase.

3.2.1 Functional performance methodology

The existing remaining functional life methodology from Rijkswaterstaat developed in the research by Cuendias González (2018) has been used. This research is limited to the current functional performance of viaducts and roads. Additionally, only the performance indicators within the pre-evaluation are used. There have been some changes to the naming of certain performance indicators:

- 'Traffic volume carried' has been renamed into 'traffic flow', because it is more precise.
- 'Bridge geometry' has been renamed into 'geometry'. There are no bridges used in the methodology, but viaducts.
- 'Load bearing capacity' has been renamed into 'load class'. The original naming of this performance indicator suggests that data that has been used in the methodology to reflect this indicator is continuous and quantitative. However, the data is, in fact, ordinal and qualitative (load classes).

Additionally, some definitions of the performance indicators are slightly changed. The following performance indicators are used within this research:

- Traffic flow: whether the viaduct or road has enough capacity to carry the traffic.
- Geometry: the adequacy of the dimensions of the viaduct or road.
- Load class; whether the load class of the viaduct is high enough, mainly based on freight traffic.
- Safety to users: whether the safety to road users fulfills the requirements.
- Noise emissions: whether the noise emissions caused by traffic are according to the requirements.

Another consequence of only using the pre-evaluation is that the worst score for a performance indicator will be leading to the overall functional performance of an asset. Hence, the global functional performance can only be an integer:

- 1: Perfect score;
- 2: Good score;
- 3: Fair score;
- 4: Poor score.

The performance indicators identified by Cuendias González (2018) provide a good structure for the functional analysis of viaducts. However, the performance indicators are not always specific enough to be directly linked to one data source. Additionally, for some performance indicators multiple data sources are needed (e.g. safety: the number of accidents with different consequences). To evaluate the performance indicators of viaducts and roads, this research introduces sub-indicators. Additionally, Cuendias González (2018) directly links the score of the functional performance of a viaduct to the remaining functional life (based on the uncertainty range) viaduct. Within this research, the global functional performance and the replacement interval will be separated. This choice has been made because:

- One needs to include in the decision to replace an asset if a poor functional performance is a real problem. A limitation in the geometry of a viaduct is, for example, a bigger problem or has larger consequences if there are limited alternative routes nearby. This question is named the ‘problem analysis’.
- Not every time a viaduct or road that has a poor or fair global functional performance, this will lead to replacement. The performance can, for example, be improved or solved without replacing the asset. Or to put differently, we cannot always directly link a poor functional performance of an asset to the end of the functional life. An example is traffic flow, where it can be analyzed if there is room available on the deck for an additional traffic lane. Within this research, this analysis is named the ‘solubility analysis’.
- One could argue if the functional performance of an asset is reflected by aspects of the problem analysis and solubility analysis.
- The functional performance can be indicated relatively easily by data, but the solubility and problem analysis are harder to indicate and visualize by data. These aspects are more location specific and there is not always data available.
- There are also other aspects that need to be considered in the decision to replace an asset, beyond the functional analysis. Examples are the economic end of life indicator (EELI), technical condition, political aspects and already planned replacement activities in the network.

The process to decide whether and when to replace a viaduct or road is shown in Figure 3.1. Cuendias González (2018) includes aspects in his analysis that can be grouped under the problem or solubility analysis. However, in this research, these aspects are not included in the determination of the functional performance. The decision-support tool will be limited to showing and visualizing the current functional performance of assets.

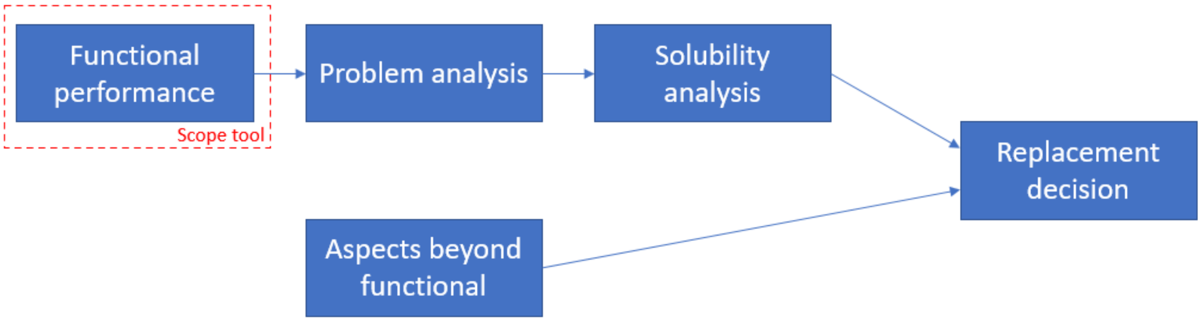

Figure 3.1: Process to determine the moment of replacement of viaducts and roads

The main focus of the design of the decision-support tool is, therefore, the visualization of the performance indicators and the overall functional performance. This is expected to reduce the complexity to determine the functional performance and can help when making replacement decisions. To conclude, a poor functional performance of a viaduct in the tool will not directly mean that the viaduct needs to be replaced in a short-term. The objective of this research differs from previous research of Cuendias González (2018); Xie (2017). These studies determine the functional performance and the replacement year of a few viaducts in greater detail. The current research is focused on determining the functional performance, without a replacement year, of all viaducts of Rijkswaterstaat. The next section will introduce the chosen sub-indicators.

3.2.2 Sub-indicators

In order to determine the functional performance of performance indicators, sub-indicators are used. To determine the sub-indicators, the following inputs have been used:

- The research by Cuendias González (2018) has been used as a starting point.
- Other relevant literature.
- Unstructured interviews with employees of Rijkswaterstaat.
- Data availability at Rijkswaterstaat.

On one hand, the indicators should be valid: they have to clarify and support the actual situation or in this case, the performance indicator. On the other hand, it must be noted that they indicate the performance. They do not always directly measure the specific performance indicator or give a complete representation. The sub-indicators are shown in Table 3.2 and are linked to the corresponding performance indicator. The sub-indicators will be described shortly and the corresponding data sources are described in Appendix E – Description data sources.

Table 3.2: Sub-indicators based on the performance indicators identified by Cuendias González (2018).

Performance indicator	Sub-indicator	Unit of measurement
Traffic flow	User delay costs (UDC)	€ / km[1]
Geometry	Height (lower side deck)	m
Load class	Load class (design)	Ordinal scale
Safety to users	Safety score based on the number of accidents with different consequences	Dimensionless quantity
Noise emissions	Exceedance of noise production limit	dB

Traffic flow

User delay costs are used to calculate the social costs of a reduced traffic flow, caused by for example, traffic jams. They are calculated by multiplying vehicle delay hours (VDH) by the value of time (VoT), as shown in equation 3.1.

$$UDC = VDH * VoT \tag{3.1}$$

Vehicle delay hours are obtained by multiplying the number of vehicles with the time delay, as shown in equation 3.2.

$$VDH = Number\ of\ vehicles * Time\ delay\ per\ vehicle \tag{3.2}$$

When 100 vehicles are each delayed with an hour due to a traffic jam, the vehicle delay hours are 100. If the value of time is 12 euros, the user delay costs will be €1200. The data has been provided for every road section, but the lengths of these differ significantly. To cancel this effect out, the user delay costs are divided by the length of the road section to achieve the UDC per km[1]. Previous research of Cuendias González (2018); Xie (2017) has used the I/C-ratio to analyze the traffic flow. However, this research found some problems in terms of validity for the I/C-ratio, these are explained in Appendix D – Explanation I/C-ratio.

Geometry

This performance indicator is reflected by the height of the viaduct. This performance indicator is only used for viaducts, not for road sections. The methodology of Cuendias González (2018) also includes the width of a viaduct, but the width under or above a viaduct only is not really representative of the functional performance. It would be better to consider the width of traffic lanes, however, there is no data available (to the knowledge of the author) for that aspect within Rijkswaterstaat.

Load class

The load is reflected by the design load class, used to design a viaduct.

Safety to users

The performance indicator 'safety to users' will be based on a safety score. This score will be based on the amount of accidents causing injuries and with fatal consequences. For road sections, the length of the road section will also be included in the calculation. The calculation of the safety score will be elaborated in section 3.2.4.4.

Noise emissions

The noise emissions are evaluated with the average exceedance of the noise production limit. This exceedance will be obtained by subtracting the noise production limit from the noise emissions in a certain point (see equation 3.3).

$$\Delta_{exceedance} = noise\ emissions - noise\ production\ limit \qquad 3.3$$

Difference between roads and viaducts

The difference between indicating the functional performance of viaducts and roads is mainly the used (sub-)indicators. The sub-indicators 'height' and 'design load class' are excluded from the evaluation of road sections.

3.2.3 Sub-indicators linked to assets

In the previous sections the separate datasets are formed, this section will focus on linking the data to individual assets: road sections and viaducts. The data can be joined based on two options:

- Attribute join: linking the data based on a common field or attribute.
- Spatial join: linking the data based on spatial location.

The first option is a more general manner to link data, that can also be done in for example Excel. GIS has the advantage that it can also utilize the second option. In GIS, road sections are saved as a line geometry between two points (A and B), while viaducts are a point geometry on one specific location (A). The starting point for the datasets are:

- For viaducts: the DISK database, a shapefile containing 3521 viaducts as a point geometry.
- For road sections: the national roads file (in Dutch: NWB, nationaal wegenbestand), a shapefile containing 16591 road sections (line geometry, version 1-10-2018).

The used datasets for the indicators are sometimes saved as a line geometry (UDC) and in other situations as a point geometry (load class, height, safety and noise emissions). The following paragraphs will illustrate how this linking of the data has been performed by using an example for an attribute join and spatial join. A detailed description of this process per performance indicator is provided in Appendix J – Linking of the datasets to individual assets.

3.2.3.1 Attribute join

An attribute join is based on a common field or attribute in two datasets. An example where an attribute join has been used is the load class. In the beginning, there are two separate datasets, as shown in Figure 3.2. These are the DISK dataset and the dataset with the load classes.

DISK dataset

KW_Code	Type of object
0001	Viaduct
0002	Viaduct
0003	Viaduct

Load class dataset

KW_Code	Load class
0001	60
0002	A
0003	45

Figure 3.2: Two datasets that can be joined based on a common attribute (KW_Code).

The common field is 'KW_Code', this is a Dutch name similar to an object ID. This field provides a number to all viaducts in the dataset. Both shapefiles are loaded into ArcMap as separate layers. After this, the following steps have been run through:

1. Right-click on the layer 'DISK dataset', move to 'join and relate' and select 'join'.

A pop-up opens, as shown in Figure 3.3.

2. Select in the first tab 'join attributes from a table'.
3. Select in the first drop-down menu 'KW_Code'. This is the field that will be used as the common attribute.
4. Select in the second drop-down menu 'DISK_BK'. This is the Dutch name for the load class dataset.

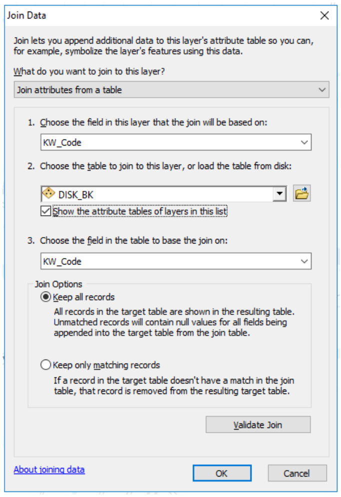

Figure 3.3: Pop-up for the join to select the settings for the join.

5. Check if in the third drop-down menu 'KW_Code' is selected. This is done automatically based on the input in the first drop-down menu.
6. Select the join option 'Keep all records'. This will ensure that the viaducts that cannot be linked to a load class will remain present in the dataset.
7. Click 'OK'

Now, the field with the load class has been added to the DISK dataset. This results in a layer as shown in Figure 3.4.

KW_Code	Type of object	Load class
0001	Viaduct	60
0002	Viaduct	A
0003	Viaduct	45

Figure 3.4: Result after the attribute join.

The data has been added to the original DISK dataset and saved in the original layer. The final step is to export the layer with the joined data to create a new layer. In order to achieve this, the following steps are taken:

1. Right-click the original layer.
2. Move to 'data' in the tab and select 'export data'.
3. Select in the pop-up:
    a. Export 'all features'.
    b. Use the same coordinate system as 'this layer's source data'.
    c. Save as a shapefile.

3.2.3.2 Spatial join

In most cases, the datasets do not have a common attribute that can be used. A spatial join can then be used. In this way, two datasets are combined based on their location on the map. To illustrate this, the height of viaducts will be used, as shown in Figure 3.5.

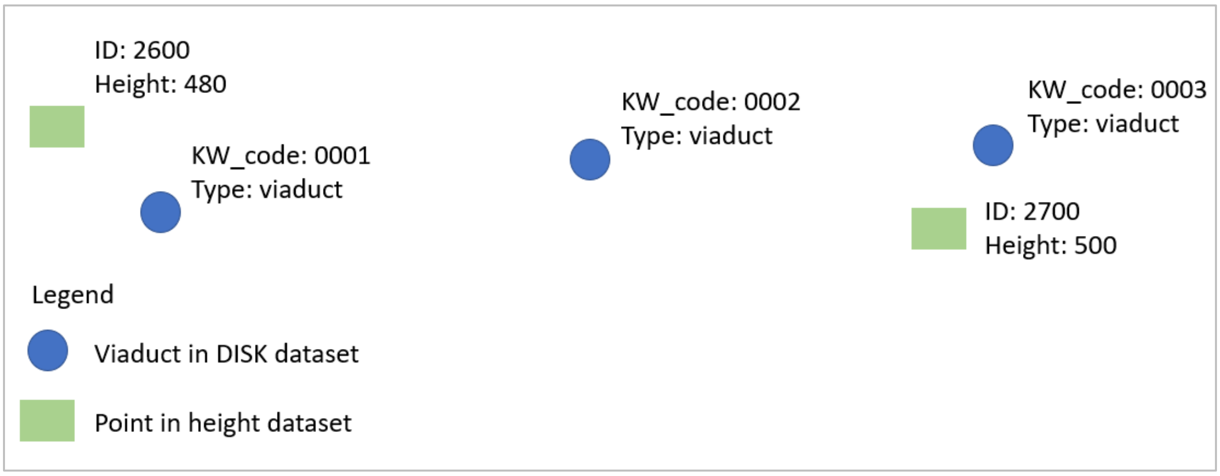

Figure 3.5: Illustration of two datasets in ArcMap. The blue circles indicate viaducts in the DISK dataset, while the green rectangles are the viaducts in the dataset with the heights.

There are multiple options within a spatial join, in this example, the option 'closest' has been used. This option integrates the two points that are closest to each other in the two datasets. Additionally, a maximum search distance can be implemented. For the height, the maximum distance has been set on 30 meters. Within ArcMap, the following steps are taken:

1. Open the 'spatial join' tool.

A pop-up opens, which is shown in Figure 3.6. Within this pop-up, the following options are chosen, similar to the figure.

2. Select in the pop-up:
    a. Target features: DISK dataset.
    b. Join features: Height dataset (RDW_PUNTEN2).
    c. Output feature class: select the location where the new output will be saved on the system.
    d. Join operation: JOIN_ONE_TO_ONE.
    e. Select the features that need to be included in the new output (Max_doorri)
    f. Select match option 'CLOSEST'
    g. Insert a search radius of 30 meters.
    h. Click 'OK'

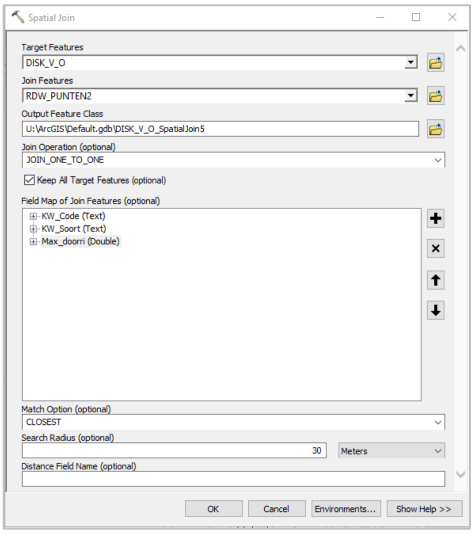

Figure 3.6: Pop-up when using the spatial join tool in ArcMap.

The result is a new layer with the data from DISK and the height dataset, as illustrated in Figure 3.7.

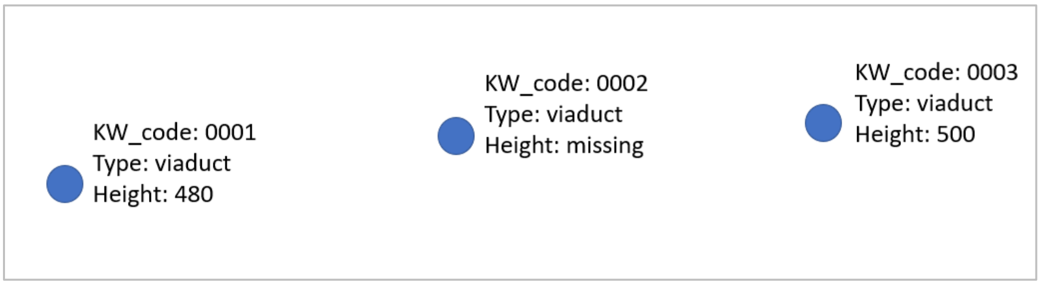

Figure 3.7: The end result of the spatial join. Viaducts 0001 and 0003 could be linked to a value in the dataset, but for viaduct 0002 this is not possible because there is no point within a distance of 30 meters.

3.2.3.3 Summary

The total amount of assets in the datasets are 3521 viaducts and 16591 road sections. After joining and integrating all data, Table 3.3 provides an overview of the percentages of assets for which data is available for each sub-indicator. For viaducts, the height is the indicator with the lowest percentage of data available. For road sections. The UDC have the lowest percentage of data available.

Table 3.3: Percentages of available data, divided by indicator and type of asset (viaducts and road sections).

	% of assets with data	
Sub-indicator	**Viaducts**	**Road sections**
UDC	58%	17%
Height	36%	not applicable
Load class	82%	not applicable
Accidents	100%	100%
Exceedance noise production limit	95%	99%

3.2.4 Performance indicators score categories

The next step is to determine how the functional performance will be determined based on the sub-indicators. The objective of this section is to convert all data sources into the same ordinal scale. The data sources have different types of data. We distinguish four score categories:

1. Perfect
2. Good
3. Fair
4. Poor

The division of categories are based on various motivations:

- Non-arbitrary values from guidelines (e.g. height viaduct);
- Statistics (e.g. user delay costs);
- Law (e.g. exceedance of noise production limit);
- Input from experts at Rijkswaterstaat;
- Assumptions.

3.2.4.1 Traffic flow

Traffic flow is indicated by the user delay costs per km[1], where more UDC are considered to be a worse score. This indicator does not contain a common threshold based on for example guidelines or input from experts. One could compare the user delay costs with the costs to improve the situation, but the costs to improve the situation are hard to compute and do not fit within the scope of this research. Therefore, this indicator is based on statistics. Because the data is skewed and contains outliers, the median gives a better indication of the middle of the data than the mean. The data will be sorted from the lowest to the largest value, where the middle value is the median. After sorting, the data can be divided into ten parts, each part is then a decile. The first decile thus contains 10% of the lowest values of the dataset. The ninth decile contains the 10% highest values. The categories are determined as followed:

1. Perfect score: 0 – 10% (first decile);
2. Good score: 10% - 50% (all values between the first decile and the median);
3. Fair score: 50% - 90% (all values between the median and the ninth decile);
4. Poor score: 90% - 100% (ninth decile).

This leads to the categories shown in Table 3.4 based on user delay costs per km1. The values are rounded to 1.000.

Table 3.4: Performance categories for traffic flow.

User delay costs per km1	
Value (€/km1)	Score
0 - 2.000 (first decile)	1
2.000 - 36.000 (median)	2
36.000 - 347.000 (9th decile)	3
> 347.000	4

These categories lead to the map with user delay costs per km1 shown in Figure 3.8. One could notice that almost all roads within the Randstad (the area between Amsterdam, Rotterdam, the Hague and Utrecht) have a high amount of user delay costs. Therefore, the performance categories may not be distinctive enough, but this is an aspect that can be evaluated during the verification and validation phase.

Figure 3.8: User delay costs per km1 with visualization from ArcMAP.

3.2.4.2 Geometry

To determine the functional performance of the geometry of a viaduct, non-arbitrary values from guidelines and other documentation are used. The height of the deck of the viaduct has to be designed according to guidelines. In the Netherlands, there are two major guidelines for the design of highways and viaducts. These are the ROA (Rijkswaterstaat, 2019), which is the guideline for the design of highways, and 'Handboek wegontwerp 2013' (CROW, 2013), for the design of non-highway roads. The ROA specifies the needed vertical space based on the following elements:

- Design vehicle: 4,00 m;
- Buffer for a driving vehicle, due to unevenness in the road surface: 0,20 m;
- Needed free space: 0,30 m;
- Buffer for re-asphalting: 0,10 m.

The CROW (2013) uses slightly other values for the different elements, but in the end provides the same vertical space: 4,60 meters. This does not mean that a height below 4,60 meters will automatically limit all freight traffic with a height of 4 meters because there is still some slack (0,40 meters). Additionally, it must be noted that this is based on a guideline and that one can choose to differ from it, when there are good reasons to do so. At tunnels, which are outside of the scope of this research, there are sometimes height limitations because of construction costs. Lastly, there are also trucks that have a height above 4,00 meters, for these, it is mandatory to apply for an exemption at the RDW (Dutch: Rijksdienst voor Wegverkeer) (RDW, 2012). This value of 4,00 meters matches with the design vehicle from the design standards. In conclusion, the minimum needed space for a driving vehicle is 4,20 meters. Due to the fact that the RDW subtracts 0,15 meters from the received data, a height of 4,20 meters of a viaduct matches with a height in the dataset of 4,05 meters. The threshold is thus set at 4,05 meters in the dataset.

For the evaluation of the sub-indicators height, the following structure is used:

1. Perfect score: indicator is above the threshold, and the buffer is significant.
2. Good score: indicator is above the threshold, but the buffer is limited.
3. Fair score: indicator is below the threshold, but the distance to the threshold is limited.
4. Poor score: indicator is below the threshold, and the distance to the threshold is significant.

This results in the score defined in Table 3.5, where the threshold is used at the lower bound of a good score (2).

Table 3.5: Performance categories for height viaduct.

Height viaduct	
Value (m)	Score
$H \geq 4{,}45$	1
$4{,}05 \leq H < 4{,}45$	2
$3{,}85 \leq H < 4{,}05$	3
$H < 3{,}85$	4

For the scores, a comparison has been made with applications for exemptions. This is shown in Appendix K – Applications for exemptions due to vehicle heights. The conclusion is that a viaduct with a perfect score (1) will, in most cases, not be a limitation for exemptions. After having created these categories, it turned out that there were no viaducts in category 3 (fair) and only one in category 4 (poor). All the other values have a perfect or good score. This can be explained by the fact that the dataset is used for exemptions, which are only needed when the height of a vehicle is above 4 meters. This is the main limitation of this dataset.

3.2.4.3 Load class

The functionality of the load class indicates the types of trucks that can use a viaduct or not. However, the sub-indicator is based on design guidelines and cannot be very easily linked to the maximum allowed weight of vehicles. Also, sometimes the axle loads are more relevant than the total load of a truck. In order to link the different load classes to the categories, literature has been used and an expert at Rijkswaterstaat has been consulted. Within the dataset, there are different load classes that reference to older and newer design guidelines. In the past, it was more common to design a viaduct according to their importance in the road network: a viaduct in an important highway had to be designed with a higher load class than a viaduct in a remote location. In 1938, this led to the load classes A, B, C and D from the VOSB. In 1963, the new design guidelines changed slightly with the load classes 60, 45 and 30. However, the most important change occurred in 2005: the NEN 6706 uses only one load model from the Eurocode NEN-EN 1991-2 and no longer distinguishes different load classes. The argument behind this is that a heavy truck (e.g. concrete mixer, mobile crane or trucks that transports milk) can drive everywhere, not only on the most important highways (Weemaes, 2018). Load classes according to the NEN 6706 or NEN-EN 1991-2 are comparable with the 'old' load classes A and 60.

Another important aspect is that, similar as for the height, traffic weights can be divided among vehicles that need to apply for an exemption and vehicles that do not have to. In the Netherlands, this maximum legal allowed weight is set at 50.000 or 60.000 kg, depending on the type of vehicle (RDW, 2012). As previously mentioned, load classes cannot be directly linked to the weight of trucks that can use them, but in general, the categories can be defined as followed:

1. Perfect score: viaducts suited for vehicles within legal restrictions and in most cases suited for vehicles with a weight of up to 100.000 kg.
2. Good score: viaducts suited for vehicles within legal restrictions, but in most cases not suited for vehicles above the legally allowed weight.
3. Fair score: viaducts not suited for vehicles above legal restrictions, and regularly a limitation for vehicles below legal restrictions as well.
4. Poor score: viaducts only suited for light vehicles.

By studying the load classes based on the input from the expert and the guidelines, the load classes can be divided into each performance category as shown in Table 3.6.

Table 3.6: Load classes linked to their performance category.

Load class (LC)	
Category	Score
A, 60, NEN-EN-1991, NEN-6706	1
B, 45	2
C, 30	3
D	4

It must be noted that there are no viaducts that have load class 'D'. A possible explanation is that these viaducts have been replaced already. Additionally, a link with the technical lifespan can be made, because viaducts with a low load class are expected to deteriorate faster due to heavy trucks. Lastly, some viaducts with load classes 'C' and '30' have been analyzed and checked on limitations indicated with road signage in google street view. This confirmed that linking a load class to a certain functionality is hard. A few times there were limitations below the legal maximum allowed weight and in other situations not. These limitations differ according to their size (e.g. 20.000 or 15.000 kg) and sometimes there is a limitation in terms of the maximum allowed axle load. This is a shortcoming of this dataset: the current technical condition plays a role in the maximum allowed weight.

3.2.4.4 Safety to users

The safety to users is reflected by the safety score, based on the number of accidents with fatal consequences and injuries. The data about the accidents originate from the year 2017. It is very hard to define an acceptable number or a threshold for the number of accidents with injuries or fatal ending. However, these numbers also need to be split into categories. Because there is no guideline, law or expert that specifies or knows the acceptable number, assumptions are used to categorize the data. The first assumption that has been made is to compare accidents with injuries and fatal consequences and is defined in equation 3.4.

$$1\ fatal\ accident = 15\ accidents\ with\ injuries \tag{3.4}$$

The score for the safety can then be calculated and will be done by adding up the number of accidents and dividing it by the length of a road section. This is shown in equation 3.5, where the amount of accidents with a fatal ending is abbreviated to 'AWF' and the amount of accidents is indicated with 'AWI'.

$$score = \frac{\left((15 * AWF) + AWI\right)}{Length\ road\ section} \tag{3.5}$$

Because the data about accidents can be separated between viaducts and road sections, the accidents can also be linked to viaducts. However, the difference between the length of viaducts is not as significant as the differences in length for the road sections. Additionally, in the DISK dataset, the length is sometimes actually the width of the viaduct. Lastly, by including the length of the viaducts in the calculation, the viaducts which can be linked to accidents will have a very high score due to the limited length of viaducts (compared to road sections). Therefore, the length of the viaducts will not be used in the calculation of the score. This score needs to be interpreted as the number of accidents with either injuries or fatal consequences per viaduct per year. This results in equation 3.6.

$$score = (15 * AWF) + AWI \tag{3.6}$$

The categories are divided among the scores, shown in Table 3.7.

Table 3.7: Score categories for the safety score.

Safety to users	
Score (s) per km1 or viaduct per year	Score
$0 \leq s < 5$	1
$5 \leq s < 10$	2
$10 \leq s \leq 15$	3
$s > 15$	4

The categories can be explained as followed:

1. Perfect score: a few accidents with injuries per km[1] or viaduct per year.
2. Good score: a moderate amount of accidents with injuries per km[1] or viaduct per year, no fatal accidents.
3. Fair score: 1 fatal accident or less per km[1] or viaduct per year.
4. Poor score: more than 1 fatal accident per km[1] or viaduct per year.

After applying these scores to the dataset, almost all viaducts are within score category 1 (perfect), because almost all accidents are linked to a road section. When considering road sections, the majority also falls within score category 1.

3.2.4.5 Noise emissions

Noise emissions are reflected by the average exceedance of the noise production limit (in Dutch: geluidsproductieplafond) (Rijkswaterstaat, 2012). This exceedance of the noise production limit is obtained by equation 3.7.

$$\Delta_{exceedance} = noise\ emissions - noise\ production\ limit \qquad 3.7$$

Thus, a negative number will indicate a buffer to the noise production limit. The threshold, where the limit is equal to the emissions, will be used at the lower bound of a good score (2). The different categories can then be defined similarly to the categories for the geometry and load class:

1. Perfect score: indicator is above the threshold, and the buffer is significant.
2. Good score: indicator is above the threshold, but the buffer is limited.
3. Fair score: indicator is below the threshold, but the distance to the threshold is limited.
4. Poor score: indicator is below the threshold, and the distance to the threshold is significant.

This results in the categories as shown in Table 3.8.

Table 3.8: Score categories for exceedance of noise production limit.

Δexceedance	
Value (dB)	Score
Δ < -0,5	1
-0,5 < Δ < 0	2
0 ≤ Δ < 0,5	3
Δ ≥ 0,5	4

The steps of 0,5 dB and a good score are based on the report of Rijkswaterstaat (2012), which marks reference points with a buffer less than 0,5 dB as points where in the future an exceedance of the noise production limit impends.

3.2.5 Integration of sub-indicators

Now that all sub-indicators and performance indicators have a certain score, the sub-indicators can be combined. Each performance indicator still has a separate dataset, these are combined based on an attribute join (asset id) in GIS. This results in a dataset where for each asset the score per performance indicator is given. Also, the data that has been used for this score has been combined (e.g. the amount of UDC). The next step is to determine the overall functional performance of an asset. Here, similar to the pre-evaluation of Cuendias González (2018), the worst score for a performance indicator will be leading for the overall functional performance of an asset. Thus, the highest score (because a higher score is a worse functional performance) has been selected as the overall functional performance. This process has been illustrated in Figure 3.9.

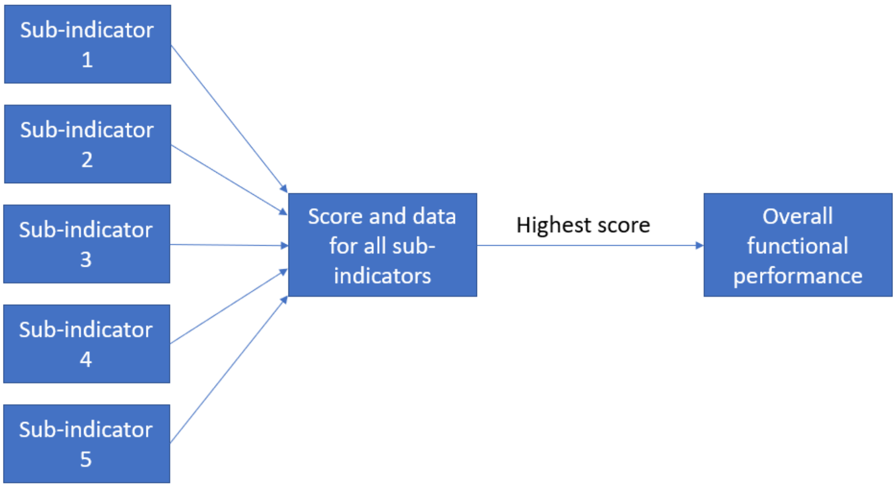

Figure 3.9: Process to integrate performance indicators and their datasets. Please note that viaducts have 5 performance indicators, but road sections are limited to 3 performance indicators.

The methodology to determine the overall functional performance of a viaduct can be explained with an example, with the data as shown in Table 3.9.

Table 3.9: Data for example viaduct.

Sub-indicator	Data
User delay costs	€80.000/km[1]
Height	4,40 m
Load class	60
Safety score	2,4
Average exceedance of noise production limit	0,40 dB

Table 3.10 provides an overview of how all indicators are scored based on the data. This table is also added in Appendix L – Overview of score categories per indicator. In Table 3.10, the data for the example is repeated in the lowest row and the scores are marked with colors.

Table 3.10: Overview of score categories per indicator.

Indicator / Score	User delay costs (UDC) per km^1 (€/km^1)	Height (m)	Load class	Safety score	Exceedance of noise production limit (dB)
1: Perfect	0 - 2.000	H ≥ 4,45	A, 60, NEN-EN-1991, NEN-6706	0 ≤ s < 5	Δ < -0,5
2: Good	2.000 - 36.000	4,05 ≤ H < 4,45	B, 45	5 ≤ s < 10	-0,5 < Δ < 0
3: Fair	36.000 - 347.000	3,85 ≤ H < 4,05	C, 30	10 ≤ s ≤ 15	0 ≤ Δ < 0,5
4: Poor	> 347.000	H < 3,85	D	s > 15	Δ ≥ 0,5
Data example	80.000	4,40	60	2,4	0,40

From Table 3.10 it can be concluded that the load class and the safety have a perfect score. The height has a good score, while the UDC and the exceedance of the noise production limit scores have a fair score. These 2 indicators have the most worse score, so the overall functional performance of this viaduct is also fair (3). Because all indicators are based on data now, this scoring methodology has been applied in the dataset. The tool determines the performance of each category and the overall functional performance for every asset. When data is missing for a certain indicator, the score is defined as '0'.

3.2.6 Visualizations and design solution

Until this point in the research, ArcMap has been used to link data sources and to develop the dataset. However, for the visualizations, ArcGIS online has been used. The advantages of ArcGIS online, compared to ArcMap, are the following:

- More user friendly.
- Easier to access: only an account is needed. There is no need to download and install software that is needed for ArcMap. Therefore, it is easier for people in the workshops to participate.
- More advanced data visualizations.

The objective of the visualizations is to help decision makers interpret the data in the tool. This is also the final step in the design part and leads to a design solution that can be verified and validated. A detailed manual, which specifies how to use the tool, has been written in Dutch so employees of Rijkswaterstaat can use the tool. This manual has been added in Appendix M – Manual for the tool. The remainder of this chapter will focus on the presentation of the design.

The dataset has been uploaded to ArcGIS online and consists out of multiple layers containing data about viaducts, road sections and for example sub-indicators (e.g. UDC). First, some basic visualizations are implemented using the webmap in ArcGIS online. These are shown in Figure 3.10, where viaducts are shown on the map with dots. The color of these dots indicates the overall functional performance of the viaduct:

- Green = perfect (1);
- Yellow = good (2);
- Orange = fair (3);
- Red = poor (4).

The link between these colors and score categories are used repeatedly in the further design of the tool.

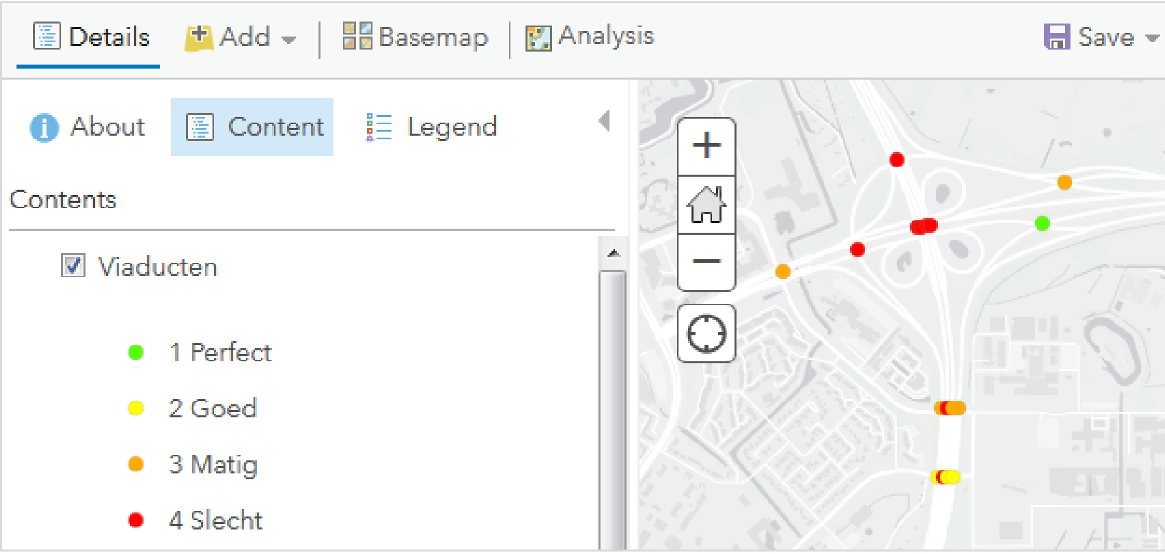

Figure 3.10: Basic visualizations using the webmap in ArcGIS online. The colors represent the overall functional performance of viaducts.

For the visualization of the different sub-indicators, the webmap has been implemented in the web appbuilder for ArcGIS. The web appbuilder has some more advanced visualizations than the webmap. There are other possibilities to design the tool in ArcGIS online, but the web appbuilder provides the desired types of standard widgets (e.g. visualization of multiple categories and selection widget). Within the appbuilder, the dashboard theme has been used, which can be used to visualize data. The widgets are mainly used to visualize and select a specific asset or multiple assets. Figure 3.11 shows the tool in the web appbuilder. The different parts of the tool are marked with colors:

- Yellow (right upper corner): the general map where the layers are shown.
- Red (left upper corner): the selection tool to select either one viaduct or multiple.
- Green (bottom and left side): the widgets with the indicators for the sub-indicators.

Figure 3.11: The tool in the web appbuilder. The yellow part (right upper corner) indicates the map, the red part (left upper corner) marks the selection tool and the green part (bottom and left side) indicates the widgets used to visualize the data of the sub-indicators.

The design of the tool will first touch upon the general map used in this tool. Figure 3.12 shows this part of the tool, with the widgets that are implemented on the map. These are shown in the upper left corner of the map and described in the next part.

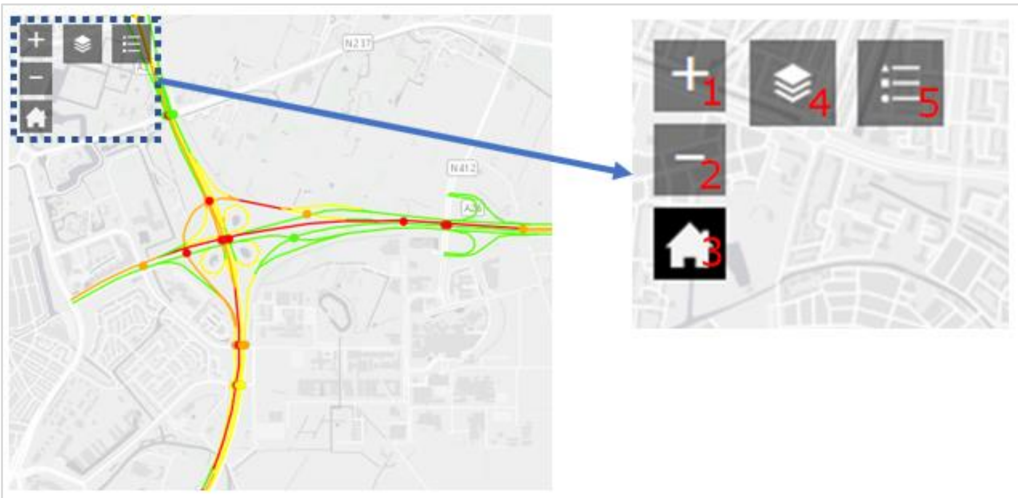

Figure 3.12: Map used in the tool, in the left upper corner a few widgets are shown. These are: (1) zoom-in button (2) zoom-out button, (3) home button, (4) layer list and (5) legend.

The basic navigation options in the map work similarly to the ones used in, for example, google maps. The widgets in the map are the following, as numbered in Figure 3.12:

1. Zoom in;
2. Zoom out;
3. Home button: when clicking this button, the user will return to the basic extent of the map. This basic extent is located on the east side of Utrecht.
4. Layer list;
5. Legend.

The last two widgets will be explained shortly because they are a little bit more complicated than the others. The layer list can be accessed by clicking on the button, as shown in Figure 3.13.

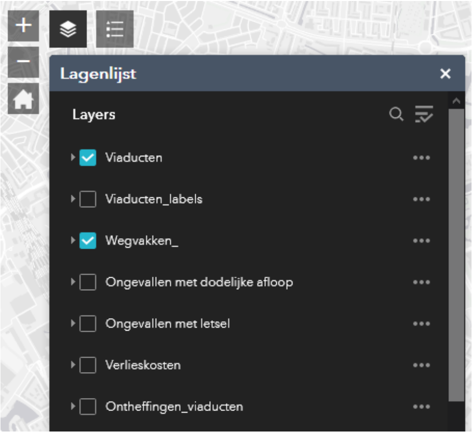

Figure 3.13: Layer list in the tool.

In this list, a user can change the data visible on the map, by turning layers either on or off. For example, Figure 3.14 shows that a user can turn off the layer ‘Wegvakken’ (Dutch for road sections).

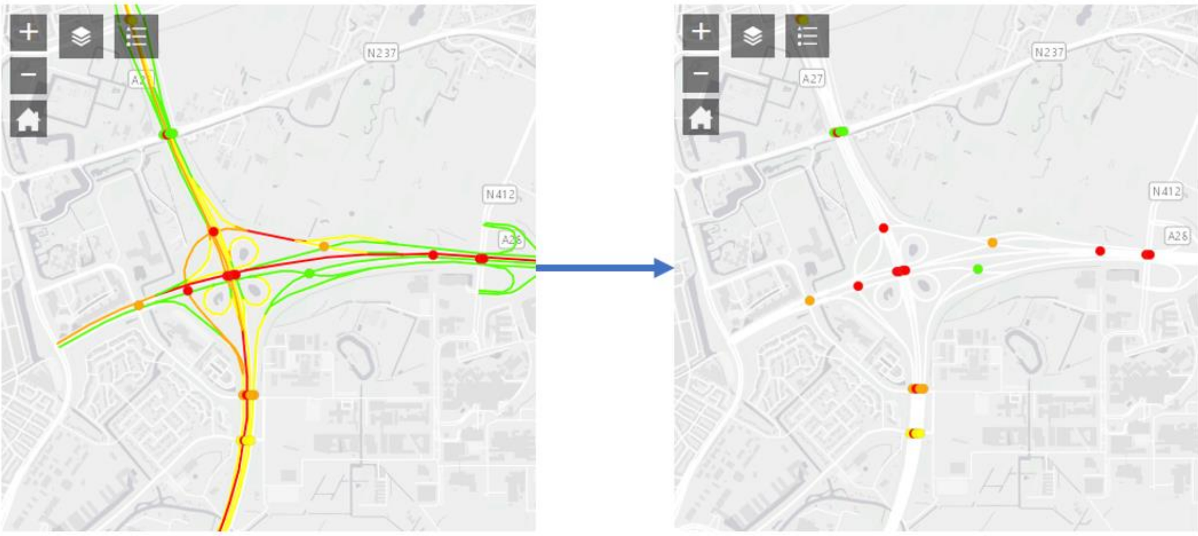

Figure 3.14: Effect of changing the layers in the layer list. The lefts side shows the map with the layers 'Viaducten' and ‘Wegvakken’ turned on. In the right picture, only the layer ‘Viaducten’ is turned on.

The legend can be used to see the description of the visualization of the layers, mostly to differentiate the colors. These are similar to the colors used in the webmap and shown in Figure 3.15. The information in the legend is dependent on the selected layers in the layer list.

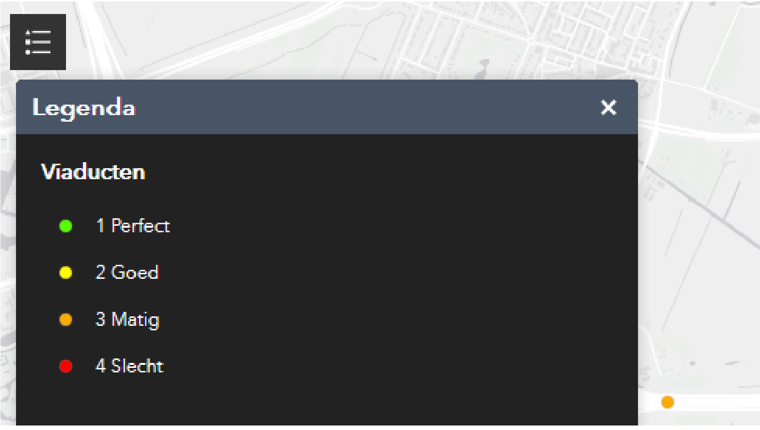

Figure 3.15: Legend in the tool. The example indicates the overall functional performance of viaducts. The different colors indicate a certain performance.

Next, the selection tool and the data visualizations are explained. These tools collaborate with each other: the data visualizations will show the data for the selected viaduct(s). Changing the selection will change the shown data visualizations. As shown in Figure 3.16, the selection widget has two options:

- Select by point: used to select a single viaduct.
- Select by rectangle: used to select multiple viaducts at the same time.

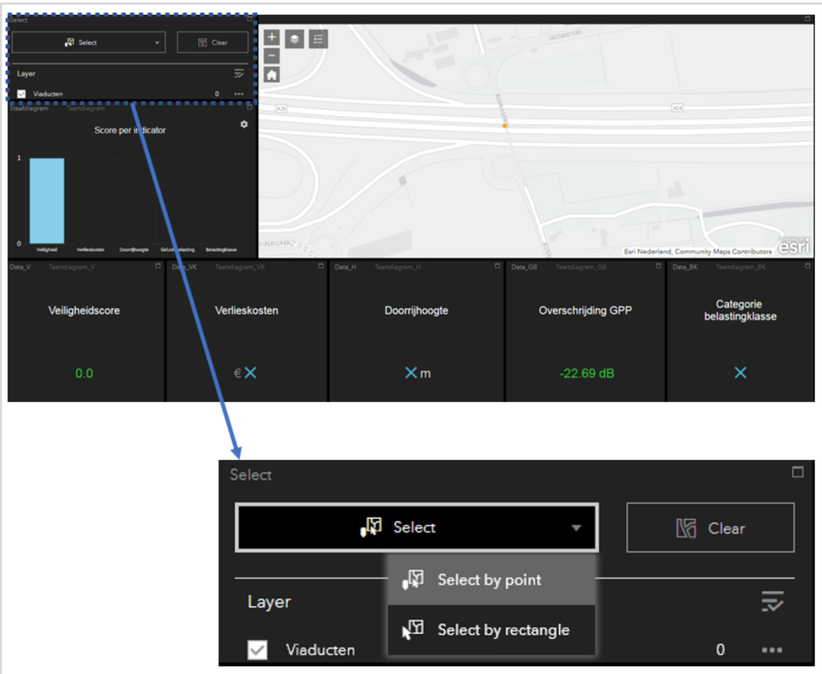

Figure 3.16: Screenshot of the selection widget.

The first example will concern the selection of a single viaduct. In Figure 3.17 a viaduct has been selected, indicated by the blue color on the map. Now, the visualization widgets change their values.

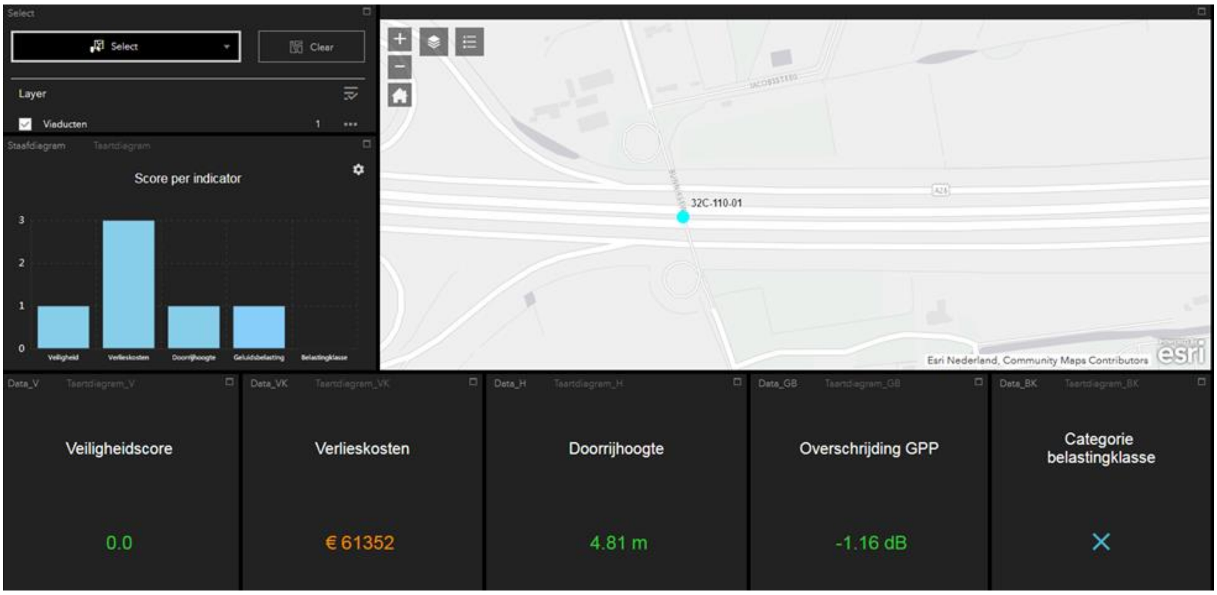

Figure 3.17: Example of a selected viaduct.

On the left side, a bar chart can be seen that shows the scores for the five categories. This visualization is enlarged in Figure 3.18. A higher score for a sub-indicator translates into a worse score, while a score of '0' or a missing bar means that data is missing for that sub-indicator. The tool has been designed in Dutch, so the translation of the sub-indicators is the following:

- 'Veiligheid' means safety to users.
- 'Verlieskosten' means user delay costs.
- 'Doorrijhoogte' means height.
- 'Geluidsbelasting means noise emissions.
- 'Belastingklasse' means load class.

These translations are similar to the widgets at the bottom in Figure 3.17, the only difference is that veiligheid is named 'veiligheidscore' and the noise emissions are indicated by the exceedance of the noise production limit (Dutch: Overschrijding GPP).

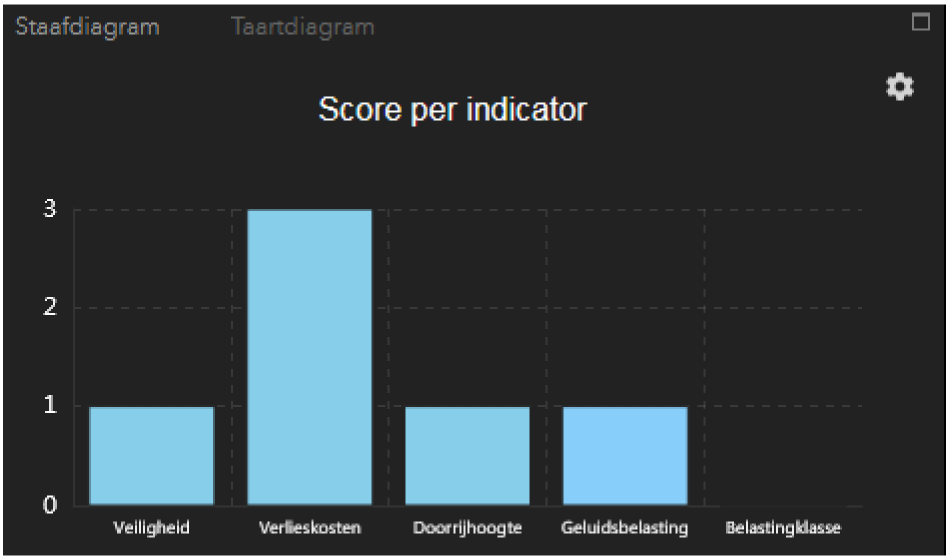

Figure 3.18: Bar chart with the score per sub-indicator. A higher score indicates a worse performance for that indicator. Thus, for this example, the conclusion can be made that the sub-indicator 'verlieskosten' or user delay costs has a fair score (3).

The bar chart can be used to get a quick overview of the different sub-indicators and how they score. A helpful addition to the bar chart would be to color the bars based on their score (e.g. poor score colors red), but this is not possible (yet) within ArcGIS online. From the example in Figure 3.18, one can conclude that:

- The sub-indicators safety to users, height and noise emissions have a perfect score (1).
- The sub-indicator user delay costs (verlieskosten) is the worst scoring sub-indicator with a fair score (3). This causes that the overall functional performance of this viaduct is also 'fair'.
- There is data missing for the load class.

In the bottom part of the tool, the data is shown that is used to make these categories, this is shown in Figure 3.19. This is the same example as previously described. With these widgets, one can see that the amount of user delay costs are €61352 and that data for the load class is missing (indicated with the cross). Again, the different colors refer to the scoring (green = perfect, yellow = good, orange = fair and red = poor). The user delay costs are shown in orange, which corresponds with a fair score.

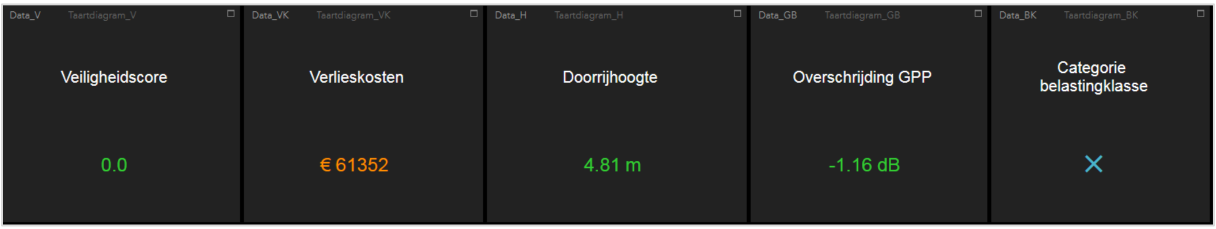

Figure 3.19: Data for the five different sub-indicators.

When selecting a different viaduct, the visualizations will also change. There is also an option in the tool to select and visualize the data for multiple viaducts at the same time. This option is accessed by the user by changing the visualization widgets, as shown in Figure 3.20.

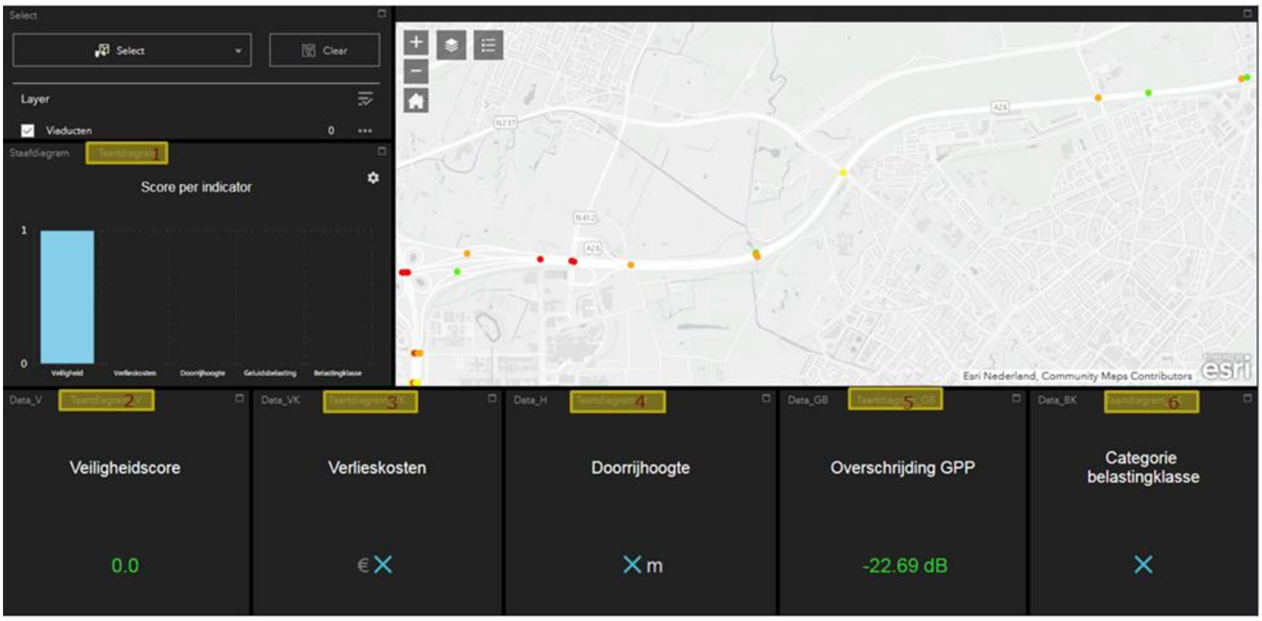

Figure 3.20: The six buttons in the tool to access the visualizations for multiple viaducts.

This will result in the tool as shown in Figure 3.21. Instead of the bar chart and the data, pie charts are now used. These indicate the number of viaducts that are in each score category (1, 2, 3 or 4). On the left side, in the middle, the overall functional performance of the selected viaducts is shown.

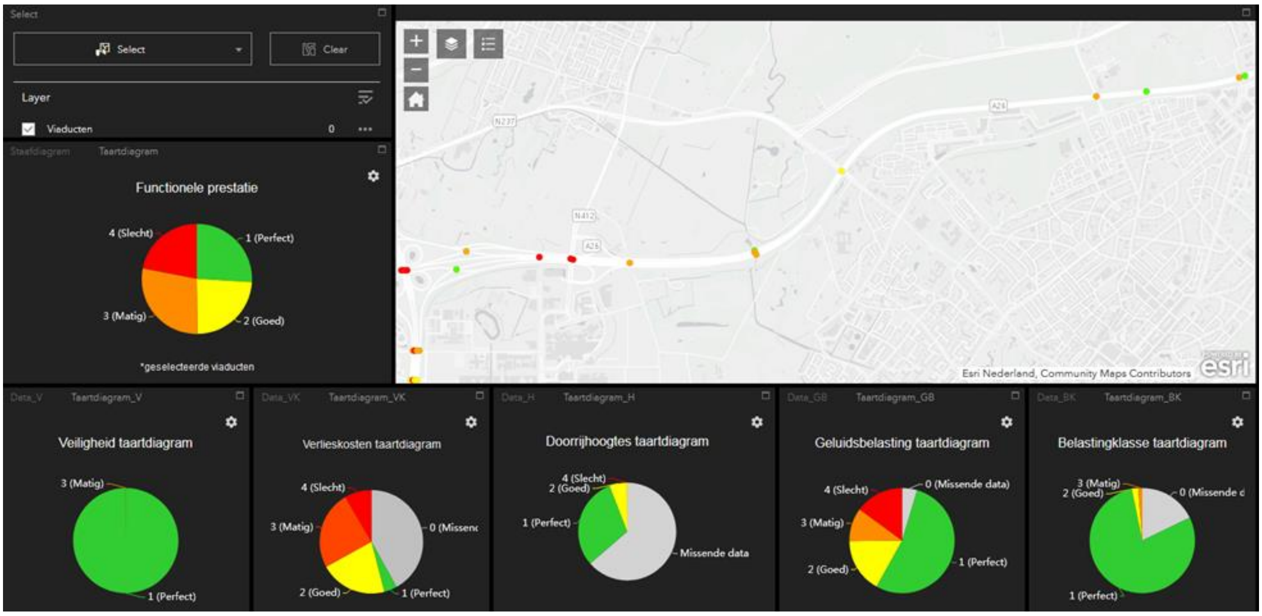

Figure 3.21: Visualizations for multiple viaducts. The visualizations at the bottom of the figure indicate the performance of the separate performance sub-indicators. The pie chart on the left side, with the title 'Functionele prestatie' indicates the overall functional performance of viaducts.

These pie charts show the proportion of viaducts that are within a certain score category and will be explained using an example. In order to select multiple viaducts, the option 'select by rectangle' can be used (see Figure 3.16). By drawing a rectangle, the viaducts that fall within this rectangle are selected. Figure 3.22 shows a selection of viaducts in the tool, which are indicated with a blue color.

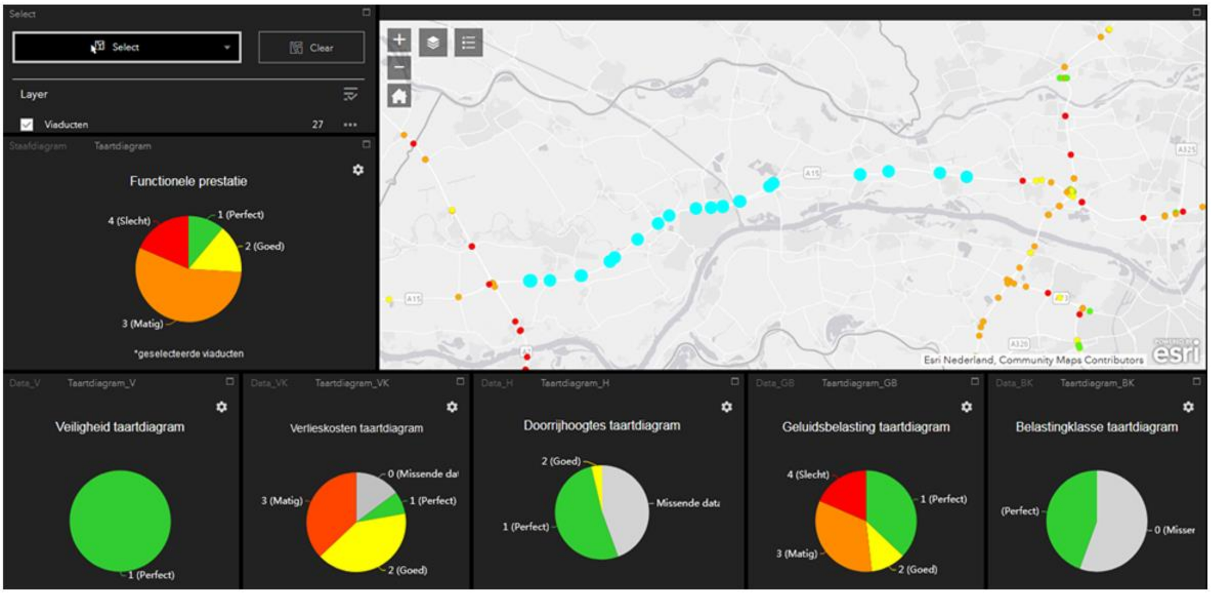

Figure 3.22: Selection and visualization of multiple viaducts. The viaducts that are selected are displayed in blue on the map.

Within Figure 3.22, the overall functional performance can be seen on the left, middle side. From this visualization, it can be concluded that the largest proportion of viaducts has a fair score for the overall functional performance (in Dutch, fair is equal to 'matig'). Additionally, the percentage of viaducts with a poor score (in Dutch 'slecht') is approximately 20%. When placing the mouse cursor on the slices, the exact amounts and percentages will show up, as shown in Figure 3.23. This is close to the initial guess of 20%. Additionally, placing the mouse cursor on one of the slices will cause that the viaducts that have this score will light up on the map with a square around them.

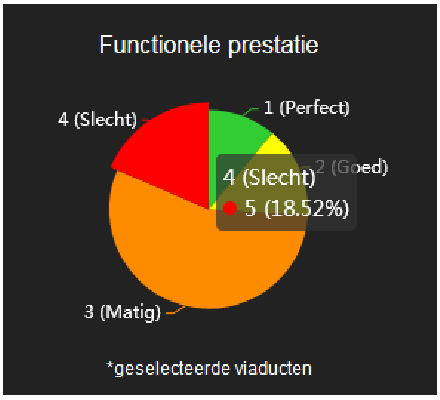

Figure 3.23: The visualization will show the exact amount of viaducts (5) and percentage (18,52) for each score category, in this example the score category 'poor'.

The visualizations on the bottom of Figure 3.22 show the proportion of each sub-indicator and will be explained for the selection in Figure 3.22:

- Safety: all selected viaducts have a perfect score.
- User delay costs: large proportions for both a fair and good score.
- Height: around 50 percent have a perfect score, also a large proportion of missing data (in Dutch: 'missende data' or 'geen data').
- Noise emissions: around 20% have a poor score.
- Load class: 50 percent have a perfect score, the other half has missing data.

From these sub-indicators, the conclusion is that the poor score of the viaducts is caused by noise emissions, because it is the only sub-indicator that has a poor score. Furthermore, fair scores are seen at noise emissions and user delay costs.

The visualizations for multiple viaducts can also be used to get a quick overview of the complete dataset. A detailed description of this analysis has been provided in Appendix N – Summary of the dataset. From this analysis, we can conclude that:

- The viaducts are equally distributed among the score categories for the overall functional performance (each score category has around a quarter of the amount of viaducts).
- The sub-indicators 'exceedance of noise production limit' and 'user delay costs' have worser scores compared to the other sub-indicators. The exceedance of noise production limit has the largest proportion of poor scores, while the user delay costs have the largest proportion of fair scores.

The visualization widgets are chosen to be limited to viaducts. It is not possible to incorporate the road sections in the same visualizations as the viaducts, because of the use of other indicators and the fact that road sections are in a different layer. So, in order to visualize the road sections in the same way as viaducts, there are an additional 2 visualizations (one for individual and one for multiple road sections) needed. Showing a lot of visualizations at the same time may cause confusion, so the decision has been made to limit the visualizations in the widgets to viaducts. However, the basic map does visualize road sections based on the overall functional performance, similar to viaducts:

- Green = perfect (1);
- Yellow = good (2);
- Orange = fair (3);
- Red = poor (4).

Figure 3.24 shows this basic visualization of the road sections.

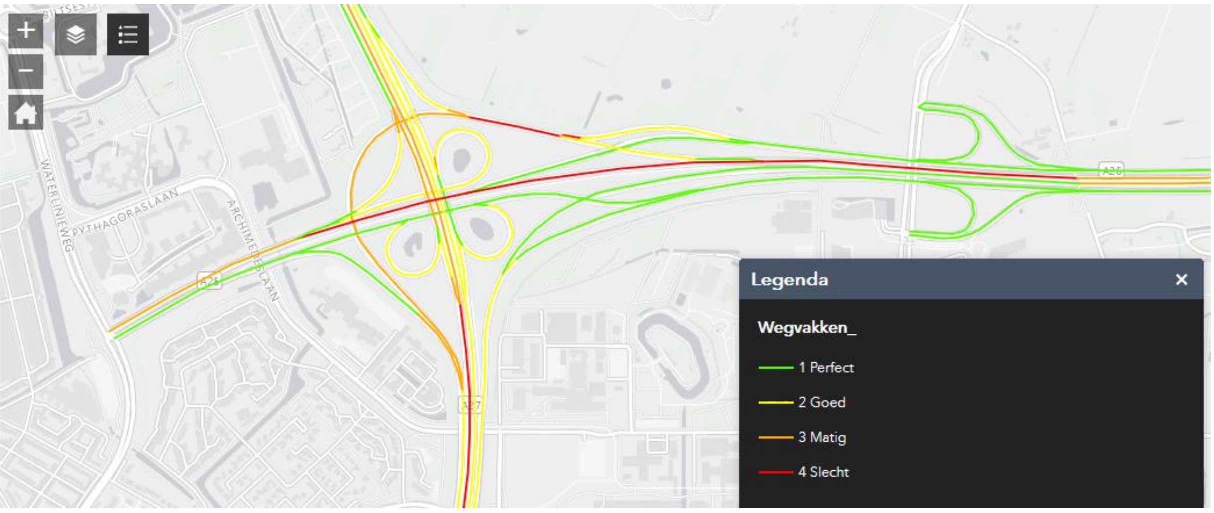

Figure 3.24: Visualizations of the road sections in the map within the tool.

When using the standard selection option within the map some more data can be accessed about the road sections. This selection option is not the same as the selection widget explained earlier and is shown in Figure 3.25. When selecting a road section, a pop-up opens which shows some data about the three indicators user delay costs, safety score and noise emissions. These can be seen within the pop-up in Figure 3.25 as ‘verlieskos’, ‘veiligheid’ and ‘GB_oversch’ respectively. The value fields within the tool are limited to ten characters.

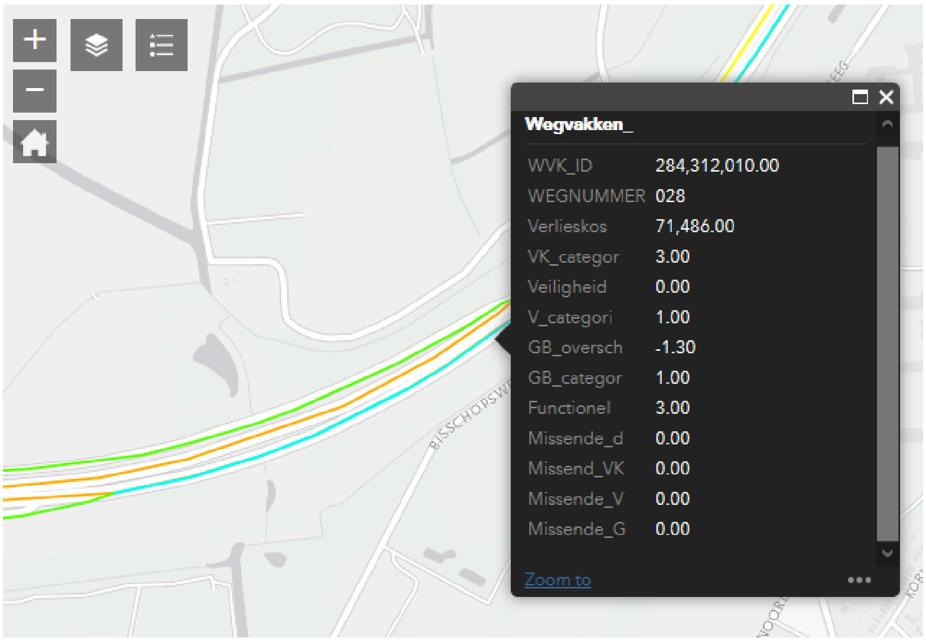

Figure 3.25: Standard selection option in the map, data in the pop-up concerns a selected road section.

In the example shown in Figure 3.25, the following data can be seen:

- User delay costs = €71.486/km[1] (score = 3).
- Safety score = 0 (score = 1).
- Exceedance of noise production limit = -1,30 dB (score = 1).

It can be concluded that the overall functional performance of this example is 3, or fair. This is caused by a high amount of user delay costs.

3.3 Verification and validation

The objective of this chapter is to evaluate if the tool is in line with the requirements in section 3.1 (verification) and the wishes of the employees of Rijkswaterstaat (validation). Verification will be performed based on the interpretation of the researcher and explaining if and how the design satisfies the requirements. For validation, 2 sessions have been organized:

- Test session: session with a limited amount (4) of employees of Rijkswaterstaat. Besides validation, this session is also used as a test for the workshop (the presentation, demonstration, use of the tool and the questionnaire).
- Workshop: a session with a larger amount of employees (25) of Rijkswaterstaat.

A detailed description of the workshop is provided in Appendix O – Description workshop. Results from the workshop originate from the questionnaire, chat function within skype, emails and the discussion at the end of the workshop. The questions in the questionnaire are in Dutch and are added in Appendix P - Questionnaire.

3.3.1 Verification

The requirements originating from the second chapter of this report are shown in Table 3.11. In this table, the type of verification and the explanation have been added.

Table 3.11: Requirements and verification.

Nr	Name	Requirement	Explanation
1.	Data		
1.1.	Data integration	The tool should integrate data sources of multiple performance indicators	The tool combines data from the 5 performance indicators based on sub-indicators (e.g. load class, height etc.). For some sub-indicators, multiple data sources have been combined.
1.2.	Data sources	The tool should contain data that indicate the overall performance of performance indicators and that are specific enough	The performance indicators are linked to sub-indicators, which are specific enough that they can be quantified by data within the tool.
1.3.	Completeness	The tool should at least contain data that indicate the current performance of all used performance indicators	Data is included for every performance indicator. For some sub-indicators (e.g. height) large parts of data are not available.
1.4.	Data quality	The tool should contain data with the desired quality to assess the functional performance	Datasets have been compared with other datasets, but linking of the data sometimes provides mistakes in the dataset.
2.	Visualizations		
2.1.	Interpretation	The data in the tool should be easy to interpret by decision-makers and users	The data in the tool has been visualized which helps decision makers to interpret the data.

2.2.	Validity	The visualization should lead to valid conclusions about the data	Visualizations of the score categories helps to draw valid conclusions about the data.
2.3.	Level of detail	The visualization should show the data on different levels of detail	Users can see the data of multiple assets at the same time, with the selection of multiple viaducts. For individual viaducts, users can not only see the score category (e.g. good) of a sub-indicator, but also the data (e.g. height: 4,20 m). Additionally, sub-indicators have been implemented as a separate layer in the tool (e.g. user delay costs).
3.	Interaction		
3.1.	Selection	Users should be able to see, select and explore data of specific viaducts and road sections	Users can select a specific viaduct or road section and see the visualizations and the data.
3.2.	Selection	Users should be able to select certain parts of the data	Users can select, within a selection, all viaducts with a poor score and see them light up on the map.

3.3.2 Validation

In general, employees confirmed the overall usefulness and relevance of the tool within the intended problem context: the replacement and renovation program at Rijkswaterstaat. The validation results will focus on the current scope of the tool. The scope is the integration of performance indicators and visualization of the current functional performance of viaducts and road sections within replacement decisions. Feedback concerning suggested further developments of the tool will be discussed in the final two chapters. In general, employees were quite positive about the tool. This section has been divided into the following parts:

- Data;
- Visualizations;
- Interaction;

This structure is similar to the structure of the requirements.

Data

This part of the tool has received the most feedback, especially the naming and determination of the score categories. In general, employees found that the used data and indicators are relevant within replacement and renovation decisions. They also appreciated the integration of the performance indicators in one central tool, instead of separate elements. Based on the available data, the functional performance could be upscaled to almost all viaducts and a large part of road sections. One employee noted: *"Previously, we would always take the viaduct that has been evaluated by the methodology of Cuendias González (2018) as an example, the tool expands the methodology to all viaducts".* The next sections will comprise of the feedback for each used sub-indicator.

<u>*User delay costs*</u>

The user delay costs (UDC) seems to be the most relevant sub-indicator leading to the replacement of a viaduct. The exact Dutch definition (verlieskosten) of this sub-indicator has been criticized, because it is questioned if it is clear for a person that is not familiar with the topic. A suggestion has been made to change it to 'reistijdverliezen', but this naming does not stress that it is a monetary term (expressed in euros per km[1]).

Height
An employee confirmed the relevance to know where viaducts do not meet the minimal height (4,05 meters).

Load class
The load class is, as previously mentioned, used to design a viaduct based on a determined traffic load. However, this does not take into account the actual technical condition of the viaduct (based on inspections and recalculations), which may cause a limitation in the vehicles that are allowed to use a certain viaduct. It would, therefore, be more accurate to look if, and the extent of a limitation in the maximum allowed weight or tonnage that can pass it. This data can then be used as a sub-indicator instead of the load class. However, this sub-indicator has difficulties in terms of data availability within Rijkswaterstaat. At the beginning of this research and after this suggestion has been made there has been searched for this data within Rijkswaterstaat, but with no result. However, it cannot be excluded that this data is still available somewhere within Rijkswaterstaat. Another suggestion is that load classes 'B' and '45' are not considered good scores.

Safety score
The safety score has been based on the number of accidents causing injuries and fatal consequences. Employees noted that this sub-indicator is a little bit difficult to understand, also because the scores for the viaducts often have a perfect performance. This can be explained by the fact that most of the accidents are linked to road sections and not to viaducts. A suggestion has been made to not link the score to individual assets but to a part of the road network. In this way, all assets within the same part of the road network will have the same score, instead of a separate score per asset.

Exceedance of noise production limit
Most feedback on this sub-indicator originates from employees that are working with noise production limits. The tool uses the noise model from 2016, but it has been noted by employees that this model is updated each year based on the input parameters (traffic intensities, maximum speed, type of top layer). The noise model from 2016 is part of a European obligation to do this once in a 4 year period. The data in the tool can thus be updated from the noise model from 2019 for example. Furthermore, the aggregation of multiple reference points to one asset could be done differently. In the tool, the average exceedance is taken as the sub-indicator for the score. This is described more extensively in Appendix E – Description data sources. An exceedance of the noise production limit in point A can be compensated by a buffer to the noise production limit in point B. An exceedance of only one reference point is already considered too much in the regular legal procedure for this topic. Thus, instead of taking an average, it would perhaps be better to use the number of reference points that exceed the noise production limit as the sub-indicator.

The Dutch naming of the sub-indicator could also be improved. 'Geluidsbelasting', which means noise loads, should be changed in 'Geluidsproductie', which means noise production. Because reference points reflect the noise production level in a certain location, the latter would be a better naming and consistent with this report. Another employee noted that the noise model is mostly dependent on the traffic intensities of the road network and not the exact performance of a viaduct. The only exception is when the viaduct has a different asphalt layer than the road network. Furthermore, an exceedance of the noise production limit may also be seen as a good score, because in most cases, this exceedance is caused by an increase in the traffic intensities at a certain location.

The feedback also provided more insight into how Rijkswaterstaat works with noise production limits. They are, as previously indicated, not influenced by the context of the surroundings (e.g. amount of people living in an area). However, when there is an exceedance of the noise production level, the context will be analyzed. When there are no people living in the area of the exceedance, a procedure will be started to higher the noise production level. When there are people living in the area, interventions are needed to reduce the produced noise by a road. However, these interventions do not lead to the replacement of the viaduct, but are limited to replacement of the top asphalt layer or the placement of noise barriers. One respondent stressed that these types of interventions are very relevant when making replacement decisions. There are also viaducts that have a limited load-bearing capacity and therefore it is not possible to apply a porous (noise reducing) top layer. When there is an exceedance of the noise production limit in these situations, Rijkswaterstaat can apply for an exemption of the noise production level. Or, to put differently, only an exceedance of the noise production limit will not lead to replacement of a viaduct. When the viaduct is replaced due to other reasons in the future, it has to conform with the noise production limits. This example conforms with the structure of this research: the functional performance of an indicator cannot directly be linked to a certain replacement decision.

Quality of the data

Someone also questioned whether the linking of the data from road sections to viaducts (e.g. user delay costs and safety score) has been executed correctly. This can be checked by users by reviewing the underlying data. This underlying data is available in the tool, but no instruction has been included in the manual to review this has been made. There are indeed locations where this error occurs, this has been illustrated and explained in Figure 3.26. The mistake is caused by inaccuracies of the geometry of viaducts. A detailed explanation is provided in the section 'user delay costs' in Appendix J – Linking of the datasets to individual assets. It is thus important that users can check the tool on mistakes and be critical when using the data.

Figure 3.26: Example where linking of the data provides mistakes of the dataset. The lines indicate the user delay costs of road sections, while the dots indicate viaducts. The marked viaduct with the blue color should use the data from the orange or yellow road section. However, the data from the indicated road section (blue) has been linked to this viaduct. This is not correct, because that road section does not cross the viaduct.

Visualizations

Participants of the workshop agreed that the tool makes it easy to interpret the data. Additionally, the employees (3) that carried out the steps in the manual (Appendix M – Manual for the tool) managed to draw conclusions and retrieve data from the tool did this without problems or faults. The level of detail in the visualizations allowed people to retrieve mistakes in the dataset, as described in Figure 3.26. Lastly, it has been suggested during the test session to repeat the range of the score categories in the visualizations. This is shown in Figure 3.27.

Figure 3.27: Change in visualization: for every sub-indicator the range of each score category has been repeated in the visualization. In this example, user delay costs are shown.

Interaction

Respondents also noted some comments about the interaction with the tool. They noted that it is relatively easy to work with the tool, especially when you are already familiar with GIS. Respondents experienced that selection of a single viaduct is easy. Selecting multiple assets at the same time is a bit harder, especially when the road network has a big bend in it. The ability to select multiple viaducts at the same time has been perceived as valuable, because it is easy to see an overview of a road network. Lastly, the labels are, for some, difficult to read, which can be solved by increasing the size of the labels.

Questionnaire results

Within the questionnaire, respondents have been asked to rate the different aspects of the tool on a scale of 1 to 10. The aspects of the tool have been divided into:

- Used data and indicators;
- Division of indicators into score categories;
- User-friendliness;
- Visualizations.

Table 3.12 shows the results of this part of the questionnaire. While the number of respondents is limited (5), the results are in line with the received feedback. When suggestions for improvements to the tool have been made, this concerned mostly the used data and the division into categories, which have the lowest score in the questionnaire. Fewer improvements have been suggested to improve the user-friendliness or the visualizations and these aspects score higher in the questionnaire.

Table 3.12: Rating of the tool on different aspects. The visualizations have the highest rating on average, while the used data and indicators have the lowest rating. N (number of respondents) = 5. In total, 6 employees filled in the questionnaire, but one response has been deleted from the answers, due to possible unreliable answers. The min and max value shows the lowest and highest rating of all respondents on that aspect.

	Used data/indicators	Division of indicators into score categories	User-friendliness	Visualizations
Mean	6,8	7	8	8,4
Min	4	4	6	6
Max	8	8	10	10

A few suggestions have been implemented in the tool, which leads to the final design solution. These are:

- The change in visualizations as shown in Figure 3.27.
- The Dutch naming of noise emissions (geluidsproductie instead of geluidbelasting), shown in Figure 3.28.
- The size of the labels has been increased, see Figure 3.29.

The final design solution, with the changes as shown above, is provided in Appendix M – Manual for the tool. There are also a lot of opportunities to improve the tool further, but which fall beyond the scope of the tool. These recommendations are presented in the next chapters.

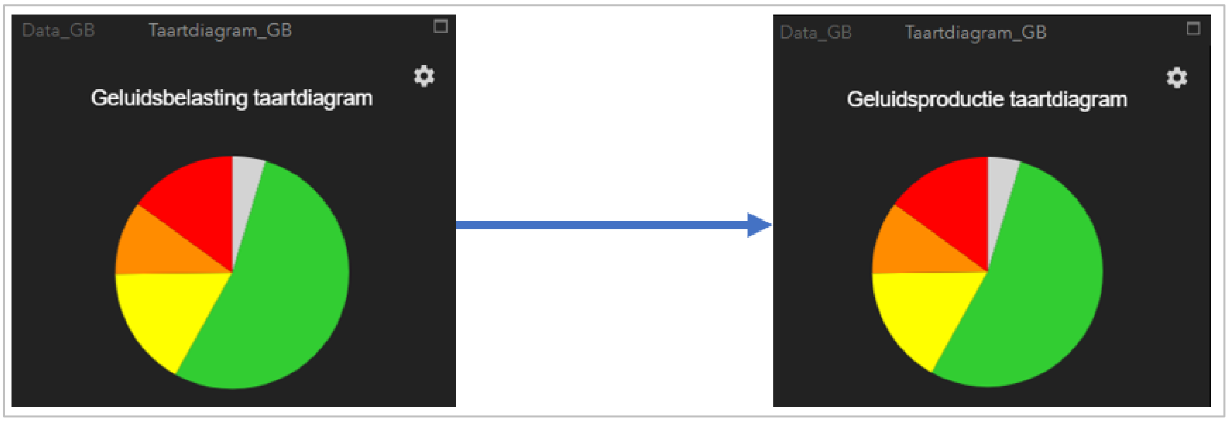

Figure 3.28: Change of the naming of 'geluidsbelasting' into 'geluidsproductie' in the tool.

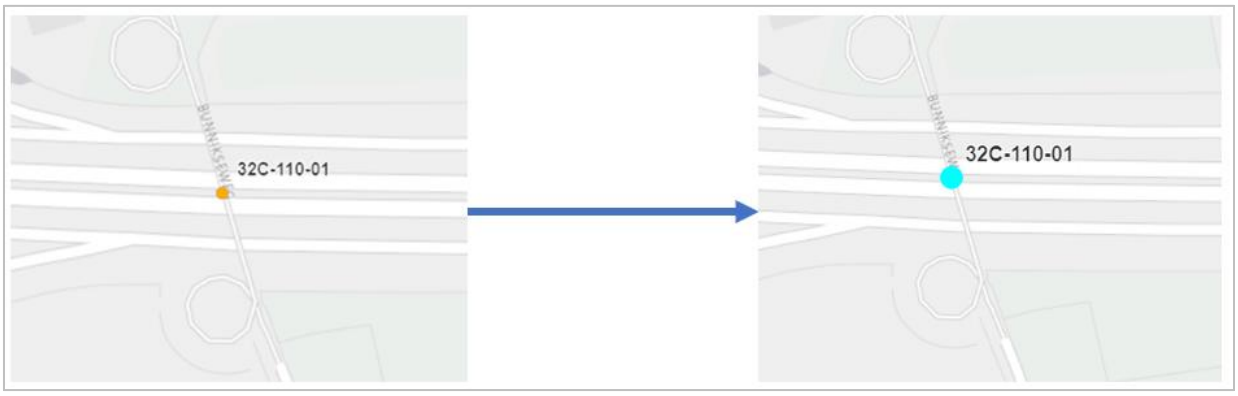

Figure 3.29: The size of the labels in the tool has been increased, in order to improve the readability.

4 Limitations

The evaluation of the spatial decision support tool confirms that the tool can reduce the complexity to determine the functional performance of viaducts and road sections. This has been achieved by using sub-indicators that are based on data. In this way, each performance indicator could be assessed and visualized. Furthermore, the tool integrates the performance indicators and determines the overall functional performance of each viaduct and road section. Consequently, the functional performance methodology that is based on the work of Xie (2017) and Cuendias González (2018) has been modified and applied to all viaducts and a significant amount of road sections. Geographical information systems (GIS) proved to be useful for integrating the data. Most datasets do not share a common attribute that can be used to link the data. However, in GIS, the data can also be linked or integrated based on spatial location. Additionally, visualization tools help to interpret the data. However, there are some limitations to this study, which are circumstances that influence and are relevant for the research objective. The remainder of this chapter will describe how these influence the objectives and the results of this research.

Data availability

Perhaps the biggest limitation of this research is data availability. Based on the performance indicators (e.g. traffic flow) of Cuendias González (2018) the sub-indicators have been defined that would reflect the performance indicators in a good and precise way. The next step was to search for the relevant data, this has been done in multiple ways. But for a few sub-indicators, the data was not available. Therefore, for the load class, the design load class has been used. A better indicator would be the maximum allowed vehicle or axle weight, but this data is not available in an overview. In this way, locations can be mapped where a limitation occurs that is below the legal maximum weight that does not need an exemption at the RDW. The difference between the maximum allowed vehicle weight and the design load class is that the first also takes the current technical state of the object into account. This confirms that technical aspects also influences functionalities of a viaduct. Another performance indicator that is prone to difficulties in data availability is 'geometry'. Besides the height, the width and more precise, the available space under or on top of a viaduct is also relevant, for expansion opportunities. Unfortunately, this data was not available. It seems hard to understand that Rijkswaterstaat does not have a central dataset that gives an overview of the height of viaducts (this data has been found outside of Rijkswaterstaat), the viaducts with a limitation in vehicle or axle weight or the available space at viaducts. The question thus arises if either:

- The data is not available at Rijkswaterstaat or outside the organization;
- The data is not findable at Rijkswaterstaat or outside the organization.

Employees confirmed that they sometimes want to use the same data, but they do not know where it is available. Every dataset that has been found within this research often served a different purpose or need. The height dataset is originally used to evaluate exemptions for traffic that are beyond legal restrictions. Additionally, user delay costs are firstly used by Rijkswaterstaat in cost-benefit analyses for new projects, not for monitoring the current road network. The different purposes also limit the usefulness within this research: the height dataset is used for exemptions and therefore there are a limited amount of viaducts in it with a height lower than 4 meters (the maximum legal allowed height of vehicles). As a result, the coverage of the dataset is limited. Also, the coverage of the dataset with user delay costs is limited. This lack of data availability seems to be especially relevant when a viaduct crosses a road that is owned by another road authority then Rijkswaterstaat (e.g. provinces or municipalities). A possible explanation that the data is not available at Rijkswaterstaat is that there is no need or purpose for the data yet. The data might not be findable at Rijkswaterstaat due to the context of the organization: a large organization, both centralized and de-centralized may lead to fragmentation of data across the organization. Lastly, it must be noted that for some sub-indicators the search for data was more extensive (e.g. height) than others (e.g. load class). One could argue that the largest relevance of this research is data fragmentation, because the tool integrates multiple sub-indicators based on data. At the same time, data availability can be seen as the biggest limitation of this research: this has influenced the decisions for sub-indicators and limits the coverage of the tool.

Functional performance and link to replacement decision

It is beyond the scope of the tool to determine the replacement year of viaducts or road sections. In this way, this research differs from the research of Cuendias González (2018) and Xie (2017). These previous efforts focus on studying a limited amount of viaducts in greater detail, while this research focuses on applying the methodology automatically on a very large group of viaducts and road sections. Therefore, the results from the tool do not concern the context of a viaduct based on its location or characteristics. Two examples are:

- Noise emissions may have a poor score in the tool, but when the viaduct is located in a remote location, this is possibly not a very big problem.
- Other interventions than the replacement of a viaduct can improve the functional performance. For example the possibility of adding a traffic lane on an existing viaduct.

In previous parts of this report, the first example reflects the 'problem analysis' and the second part to the 'solubility analysis'. There are also differences between sub-indicators: user delay costs already take into account a part of the problem analysis, while noise emissions probably need a more elaborate problem and solubility analysis. Additionally, the impact of replacement interventions is different across sub-indicators. When replacing a viaduct, the height can be increased in the design, therefore leading to a better performance of this sub-indicator. However, considering safety, it is hard for Rijkswaterstaat to predict what effects replacement has on the number of accidents. This statement has been based on reports that predict the impact of future project alternatives (Antea Group, 2019) (De Pater, 2019). To conclude, it is important to realize that a poor functional performance will not directly lead to the replacement of a viaduct or road section. This is dependent on the sub-indicator that causes this poor performance and the context of the viaduct.

The weighting of the indicators

This research uses the methodology to determine the functional performance similar to the pre-evaluation from Cuendias González (2018). In this way, the performance indicator with the worst score will be leading for the overall functional performance. The tool does not take into account the relative importance of performance indicators. One performance indicator may be more relevant for the overall functional performance than others. Employees noted that they found it difficult to give input for the weighting of indicators. In general, the most relevant sub-indicator related to the replacement of viaducts and road sections seems to be user delay costs.

Feedback during evaluation

During the workshop, it has been observed that a part of the employees found it difficult to stay within the scope of the tool in their feedback. Or to put differently, some respondents did not focus their feedback on the current scope of the tool, but on how to develop it further. The questionnaire helped to gather feedback within the current scope of the tool, but the number of respondents was limited (6). It is possible that, within the current scope of the tool, there are more possibilities to improve the tool.

5 Conclusion and recommendations

The first part of this chapter contains the conclusion, which will focus on answering the research questions. The second part will focus on the recommendations, which are mainly based on the limitations in the previous chapter and feedback from employees.

5.1 Conclusion

This research develops a spatial decision support tool that visualizes the functional performance of viaducts and road sections. The structure of this research follows a combination of systems engineering and the design cycle of design science. Based on input from employees, requirements have been made which are used to design the tool. After the design has been finished, the tool has been verified and validated in a workshop setting by employees.

This structure has been followed to answer the following main research question:

- *How can a spatial decision support tool be developed and evaluated that integrates performance indicators and visualizes (1) performance indicators and (2) the current functional performance of viaducts and roads within the replacement and renovation (V&R) program at Rijkswaterstaat?*

This main research question has been divided into sub-questions, which will be answered in this final part of the main report.

1. ***Which sub-indicators and data sources can be used to indicate the performance of the performance indicators?***

This research uses the performance indicators identified by Cuendias González (2018) in the pre-evaluation: traffic flow, geometry, load class, safety to users and noise emissions. These indicators are not always specific enough to be evaluated based on data, hence, sub-indicators are used for these performance indicators. The choice for sub-indicators has been based on validity (how representative is the indicator for the actual situation) and data availability at Rijkswaterstaat. Eventually, the following sub-indicators have been used in the tool:

- User delay costs per km[1] (performance indicator: traffic flow).
- Height (performance indicator: geometry).
- Load class (design, performance indicator: load class).
- Safety score based on the number of accidents with injuries and fatal consequences (performance indicator: safety to users).
- Average exceedance of noise production limit (performance indicator: noise emissions).

For some sub-indicators, multiple data sources have been used.

2. ***How can these data sources be integrated into a spatial decision support tool?***

The next step, after identifying the sub-indicators and separate data sources, has been to integrate the data sources into one dataset by linking them to individual assets (viaducts and road sections). In order to do so, the viaducts and road sections under the management of Rijkswaterstaat have been exported to a geographical information system (GIS). These contain the basic information of assets such as the object ID and the location. The data for each sub-indicator could then be linked to these assets, either based on a common attribute (object ID) or based on the spatial location. Most of the indicators have been linked based on its spatial location, so this proved to be a useful tool within GIS. Each sub-indicator has a certain score, based on the data: perfect, good, fair or poor. The worst score of a sub-indicator is leading for the overall functional performance of each asset. A poor functional performance is often caused by the sub-indicators exceedance of noise production limit or user delay costs.

3. **How can the data be visualized in the spatial decision support tool?**

The result of the second sub-question is a dataset with for each asset, the current overall functional performance. Also, the scores for each sub-indicator are included. Visualizations should help users of the spatial decision support tool to understand and to interpret the data. For the visualizations of the overall functional performance and the separate sub-indicators colors have been used. Also, for each viaduct a bar chart visualizes the scores for all sub-indicators. The tool also provides visualizations using pie charts, which are used when multiple assets are analyzed at the same time. The pie charts show the proportions of each score category for both the overall functional performance as the performance for each sub-indicator.

4. **To what extent is the tool useful within replacement decisions at Rijkswaterstaat and what improvements can be made?**

The evaluation of the tool is mainly based on the online workshop. During this workshop, the sub-indicators, the used data sources, the integration of the data and the scoring of each sub-indicator have been explained. After this, the tool has been presented and participants could use the tool themselves. Feedback about the tool has been collected using a questionnaire, emails, the chat function within skype and a discussion at the end of the workshop. The participants, on the whole, reported that:

- The functional performance and the tool are relevant within the replacement and renovation program.
- The integration of performance indicators and basing their score on data helps the tool to define the functional performance for a very large group of viaducts and road sections.
- The tool helps to get a quick overview of the functional performance of multiple assets at the same time.

In general, respondents were quite positive about the used visualizations and the user-friendliness of the tool. When using the tool, employees could retrieve the correct data from it. Most suggestions for improvements that fall within the scope of the tool concern the used data, indicators and the division into score categories. The load class has been based on a design load class, which does not take into account the current technical condition of the viaduct. It would be more accurate to use the maximum allowed vehicle weight or axle weight as a sub-indicator. However, this data is not available, or to a limited extent. Data availability has, therefore, influenced the choice for the sub-indicators and the coverage of some data sources is also limited (e.g. height). Another limitation of the tool is that the functional performance cannot be directly linked to a replacement decision.

5.2 Recommendations

The recommendations are divided into practical recommendations and suggestions for further research. The practical recommendations are more focused on processes within Rijkswaterstaat. Suggestions for further research are more focused on possibilities for further academic research. Most recommendations are based on the limitations and feedback received during the workshop that is outside of the scope of this research.

5.2.1 Practical recommendations

These recommendations are relevant for Rijkswaterstaat as an organization.

Data availability

One of the biggest limitations of this research is data availability. Rijkswaterstaat already acknowledges that data plays an important role in the daily processes (Allewijn, 2019) and aims to improve the management and availability of data. This research confirms this need, and it would be helpful if data is easier to retrieve for employees that want to use it. When the data is not available at Rijkswaterstaat, but there is a need to use it, this may lead to new data within the organization. However, the management of data requires recourses, such as employees and money, so Rijkswaterstaat cannot store a large amount of data that does not have a clear purpose. However, because some employees confirmed that they also had a need to use certain data that they could not find, it is questioned whether Rijkswaterstaat has an overview of possible new needs or applications for data.

Netwerkschakelplannen

Rijkswaterstaat works with 'Netwerkschakelplannen', this is a Dutch name for plans where the performance of a part of the road network is evaluated and objectives are set what performance a specific part of the road networks should have. In these plans, the functional performance is also evaluated, using similar categories than this research, (e.g. accessibility, safety and a sustainable environment). The scale is different, because these plans consider a part of the road network, while the tool developed in this research determines the score for individual assets. In the workshop, employees that worked with these plans proved to have valuable feedback for the tool. It is therefore recommended, based on the interfaces between the plans and this research, to keep these employees involved in the further development of the functional performance methodology. Also, this will probably help to expand the methodology further where an analysis of networks is possible more easily, the tool presents the first steps towards this.

Economic perspective

Employees found it difficult to make a distinction between the importance or relevance of certain sub-indicators. Looking at the indicators from an economic perspective may help in this complexity. The suggestion has been made to express for example safety in monetary values. There are ratios or figures for the costs of traffic deaths and injuries available (Rijkswaterstaat, 2015). By expressing the safety score into monetary terms, a comparison in weight can be made with user delay costs. There are also ratios and figures for the effects of noise nuisance. For the sub-indicators 'load class' and 'height' it is a bit more complex to express them in monetary terms, because there are no ratios or figures available for them. A possible solution could be to look into the average user delay costs that occur as a result of trucks that need to use a longer, alternative route due to height or weight restrictions.

More focus on underlying road network

The road network that is under the management of Rijkswaterstaat mainly consists of the large highways in the Netherlands. These cross other road networks such as roads from provinces or municipalities. These road networks are often referred to as the 'underlying road network' (in Dutch: onderliggend wegennet). As previously mentioned, for some indicators these road networks or roads have missing data (e.g. user delay costs). To include user delay costs of the road networks not under the management of Rijkswaterstaat, the national data warehouse for traffic information (in Dutch: NDW) can be consulted. Additionally, some indicators often have a worse score when the viaduct is part of the underlying road network. All of the viaducts that have a poor or fair score for the load class have a road on the deck that is managed by a municipality or province. Limitations in terms of height often occur when the road that goes under a viaduct is owned by a province or municipality. It is therefore important for Rijkswaterstaat that they not only focus on their own road network, but also the underlying road network. Here, collaboration and coordination with other road authorities seems to be inevitable. This is also an aspect that makes asset management more challenging (Sinha et al., 2017).

Additional indicators for functional performance

Beyond the used 5 sub-indicators, additional data and indicators can be used. It must be noted that the research of Cuendias González (2018) identified more performance indicators, this research is limited to the 5 performance indicators used in the pre-evaluation. Examples of additional indicators that are mapped by Cuendias González (2018) are maintenance hindrance and aesthetics. Although, these indicators would be more difficult to quantify based on data. Furthermore, for road sections, other performance indicators can be used. This research has adopted performance indicators from viaducts and has used these for road sections as well. It may be possible that road sections have other functionalities than viaducts.

5.2.2 Further research

The next recommendations suggest opportunities for further research.

Functional performance and link to replacement decision

One employee noted that it is a useful tool, but that implementing new aspects, such as these, within the decision-making process at Rijkswaterstaat is quite hard. As mentioned earlier, the scope of the tool is limited to integrating and visualizing the current functional performance based on indicators that derive from existing data sources. This is shown in Figure 5.1, where also the problem analysis, solubility analysis and other aspects are shown. A possible opportunity for further research is how to link the functional performance to a replacement decision. Therefore, the different steps to do so are explained again:

- Problem analysis: whether a poor functional performance of a sub-indicator is a large problem or has large consequences for the surroundings or users.
- Solubility analysis: whether the functional performance can be improved or will be improved by replacement or renovation, or that other interventions can also improve the performance (e.g. noise emissions: placing sound barriers).
- Aspects beyond functional performance: the technical condition, economic end of life indicator (EELI), political aspects, already planned replacement activities or aspects in the whole road network that play a role in the decision to replace the asset.

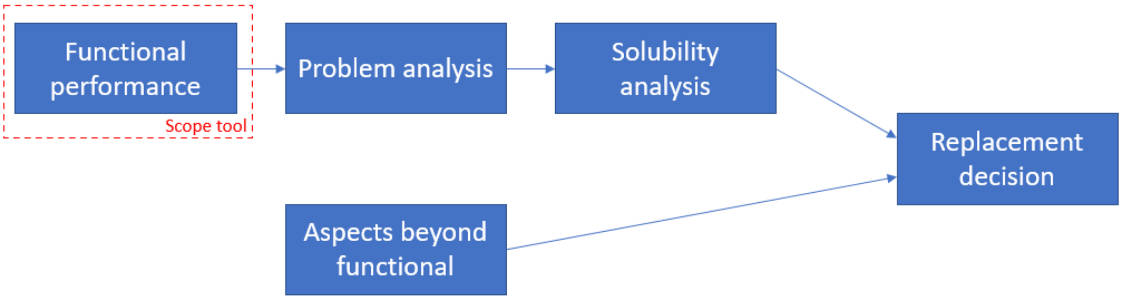

Figure 5.1: Scope of the tool and location within the decision to replace an asset.

Possibly, the problem analysis, solubility analysis and the other relevant aspects beyond functional performance can also be based on data. During the workshop, participants have been asked to give their opinions on this, which may be helpful for further research. These suggestions have been elaborated per sub-indicator.

User delay costs:
One can evaluate the effect on interventions on other parts of the road network. Improving the capacity in some areas of the network may lead to more bottlenecks in other parts of the network. This can, for example, be used in the solubility analysis of this indicator. Another solubility indicator that can be used is the possibility to expand a viaduct to add an additional traffic lane. In the problem analysis, other bottlenecks such as merging lanes can be used.

Height:
The consequences for a reduced height are less in a road network that is less important than in a road network that is an important traffic link. This can be seen as part of the problem analysis.

Load class:
While the load class did not receive feedback for the problem or solubility analysis, the importance of the road network is expected to be relevant, similar to the suggestion for the height.

Safety score:
A suggestion was to look at the consequences of an accident as well: a road with higher traffic intensities and a more important role in the network will lead to more user delay costs when an accident occurs that causes a traffic jam. Furthermore, the numbers themselves do not say enough, but analysis of the accidents (Dutch: ongevallenanalyses) give a more clear picture. This can help in the solubility analysis.

Exceedance of noise production limit
As previously indicated, an exceedance of the noise production limit on its own will not lead to the replacement of a viaduct. The interventions are limited to resurfacing the top layer or the placement of noise barriers. It is convenient to know where temporary exemptions are applicable, because a distinction can be made between two situations:

- An exceedance of the noise production limit where no temporary exemptions are applicable;
- An exceedance of the noise production limit where a temporary exemption is applicable.

In the first situation, Rijkswaterstaat has an obligation to bring the noise production level under the limit. In the second situation, Rijkswaterstaat does not have to improve the situation within the duration of the exemption (max 5 years). When making replacement decisions, it is important to know if there are other types of interventions planned. When there is no exemption and an exceedance of the noise production limit, one could expect future interventions and take this into account in the replacement decision. Table 5.1 provides a summary of the mapped indicators that could be used for the problem and solubility analysis.

Table 5.1: Overview of indicators that can be used in the problem and solubility analysis.

Sub-indicator	Problem analysis	Solubility analysis
User delay costs	Bottlenecks: merging lanes	Impact of interventions on other parts of the road network. Expansion opportunities
Height	Importance of road network	
Load class	Importance of road network	
Safety score	Importance of road network	Accident analysis
Exceedance of noise production limit		Temporary exemptions

<u>Aspects beyond functional</u>
Other aspects that are already implemented in the current decision to replace viaducts are for example the technical condition or other replacement activities in the road network. The economic end of life indicator (EELI) is another example that could be used when making a replacement decision. One employee noted that it is a challenge to incorporate this relatively new methodology into the decision making process at Rijkswaterstaat. This on its own can be a focus for further research, because this research does not dig deep into how these decisions to replace viaducts are made. However, we also acknowledge that there are some limitations in the current tool or methodology (e.g. data availability) and it would perhaps be better to first focus on these limitations.

Multi-criteria analysis
Future research can also focus on the relative weights of the different performance indicators. User delay costs seems to be a very important indicator for replacement decisions based on functional performance. The height and load class are also important indicators. Safety is a bit more complicated and the findings in this research question the relevance of this indicator for replacement decisions of viaducts. Firstly, after linking the data of accidents to viaducts, only a very limited amount of accidents could be linked to viaducts based on their location. This suggests that the probability that an accident occurs on a viaduct is the same (or lower) as the probability that an accident occurs on a normal road section. In line with this finding, several employees suggested to review safety on the road network level, instead of single viaducts or road sections. Secondly, the impact of a replacement intervention on the safety is limited and hard to predict. This is confirmed in cost-benefit analysis which predict the future impact of projects. These cost-benefit analyses can even predict a negative influence on safety of projects, when for example traffic intensities are expected to increase. Lastly, only an exceedance of the noise production limit will not lead to replacement of a viaduct. However, it is relevant to know, because it can lead to interventions other than replacement of a viaduct (e.g. new top layer on the asphalt).

As suggested by Cuendias González (2018), the relative importance of performance indicators is dependent on the location and context of the viaduct. A possible opportunity for developing the weights is to express the indicators in monetary terms. Another interesting perspective could be to divide the performance indicators into basic factors, performance factors and excitement factors (Matzler, Sauerwein, & Heischmidt, 2003):

- Basic factors lead to dissatisfaction of road users if not fulfilled, but no satisfaction if fulfilled or exceeded.
- Performance factors can cause both satisfaction and dissatisfaction of road users.
- Excitement factors only cause satisfaction when exceeded, but no dissatisfaction when not fulfilled.

The idea behind this division is that the importance of factors is dependent on the performance (Matzler et al., 2003). One could argue that the height of a viaduct is an example of a basic factor: when the height of a viaduct is for example only 3 meters this may lead to dissatisfaction because trucks cannot pass the viaduct. When two viaducts with a height of 5 and 7 meters are compared, there will probably be no significant difference in the satisfaction of road users. Almost all trucks can pass both types of viaducts, so the satisfaction of road users will not increase when the height is increased from 5 to 7 meters. The sub-indicator user delay costs is possible an example of a performance factor: dissatisfaction occurs when there are often traffic jams (high UDC), satisfaction can occur when there is a very limited amount of traffic jams.

Functional performance over time
This has been a reoccurring topic during this research, because the tool is limited to the current functional performance of assets. There have been many suggestions to include data about sub-indicators that predict the functional performance over time. There is a current performance for each sub-indicator, but it would be interesting to know how this performance develops over time. One could include data about the expected user delay costs in the future, also taking into account the construction of new highways which will reduce traffic jams in other locations. Appendix Q - Preview of the development of traffic flow in the future, shows how this looks like on a map, based on data that has been received during the design of the tool. For the exceedance of the noise production limit, there is data available that marks the expected year of future exceedance of the noise production limit. The load class is dependent on the future technical condition of a viaduct and safety can be predicted based on traffic intensities. The height of a viaduct is expected to be less sensitive to future changes, and may be affected by resurfacing of the top asphalt layer. Additionally, the performance of sub-indicators and therefore the overall functional performance can be improved with other interventions than replacement (e.g. new top layer, addition of traffic lane). If Rijkswaterstaat can include future predictions and a more network character in the functional performance methodology, it will move towards a more strategic level.

These recommendations will help Rijkswaterstaat to develop the functional performance further and implement it earlier, more integral and objectively in the decision to replace a viaduct or road section. It would be logical to first focus on the recommendations that fall within the scope of the current tool, so data availability and multi-criteria analysis. The next step would be the link between the functional performance and replacement decisions. After this, the methodology can be upscaled to include multiple assets at the same time and to consider the development of the functional performance over time. This part marks the end of the main part of this report, however, the appendices that follow provide more insight and depth in this research. Examples are a more detailed explanation of the used data sources and linking of the data.

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Appendices

Appendices – table of contents

Appendix A – Literature review visualizations

In order to help decision-makers and users of the tool interpret the data, visualizations are used. The type of data will determine the suitable data visualization method. Hence, first, different data types are identified. Data can either be qualitative or quantitative, where qualitative data describe properties and quantitative data can be counted or measured (Theisens, 2016). Qualitative data can further be divided among nominal and ordinal data. Both are categorical in nature, but nominal data (e.g. blood type or gender) has no natural order between categories, in contrast to ordinal data (e.g. raking or scale from 1 to 5). However, ordinal data cannot quantify the differences between the categories. Quantitative data can be divided into discrete and continuous data. Discrete data is countable and can only be an integer (e.g. amount of persons in a room). Continuous data can be measured and can also take values between integers. There are two types of continuous data: interval and ratio data. Interval data have a natural order and the differences among values are comparable (e.g. temperature in °C). However, there is no meaningful zero, so there is no possibility that value A is x-times larger or smaller than value B. Additionally, ratio data contain a meaningful zero (e.g. height of a person) and therefore value A can be a multiple larger or smaller than value B (Theisens, 2016). Figure A.1 provides a summary of this section. Having discussed the types of data, the next section will focus on data visualizations.

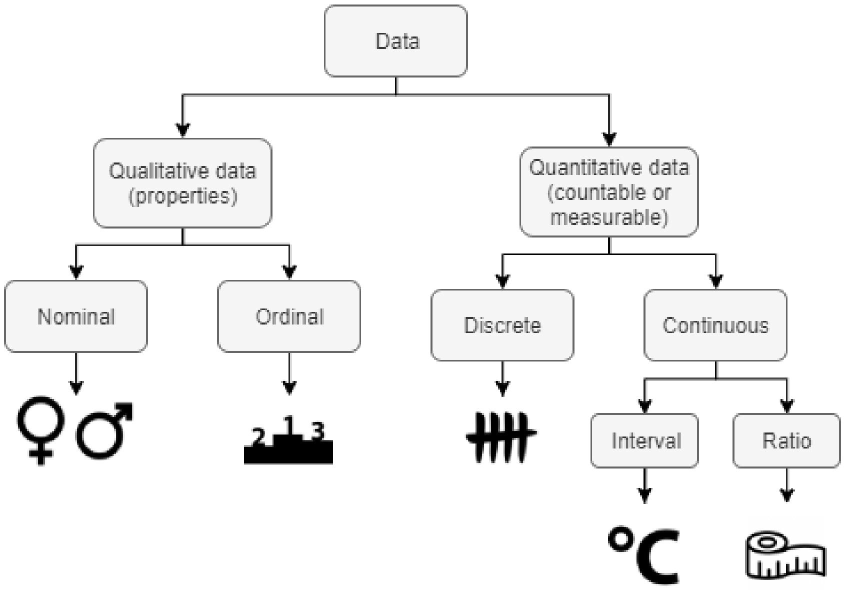


Figure A.1: Summary of the different types of data.

Data visualizations are commonly used for two main objectives. Firstly, to help people to formulate hypotheses regarding groups, trends and correlations. These can then be tested with further data collection and analysis. Secondly, to communicate conclusions or findings to other people (Theisens, 2016). People find it easier to interpret images and graphs than a raw data set (Theisens, 2016). The book written by Tufte (2001) provides some requirements for the graphical excellence of data visualizations, concerning the clarity, precision and efficiency of the visualization. Graphical displays should be able to:

- Present the data;
- Force the user to think about the displayed data and not about something else;
- Avoid giving a false impression of the data;
- Present a large amount of data in a small space;

- Create coherence among large data sets;
- Encourage people to compare several parts of the data;
- Present the data at multiple levels of detail: from a broad overview to very detailed;
- Benefit a purpose, for example, tabulation, decoration, description or exploration;
- Match and integrate with the verbal and statistical descriptions of the data.

There exist numerous methods to visualize data. Perhaps the most common and simple form of data visualization is a table, where data is arranged in rows and columns. Another simple visualization method is the use of colors, where color gradients are used for data with a natural order (e.g. the number of people living in an area) and distinctive colors for categorical data (e.g. most common religion in an area). Two examples of color visualizations are shown in Figure A.2.

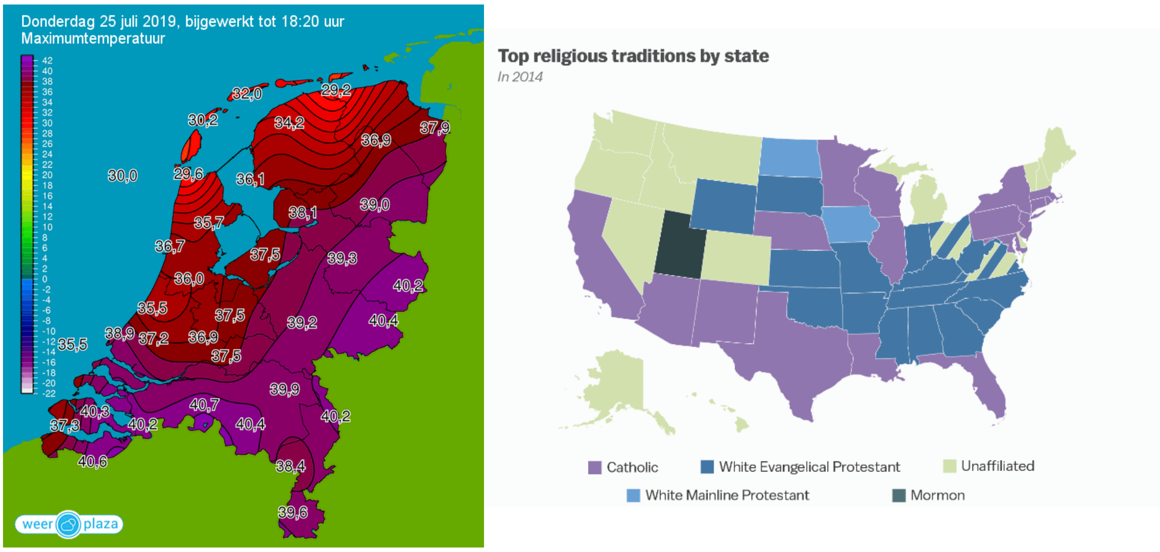


Figure A.2: On the left: use of color gradients for temperatures in °C (interval data) source: weerplaza. Right: most common religion (nominal data) in the United States of America, per state (source: public religion research institute).

In a histogram, observations are divided among intervals or categories, where every interval is represented by a bar that reaches a certain frequency of observations on the y-axis. A box plot can be used to give a summary of the distribution of data (Theisens, 2016). The lowest value, lower quartile, median, upper quartile and the highest value are indicated in a box plot. By combining boxplots of multiple data sources, one can make a comparison of the distributions. An example of a histogram and two boxplots are shown in Figure A.3.

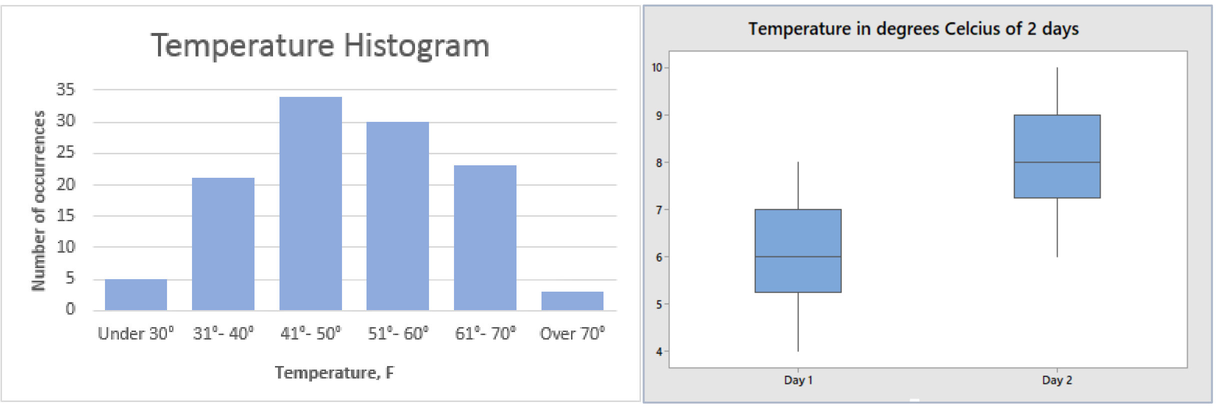


Figure A.3: Left: Example of a histogram. Right: example of 2 boxplots comparing the temperature during 2 days.

Another example of a more advanced data visualization method is a pie chart, which presents the proportion of categories and can indicate the size of each category (Theisens, 2016). Additionally, radar plots, also known as a radar chart or spider chart, can be used to visualize multivariate data (Saary, 2008). Multivariate analysis is known as the analysis of multiple variables at the same time. In a radar plot, multiple spokes, each representing a score level are shown. The radar plot is made by scoring each variable at a certain level, depending on the length of the ray and connecting these, which creates an enclosed figure (Saary, 2008). A radar plot can contain multivariate data for multiple alternatives, which enables a comparison of multiple alternatives on multiple variables at the same time. A combination of a pie chart and a radar plot is known as a pie radar chart. The difference with a radar chart is that scores are indicated by the size of the pie or triangle, instead of the length of the ray. Additionally, the relative importance of variables is indicated with the size of a surface. Another advantage of a pie radar chart is that in general, it is easier for people to identify the size of a surface than the length of a ray. A limitation of a pie radar chart compared to a radar chart is that it can only show one alternative at the same time. Figure A.4 shows a pie chart, a radar plot and a pie radar chart.

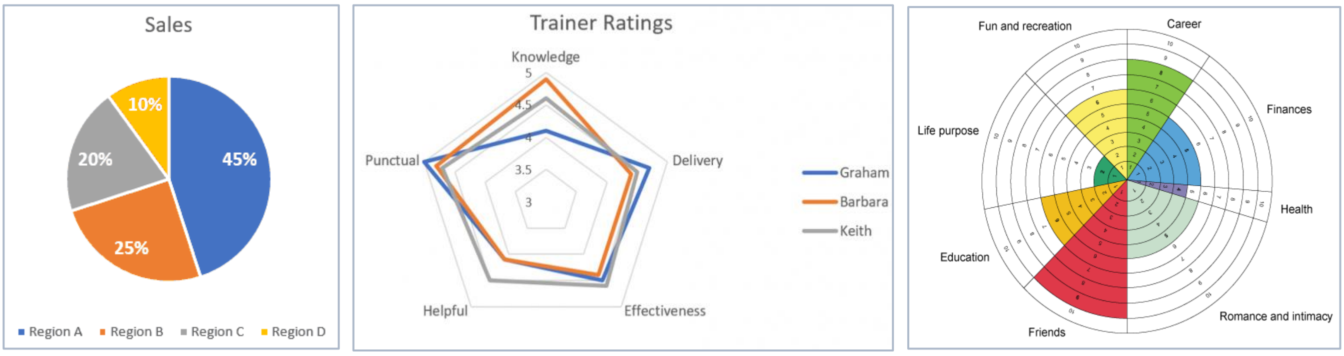


Figure A.4: Left: standard pie chart which shows the percentages of sales across regions. Middle: Radar plot with ratings of a trainer on multiple qualities given by three people. Right: Pie radar chart showing the satisfaction of a person on different categories.

Appendix B – Expert opinion workshop

In the expert opinion workshop, experts have been asked to imagine how the very first draft of the tool can interact with the given problem context (replacement and renovation). This very first draft consisted out of the existing V&R viewer on the maptable which contains the theoretical replacement year and the economic end of life indicator (EELI). The visualization of functional performance indicators from the viaduct analyzed by Cuendias González (2018) has been added to the map. This viaduct has been chosen because the needed data for the functional performance was already available in the report of the indicated research. Figure B.1 shows the visualization in ArcMAP. During the conversion from ArcMAP to Phoenix the icons were unfortunately not available on the maptable during the workshop.

Figure B.1: Visualization of the functional performance indicators (in Dutch) in ArcMAP. Location is the Schielandweg viaduct over the A20, between Gouda and Rotterdam.

Objective workshop

The objective of the workshop is to take the employees of Rijkswaterstaat to the problem context (replacement decisions within V&R) in order to get feedback and generate ideas about requirements and functionalities of the tool. Therefore, the combination of expert opinion, the maptable and the example viaduct seem to suit this objective. The example viaduct gives a practical example and helps the employees to transfer to the problem context. The maptable enables the group character of the session: multiple people can look at the data at the same time. In this manner, expert opinion gets a group character, and groups can combine and improve their ideas and generate them faster. These aspects are often the idea behind brainstorming (Rowatt, Nesselroade jr, Beggan, & Allison, 1997). Additionally, the maptable is a helpful tool to trigger the expertise of employees and questions related to underlying data or information (Eikelboom, 2015).

Description workshop

During the preparation of the workshop, the data and visualization of the functional performance indicators have been prepared in ArcMAP. This shapefile has been transformed into a file that could be used within Phoenix on the maptable. Participants of the workshop have been invited via email, eventually, eleven people participated in the workshop. The structure of the workshop was threefold: an introduction, exploring the maptable and a wrap-up.

The introduction has been used to provide background information about the relevance of the research, previous research executed and the objective of this research. After the introduction, the maptable has been used to show the geographical data and the author explained the existing data and the example viaduct. This led to the first opinions, ideas and discussions among participants. When necessary, the researcher asked additional questions and made sure that everyone could tell their opinions and indicated the scope of the research. In the meantime, a colleague made notes of opinions and discussions. The workshop ended with a wrap-up, where the opinions and ideas have been summarized on a flip over. This was used to guarantee that the researcher understood the ideas of the participants correctly.

Results

The results on the flip-over have been compared with the notes and observations from colleagues. This resulted in the following requirements.

Requirement 1: The tool should be able to switch between operational, tactical and strategic levels.

The tool should facilitate switching and interaction between the operational level, tactical and strategic levels. To put it differently, it must be possible to analyze individual assets and a group of assets.

Visualization of the tool should also be dependent on the user of the tool: at the strategic level or the management board level, the visualization should be more unambiguously. The functional performance is either perfect, good, fair or poor, which can be indicated by the use of a color gradient (e.g. green is perfect, red is poor). At the operational level, an expert wants to explore the data of a specific viaduct. He or she wants to know why a certain score is given, based on for example a performance indicator. Additionally, the data behind the performance indicator can be consulted. This means that the tool must be able to link to other databases existing within Rijkswaterstaat, such as RUPS and DISK. DISK is the management and information system of the assets of Rijkswaterstaat and is mostly used for conservation plans. RUPS is used to plan maintenance activities uniformly within Rijkswaterstaat. The requirement matches the description of graphical excellence which can be achieved by presenting the data at multiple levels of detail (Tufte, 2001).

Requirement 2: The tool should be expanded with additional data sources and visualization.

Participants of the workshop indicated several other data sources that could be included in the spatial decision-support tool as layers. The current replacement and renovation prognosis, MIRT and ‘Netwerkschakelplannen’ are examples mentioned during the workshop. MIRT is an executive plan of the Dutch government, which also includes projects from other ministries. Netwerkschakelplannen (Dutch) are management plans of a specific homogenous part of a road network. Additionally, participants indicated that the mapping of incidents can be used as a measure of safety and to use data that are used on maps for the planning and navigation of exceptional transport. Lastly, for the I/C ratio that was shown the direction of the traffic flow was missing and should be added.

Requirement 3: The tool should facilitate interaction and selection of categories of data.

Several statements, opinions and ideas during the workshop can be grouped under the third requirement. Participants indicated that it would be useful if the categories of the functional performance indicators could be changed and that the visualizations change according to them. Furthermore, a suggested functionality was to make a selection of data and then download this data for further analysis. This functionality resembles querying in geographical data: asking a GIS to retrieve data. An example is to select all viaducts in road network x with a poor functional performance.

It must be noted that not all examples that have been mentioned can be included in the tool. This is due to technical limitations of the tool. Some other suggestions for requirements or functionalities were beyond the scope of this research and therefore not included in the results above. An example is the addition of future predictions of performance indicators. This would be a valuable contribution, but this research is limited to the current performance of functional performance indicators. To conclude, the expert opinion workshop proved to be a valuable contribution to the requirements of the tool.

Appendix C – Tables requirements specification and functional analysis

Table C.1: Requirements specification and functional analysis.

Nr	Name	Requirement	Function	Object
1.	Data			
1.1.	Data integration	The tool should integrate data sources of multiple performance indicators	Integrate data sources	Data sources
1.2.	Data sources	The tool should contain data that indicate the overall performance of performance indicators and that are specific enough	Indicate performance	Data sources, sub-indicators
1.3.	Completeness	The tool should at least contain data that indicate the current performance of all used performance indicators	Indicate performance	Sub-indicators
1.4.	Data quality	The tool should contain data with the desired quality to assess the functional performance	Contain medium-quality data	Data, metadata
2.	Visualization			
2.1.	Interpretation	The data in the tool should be easy to interpret by decision-makers and users	Visualize data	Metadata, color use, line thickness, legend
2.2.	Validity	The visualization should lead to valid conclusions about the data	Visualize data	Colour use, line thickness, legend
2.3.	Level of detail	The visualization should show the data on different levels of detail	Visualize data	Zooming in and out functionality, visualization of performance sub-indicators, visualization of functional performance of individual assets
3.	Interaction			
3.1.	Selection	Users should be able to see, select and explore data of specific viaducts and road sections	Show data	Data, click functionality
3.2.	Selection	Users should be able to select certain parts of the data	Select data	Selection functionality, query

Appendix D – Explanation I/C-ratio

In previous research (Cuendias González, 2018; Xie, 2017), the I/C-ratio has been used to evaluate the traffic flow. During this research, the I/C-ratio proved to have difficulties in terms of validity. The I/C-ratio is a dimensionless number obtained by dividing the traffic intensities by the capacity of a road section.

The traffic intensity (vehicles per hour) is related to the traffic density (vehicles per km[1]) and the average speed (km/hour). This is known as the fundamental relation of traffic flow (Immers, Tampère, & Logghe, 2010), shown in equation D.1.

$$q = k * u \tag{D.1}$$

Where:

q = intensity

k = density

u = average speed

Based on this relation, three special scenarios can be distinguished:

- A: free flow of traffic: in this situation vehicles are not hindered by other vehicles and can achieve their maximum speed (u_f), based on speed restrictions (e.g. 120 km/h) and the design of the road. In this scenario, the intensity (q) and the density (k) will approach zero.
- B: complete congestion: the density (k_c) is maximal, but the intensity (q) and the average speed (u) are zero. Thus, vehicles come to a complete stop.
- C: maximum capacity: a scenario where the maximum intensity (q_c) of a road section is achieved. In this case, the capacity speed (u_c) is a little below the maximum speed. This capacity speed is often 90 km/h. In this case, the I/C-ratio is 1.

These scenarios can be plotted in one of the three fundamental diagrams, which is shown in Figure D.1. In this diagram, the horizontal axis represents the intensity (q) and the vertical axis shows the average speed (u). The density (k) is obtained by the angle, when vehicles have a higher average speed, the angle and therefore density will be smaller.

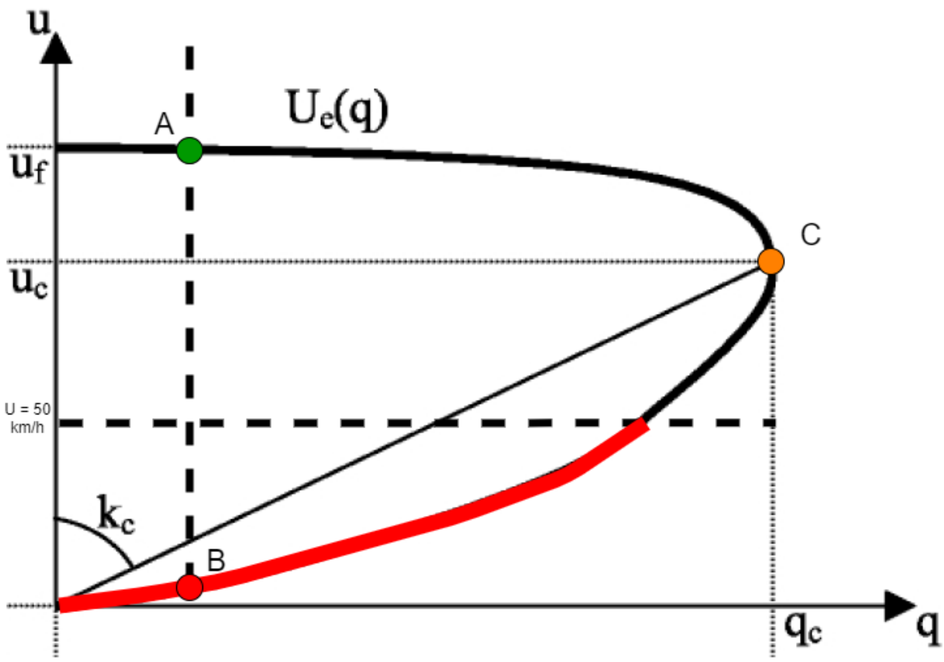


Figure D.1: Fundamental diagram from (Immers et al., 2010) with on the horizontal axis the intensity (q) and on the vertical axis the average speed (u). The angle (k) with the vertical axis is the density. The red line indicates situations where a traffic jam occurs.

The capacity of a road can be influenced by for example rainfall and daylight (Chung, Ohtani, Warita, Kuwahara, & Morita, 2006), but remains relatively constant over time. The difficulty with drawing valid conclusions from the I/C-ratio alone is that the traffic intensities can be low due to (1) a low density or (2) a low speed. In the first case, the situation is a free flow of traffic, wherein the latter, there is heavy congestion. Previous research of Cuendias González (2018); Xie (2017) links a lower I/C-ratio to a smooth traffic flow. However, this conclusion is not valid when the average speed of vehicles is low (due to a traffic jam) and therefore the traffic intensities and the I/C-ratio as well. Additionally, an I/C-ratio close to one does not indicate a traffic jam either. An I/C-ratio of one does correspond more with situation C: maximum capacity. The average speed when the capacity is maximum is often around 90 km/h, while a common threshold used for traffic jams is an average speed below 50 km/h (indicated with a red line in Figure D.1).

Additionally, it is hard to assess the capacity of highways, especially at locations where traffic is merging and exiting. This results in a large number of sideways movements, which restrains the capacity of these traffic lanes compared to standard traffic lanes. Additionally, this will also influence the downstream traffic flow. Rijkswaterstaat has developed a map that contains geographical data about the I/C-ratio. However, this map determines the capacity of roads based on the number of traffic lanes and thus does not take into account differences in capacities between normal traffic lanes and traffic lanes with merging and exiting traffic, or rush hour lanes. Hence, the map came with a clear disclaimer to use the values only indicative. The data in the map has been compared with the I/C-ratio originating from 'Netwerkschakelplannen', which is a report with future plans for a part of a road network. This comparison showed that the values from the map were significantly different than the values in the Netwerkschakelplannen (Kruitwagen & Dalen, 2016; Rijkswaterstaat, 2017). The question then arises what we can conclude from the I/C-ratio. If the line is analyzed in Figure D.1, from situation A (free flow) to situation B (complete congestion), it can be concluded that almost all traffic jams are preceded by a high I/C-ratio. Exceptions are a sudden loss of capacity due to for example an accident, and as a result, closing of a traffic lane. However, the other way around, not almost every situation where a high I/C-ratio occurs leads to a traffic jam. Traffic jams only occur when the density of vehicles further increases from situation C. To conclude, the I/C-ratio itself is not a clear indicator of the traffic flow. However, the amount of times the I/C-ratio reaches a high value (I/C-ratio > 0,95) in a certain time period can be used as an indicator of traffic flow. The main weakness of this theory is that not every time a high I/C-ratio occurs, this will lead to a traffic jam or a decreased traffic flow. These difficulties leaded to the use of UDC as the sub-indicator for the traffic flow.

Appendix E – Description data sources

This appendix describes the data sources used for each sub-indicator. These are mapped after the identification of the sub-indicators. Also the process of searching and developing the relevant data sources will be described. The search for data has been done using multiple strategies:

- Servicedesk data at Rijkswaterstaat;
- Data available in online maps (geoweb viewers);
- Open data available on the website of Rijkswaterstaat or the national geo-register;
- Data available in the workspace at Rijkswaterstaat;
- Department specialized in the management of data.

Traffic flow

Traffic flow is defined as whether the viaduct or road has enough capacity to carry the traffic. The used sub-indicator for traffic flow are user delay costs (UDC). The idea behind this indicator, compared to other indicators, is that not only the amount of traffic jams are recorded, but also their impact on the society. In the past, UDC have been used for example in cost-benefit analysis for the expected impact of a new project. However, the purpose to use it to evaluate the current performance of the network is relatively new. This is mostly done in the past based on the severity of traffic jams or vehicle delay hours. The indicator 'UDC' is also known as the new highway indicator (in Dutch: hoofdweg indicator or HWI).

An advantage of user delay costs are that the consequences of congestion are partly considered by indicating how many vehicles are affected. This favors user delay costs over the severity of traffic jams, which is sometimes also used to evaluate the traffic flow. The severity of traffic jams is calculated by multiplying the length with the duration of a traffic jam and is often given in the unit kilometer-minutes (kmmin). A limitation is that this quantity does not take into account the number of traffic lanes. Lastly, user delay costs can be used as indirect costs within asset management, because they reflect the costs for the users. The data of the user delay costs will be divided into four categories (perfect, good, fair or poor). The data is divided among road sections with different lengths. In order to compensate this, the user delay costs are divided by the length of a road section.

In order to determine the user delay costs, first, the vehicle delay hours need to be determined. For the vehicle delay hours, two datasets are available within Rijkswaterstaat. The two datasets are analyzed, where after the choice has been made to use the dataset that collects the vehicle delay hours based on traffic jams. The explanation of the analysis of the two datasets is available in Appendix F – Vehicle delay hours datasets.

Based on the vehicle delay hours, the user delay costs can be calculated with equation E.1:

$$UDC = VDH * VoT \tag{E.1}$$

Where:

UDC = user delay costs

VDH = vehicle delay hours

VoT = value of time, social benefits caused by reduction of travel times or extra costs of travel time delays

According to Rijkswaterstaat (2018), travel time delay (or VDH) occurs when a vehicle cannot achieve the reference speed of 100 km/h. Hence, not all vehicle delay hours are occurring in a traffic jam (speed lower than 50 km/h), but traffic jams account for 63% of the vehicle delay hours (Rijkswaterstaat, 2018). The other part of the vehicle delay hours are occurring when travel speeds are still above 50 km/h, this occurs often shortly before and after congestion.

Several studies and reports have studied the value of time (Bates, 2012; De Jong et al., 2014; KiM, 2013; Kouwenhoven et al., 2014) and have utilized stated-preference questionnaires. Respondents have been asked to choose their preferred alternative of two trips, where the difference was the travel time and costs of a trip. These studies have made a clear distinction between the value of time of cars and trucks. The VoT for trucks is significantly higher than the VoT for cars. As a result, a traffic jam with more trucks in it will have larger economic damage. Hence, equation E.1 needs to be further divided into equations E.2; E.3 and E.4 to accurately compute the user delay costs.

$$UDC_{total} = UDC_{cars} + UDC_{trucks} \tag{E.2}$$

$$UDC_{cars} = VDH_{cars} * VoT_{cars} \tag{E.3}$$

$$UDC_{trucks} = VDH_{trucks} * VoT_{trucks} \tag{E.4}$$

An additional dataset (INWEVA 2018) has been used to calculate the proportion of trucks and cars at road sections. This dataset provides data about the daily average traffic intensities during weekdays in 2018 and separates the traffic intensities for cars, medium trucks and heavy trucks. The percentage of car and truck traffic has been computed based on this data. The next step was to link these values to the vehicle delay hours dataset based on a common attribute or ID.

After linking the data, the total vehicle delay hours have been multiplied with the ratio of trucks and cars to obtain the vehicle delay hours for both trucks and cars. The value of time used to calculate the user delay costs are respectively €50,86 for trucks (Jonkers & Berne, 2019) and €12,53 for cars. The value for trucks is directly derived from the report of Jonkers and Berne (2019). The value of time for cars is also given in the report of Jonkers and Berne (2019), but is dependent on the motive of a trip. Therefore, these values were combined with results from research of CBS (2016), which provides insight into the proportion of trips based on motive. The calculation is shown in Appendix G – Calculation of the value of time for cars. The end result is a dataset with the user delay costs for every road section. Table E.1 provides an overview of the descriptive statistics of the user delay costs per km[1]. It can be seen that the mean and median differ, which is an indication that the data is skewed. The scatterplot in Figure E.1 confirms this, there are a couple of outliers in the dataset, which have very high user delay costs per km[1]. The main limitations of this dataset are:

- User delay costs of traffic jams are linked to the road section located at the beginning of a traffic jam. A traffic jam can occur at multiple road sections, but the UDC are only linked to one road section: the one located at the beginning of the traffic jam.
- There is no differentiation between user delay costs per traffic lane or user delay costs occurring at merging lanes, all UDC are linked to the main traffic lane.

Table E.1: Descriptive statistics of the dataset with user delay costs.

Variable	N	Mean	SE Mean	StDev	Minimum	Median	Maximum
User delay costs (€) per km1	2838	159608	9609	511877	0	35697	14417735

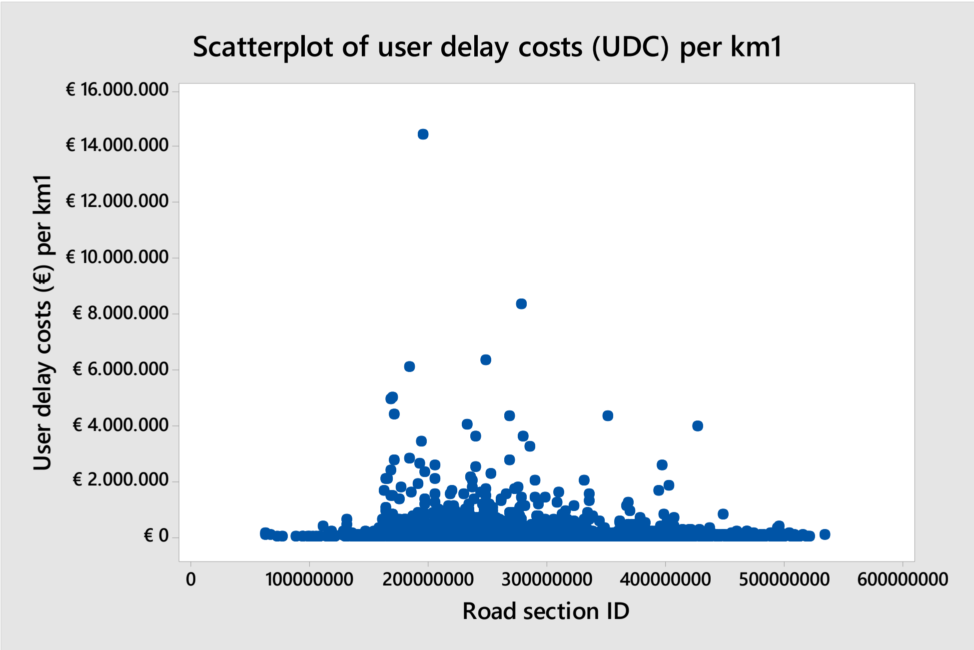


Figure E.1: Scatterplot of user delay costs dataset.

Geometry

The geometry reflects the adequacy of the dimensions of the viaduct or road and is reflected by the height of viaducts. Data about the height of viaducts proved to have difficulties with data availability at Rijkswaterstaat. Within the data information system for assets (in Dutch: DISK), there is data available about the length and width of a viaduct, but it does not contain the height of viaducts. For several road networks, Rijkswaterstaat has the height of the portals and viaducts on that road network. However, these are monitored using pictures, as shown in Figure E.2. Because of the fact that the name of the picture is a combination of the road network, the kilometer and the name of the viaduct, an automated link to GIS is not possible. An alternative would be manually linking each picture to each viaduct, but this is very work-intensive to do for all viaducts. Additionally, the coverage of these pictures is not very large: they are available for a limited amount of viaducts. This is explained by the motivation to make these pictures: they are used after a reconstruction or re-pavement project of a highway to check if the heights are in accordance with the agreed terms in the contract with the contractor.

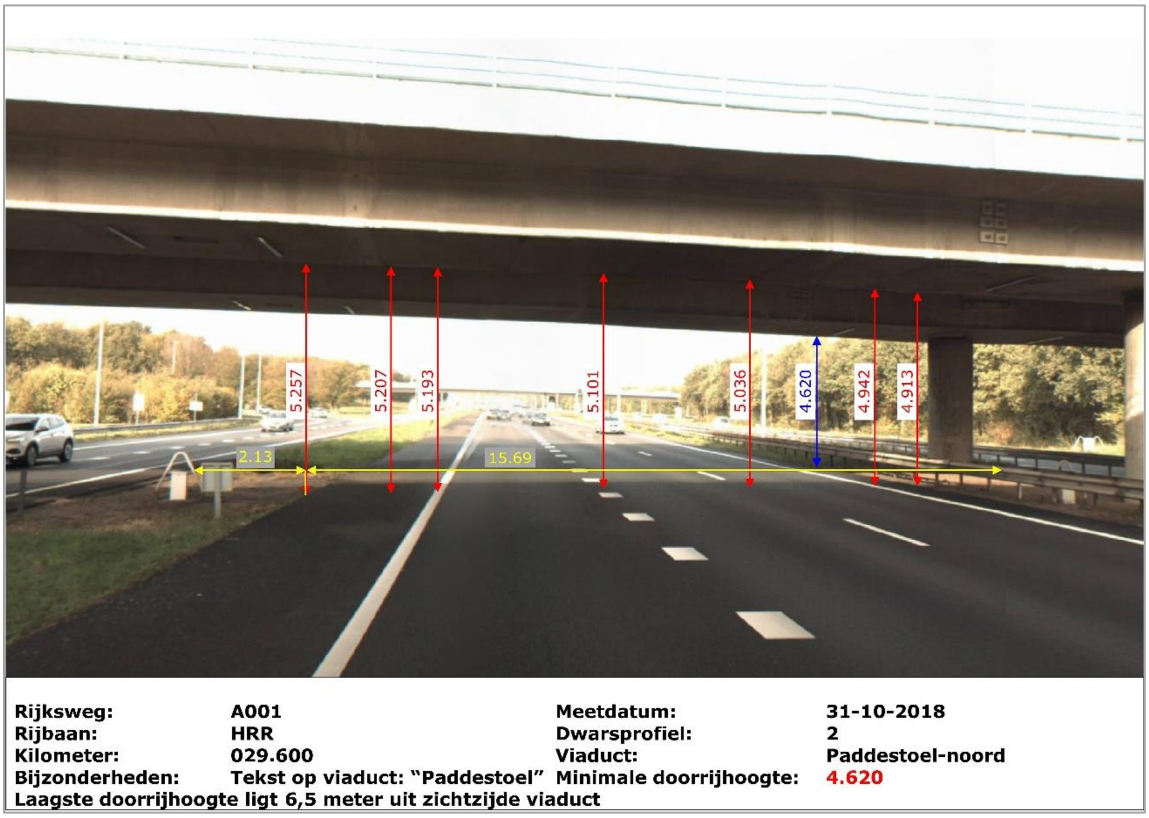


Figure E.2: Picture of a measurement of the height of a viaduct, the lowest value is indicated with a blue line.

An alternative dataset has been found at the RDW, the government service for road service in the Netherlands. They have an online viewer that can be used by for example transportation companies. Here, one can fill in the dimensions of the truck (height, but also width and weight), see where restrictions are applicable and plan a route from a start and endpoint. A screenshot of this viewer is given in Figure E.3.

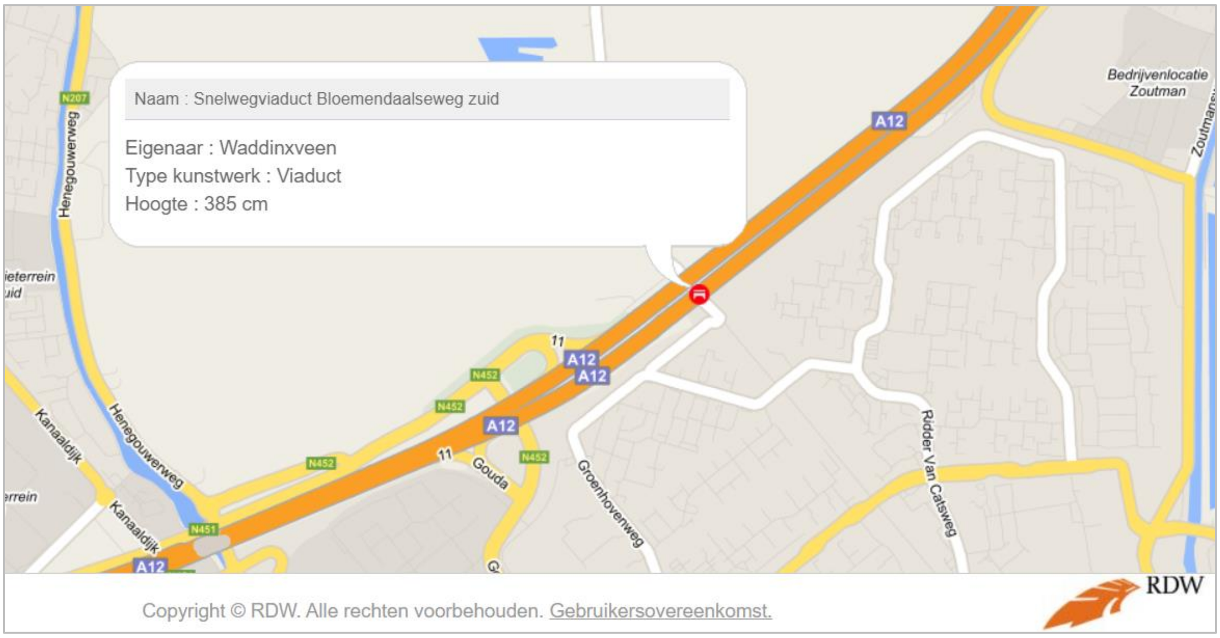


Figure E.3: Online viewer of the RDW. Source: https://dwo.rdw.nl/ConsultRestrictions/ViewRestrictions

A dataset has been provided by the RDW which contains the height of viaducts. This dataset does not only contain data about the viaducts of Rijkswaterstaat, but also for viaducts under the management of provinces and municipalities. An employee of the RDW has been asked via telephone calls and emails and explained the values in the dataset. The RDW receives the heights of the viaducts from road authorities (e.g. Rijkswaterstaat, provinces and municipalities) and combines these in one dataset. It must be noted that from the values they receive, they subtract 0,15 m and put these corrected values in the dataset. This can be explained by the increase in the height of a driving vehicle, compared to a vehicle that is at a stop. This is caused by the unevenness of a road and the suspension of a vehicle (Rijkswaterstaat, 2019). The limitation of this dataset is that it is used for exemptions. When a vehicle is higher than the maximum allowed legal height of 4,00 meters (RDW, 2012) the owner is obligated to apply for an exemption at the RDW. The RDW will then use the dataset to see which viaducts can be crossed by the vehicle. Therefore, the dataset has a very limited amount of viaducts with a height lower than 4 meters.

Load class

This performance indicator reflects whether the load class of a viaduct or road can fulfill the requirements. A load class that does not allow a certain vehicle weight can reduce the functionality of a viaduct. The load class and the geographical location of a viaduct are both available within DISK. From DISK, the data could be retrieved in an excel file with x and y coordinates which could be loaded into ArcMap and exported into a shapefile. During an inspection of the dataset, it appeared that there were sometimes multiple, different load classes within one asset. This is explained by the fact that one asset consists of multiple elements, which have individual load classes. However, after the analysis of a couple of assets, there were some strange values for these assets. For example, there was one viaduct with load class 30, which means that it is not suited for trucks. However, this viaduct was part of a highway and all highways in the Netherlands must be at least suited for trucks within legal restrictions. Therefore, the quality of the assets that have multiple different values has been questioned. For these assets, the load class has been changed to ‘multiple’, or ‘divers’ in Dutch. Within the dataset, the following categories are present:

- 60;
- 45;
- 30;
- A;
- B;
- C;
- NEN-EN 1991-2;
- NEN6706 (max);
- NEN6706 (specifiek);
- NULL (empty values);
- DIVERS (multiple different values).

The frequency of each category is shown in Table E.2, where load class ’60’ is the most common load class.

Table E.2: Frequencies for each category in the dataset.

Load class	Frequency
30	29
45	54
60	2059
A	95
B	13
C	16
DIVERS	79
NEN-EN 1991-2	110
NEN6706 (max)	169
NEN6706 (specifiek)	27
NULL	277
All	2928

Safety to users

The safety to users indicates if the safety to road users fulfills the requirements. As an indicator, the safety score has been used, based on the number of accidents in 2017. The accidents contained data about the consequences of each accident, with accidents limited to material damage, accidents causing injuries and accidents with a fatal ending. There are a huge amount of accidents limited to material damage in the dataset, which limits the possibilities to distinguish road sections based on these accidents. Therefore, these accidents have been removed from the dataset. Furthermore, the dataset is limited to accidents that occur at roads under the management of Rijkswaterstaat, so no accidents that occur at roads of a province or municipality. The number of accidents in the two datasets is 1553 for accidents with injuries and 69 for accidents with fatal consequences. For each accident, the kind of accident is one of the most explanatory variables in the dataset. Figure E.4 and Figure E.5 show the division of the accidents in the kind of accidents, for respectively accidents with injuries and a fatal ending. From these figures it can be seen that a large number of accidents are due to rear-end collisions or one-sided accidents. Other interesting values in the dataset are the maximum speed, amount of vehicles involved, type of vehicles involved and weather conditions.

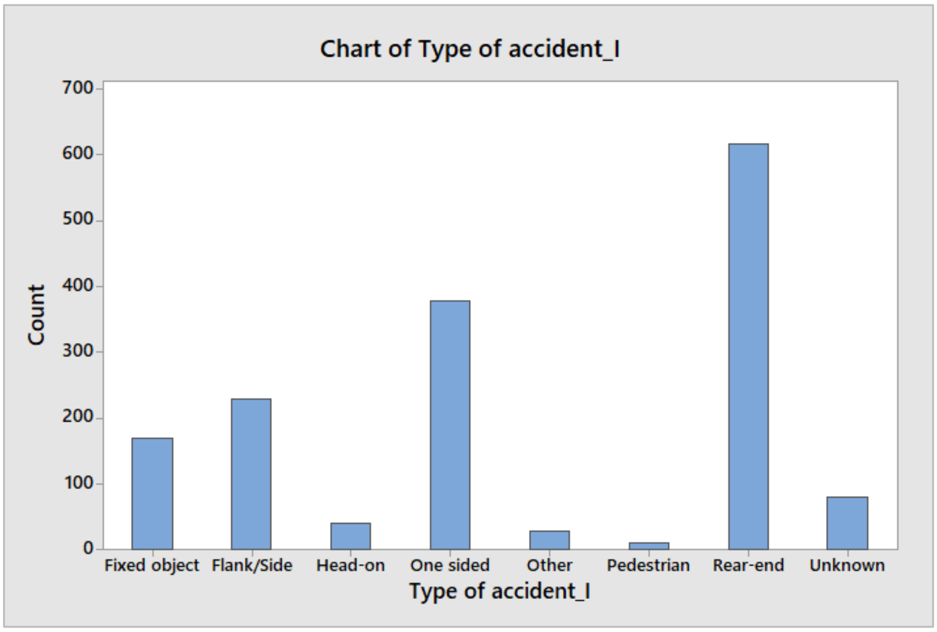


Figure E.4: Bar chart for accidents with injuries.

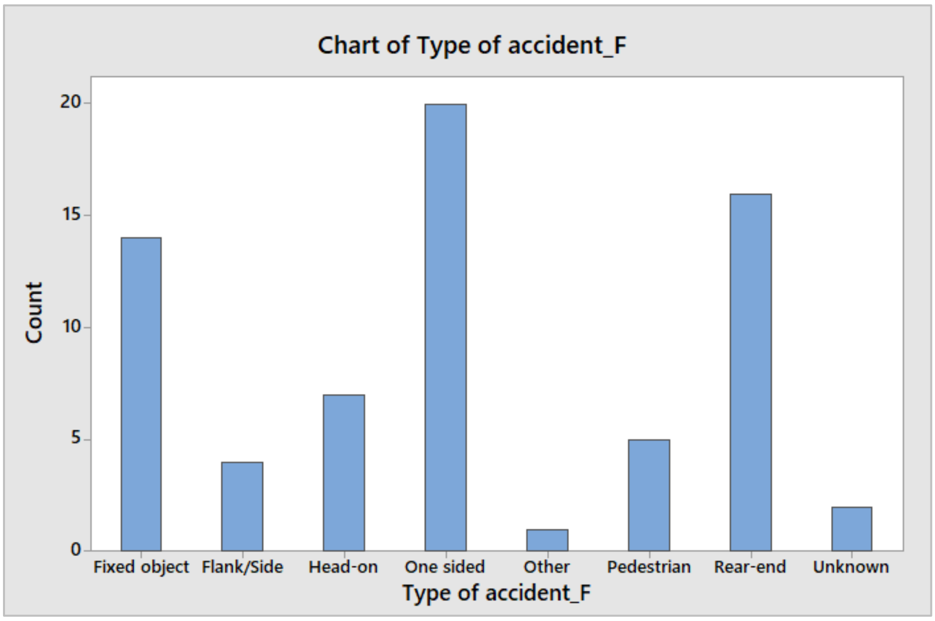


Figure E.5: Bar chart for accidents with fatal consequences. Please note that the counts on the y-axis are much smaller than in Figure E.4.

Noise emissions

This performance indicator reflects whether the noise emissions are according to the requirements and is reflected by the exceedance of the noise production limit. In order to evaluate this, two datasets are combined. Noise emissions of national highways are calculated with a model, named L_{den}, and expressed in decibel. L_{den} stands for the average noise level within a day (L). This is the average noise level during a whole year (2016) and has been calculated based on the type of road surface, traffic intensities, the speed and the presence of noise screens (Rijkswaterstaat, 2012). Within this calculation, the different periods within a day are divided into:

- in the daytime (d);
- evening (e);
- night (n).

Within the calculation, it is taken into account that the periods are not evenly distributed among the day. Additionally, the calculation includes that noise during the evening and night is more disturbing than the noise that occurs in the daytime. This is done by adding 5 decibels for the values in the evening and 10 decibels for the values in the night. The calculations are randomly validated by doing real measurements. Appendix H – Links to used open datasets provides a link to the L_{den} 2016 dataset, but the dataset in the link has the limitation that it is already divided into categories. Therefore, the original data has been obtained within Rijkswaterstaat. This is a very large dataset with the noise levels of more than 1,4 million points in the Netherlands among national highways. Hence, it is hard to determine which point(s) to pick when evaluating the noise emissions of a highway.

Luckily, the second dataset provides a solution, for the location of the dataset, see Appendix H – Links to used open datasets. The second dataset provides the location of approximately 60.000 reference points. These are used to determine the noise production limit (in Dutch: geluidsproductieplafonds or GPP) in a location. In most cases, reference points are located on both sides of a road at a distance of 50 meters from the road. The distance between them is 100 meters and the height is 4 meters above the ground surface. The general location of reference points is shown in Figure E.6.

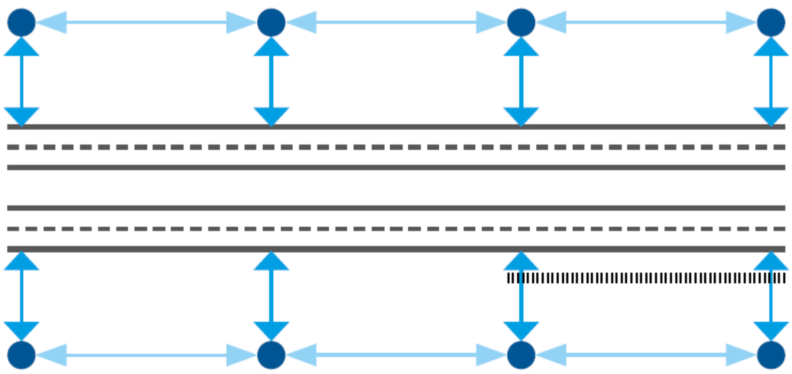


Figure E.6: Location of reference points along a road (Rijkswaterstaat, 2012).

These noise production limits are introduced in a new law in 2012, called 'SWUNG-I'. The idea behind this new law was that noise produced by national highways could not grow enormously. Furthermore, Rijkswaterstaat since then evaluates the noise produced by roads each year, and not only when constructing a new road or adding a lane to an existing road. In order to define the noise production limit, a fairly simple procedure has been used in 2012. A noise model (similar to the one used to calculate the noise produced in 2016) has been used to calculate the noise levels of 2012. This model uses similar input parameters as the 2016 model, such as traffic intensities, speed of traffic, type of road surface and noise reducing elements (Rijkswaterstaat, 2012). It must be noted that data from input parameters originates from 2008. The noise production limits are simply obtained by adding 1,5 dB on top of this noise model from 2012 (Rijkswaterstaat, 2012). Rijkswaterstaat thus has a legal obligation to keep the noise emissions of highways below the noise production level, but there are two exceptions. Rijkswaterstaat can opt to start a procedure to change the noise production level or can apply for an exemption (Rijkswaterstaat, 2012). In order to qualify for an exemption, two conditions need to be met. Firstly, noise emissions should be above the allowed production level due to special circumstances. An example is a long-lasting traffic diversion, which increases traffic intensities. Secondly, the exceedance should be temporary, when for example a decision to place noise fences in the future has been made already. Therefore, exemptions are given with a maximum duration of 5 years (Rijkswaterstaat, 2012). If there is an exemption applicable to a reference point, this is included in the dataset. A limitation of determining the noise production limit in this way is that characteristics of a location, such as population density, are not taken into account. The two datasets, the noise model from 2016 and the noise production limits, are combined into one dataset. This is described in Appendix I – Combination of the two datasets used for noise emissions.

Based on the combination of these datasets, the noise emissions can be compared with the noise production limit. This results in the sub-indicator exceedance of the noise production limit and is calculated using equation E.5. This calculation has been done in each reference point. A positive value means that there is an exceedance of the noise production limit, while a negative value translates a buffer to the noise production limit.

$$\Delta_{exceedance} = noise\ emissions - noise\ production\ limit \qquad E.5$$

Conclusion datasets

The process to retrieve data within Rijkswaterstaat proved to be challenging due to multiple factors. Data is available at the national departments, only at the regional districts and sometimes only outside Rijkswaterstaat (e.g. RDW). Also, the ability to use the data for this specific research is hard because data is often gathered with another purpose. An example is the height of viaducts collected by Rijkswaterstaat, which are used to check the work executed by the contractor after a project, and not to map the functional performance of assets. Lastly, it is sometimes unclear if data is allowed to be shared, especially if an organization besides Rijkswaterstaat is the owner of the data (e.g. provinces and municipalities).

Appendix F – Vehicle delay hours datasets

This Appendix described two datasets that could be used for vehicle delay hours (VDH) and the motivation to use the dataset that is based on traffic jams.

The vehicle delay hours can be based on two different data sources:

- Vehicle delay hours based on vehicle detection loops;
- Vehicle delay hours based on traffic jams.

The advantage of the first dataset is that it collects data for all vehicle delay hours, so also vehicle delay hours that occur outside of congestion periods. A traffic jam is defined as traffic with an average speed below 50 kilometers per hour with a length of minimal 2 kilometers. The disadvantages of the first dataset, compared to the second, are that it is limited to working days and does not cover all road sections in the Netherlands. Additionally, vehicle detection loops can be inoperative. Both datasets are covering the year 2018.

Vehicle delay hours based on vehicle detection loops

This dataset contains data about vehicle delay hours in an excel format. The detection loops use induction to detect vehicles, to measure the average speed of vehicles and to determine the average traffic intensities. Based on this, the dataset determines the average vehicle delay hours (VDH) for working days in 2018 for each road section. The first addition to this dataset is the conversion of the VDH to yearly values, by multiplying the average vehicle delay hours by 255 (the number of working days in 2018). Every road section also has a different length, in order to exclude this effect, the yearly values are divided by the length of each road section. This prevents that a very long road section will have the most VDH. Additionally, the dataset not only contains data about the total VDH, but VDH that occur during traffic jams are included as well. These are also calculated for the whole year and per kilometer. Furthermore, as a result of this division between total VDH and 'traffic jam VDH', the data can be triangulated. As mentioned earlier, The report of Rijkswaterstaat (2018) indicates that 63% of the total VDH occur during congestion or traffic jams. This percentage is calculated in the dataset to compare the dataset and to assess the reliability of the dataset. Firstly, the unreliable values in the dataset were left out of this calculation. Vehicle detection loops are not active during the whole year and as a result, do not collect data for the whole year. This is reflected in the dataset with a percentage for the missing data. The threshold commonly used for this dataset is that data with a percentage missing higher than 20 percent is defined as unreliable. The unreliable data has been excluded from the dataset and the percentage of VDH in traffic jams has been calculated, which resulted in 62%, very close to the indicated 63%.

The next step was to link the data in excel to a geographical dataset or shapefile. The data in excel contains for every road section the VDH and a number (ID) for every road section. However, geographical data about the location of the road sections are not available in excel. The road sections themselves were already available in a shapefile. Shapefiles do not only contain data about the attributes of objects, like the data in excel but also contain the location of the objects. The shapefile of the road sections contains the road section ID's, which match with the data in excel and are therefore used to link the data in excel to the existing shapefile. Subsequently, a new shapefile has been made which contains data about the VDH which is used in Arcmap. Afterwards, the data has been visualized and the unreliable data has been excluded from the visualization. The result is shown at the left side of Figure F.1, which shows the VDH occurring during traffic jams per kilometer, based on detection loops.

Vehicle delay hours based on traffic jams

The other way to calculate vehicle delay hours is based on data about vehicle delay hours in traffic jams. Again, an excel database is the starting point with data about all traffic jams (almost 150.000) in the Netherlands in 2018. In this excel file, the vehicle delay hours were already calculated based on the average speed and density of vehicles. The most common causes of traffic jams are a high traffic intensity (66%) and accidents (19%) (Rijkswaterstaat, 2018). Other causes of traffic jams are incidents (e.g. breakdown of vehicles, loss of cargo) and roadworks (Rijkswaterstaat, 2018). The cause of each traffic jams was also available in the dataset, so data was included with all VDH and with VDH limited to the cause 'high traffic intensity'.

The idea behind the second option is that replacement of a viaduct or road will not solve all accidents (which cause traffic jams) that occur. Sometimes accidents occur due to a lack of concentration of road users or extreme conditions. On the other hand, one could say that a road section where a traffic jam occurs due to an accident has not enough residual capacity. The remainder of this report uses the VDH with all causes included. The VDH of the traffic jams were linked to a specific road section with a unique ID and a known location in GIS. Then, the VDH were summed for every road section to get the total VDH per road section for the whole year. The road section ID's in this dataset have a different reference date than the ones used in the VDH based on detection loops. Therefore, the data has been linked to a different shapefile. After this, the VDH have been divided by the length of each road section to nullify the effect of the length of a road section. The results are again the VDH per kilometer and these are visualized using the same categories as the VDH from the detection loops. These are shown on the right side of Figure F.1. A comparison between the data calculated based on vehicle detection loops and traffic jams can be made based on Figure F.1.

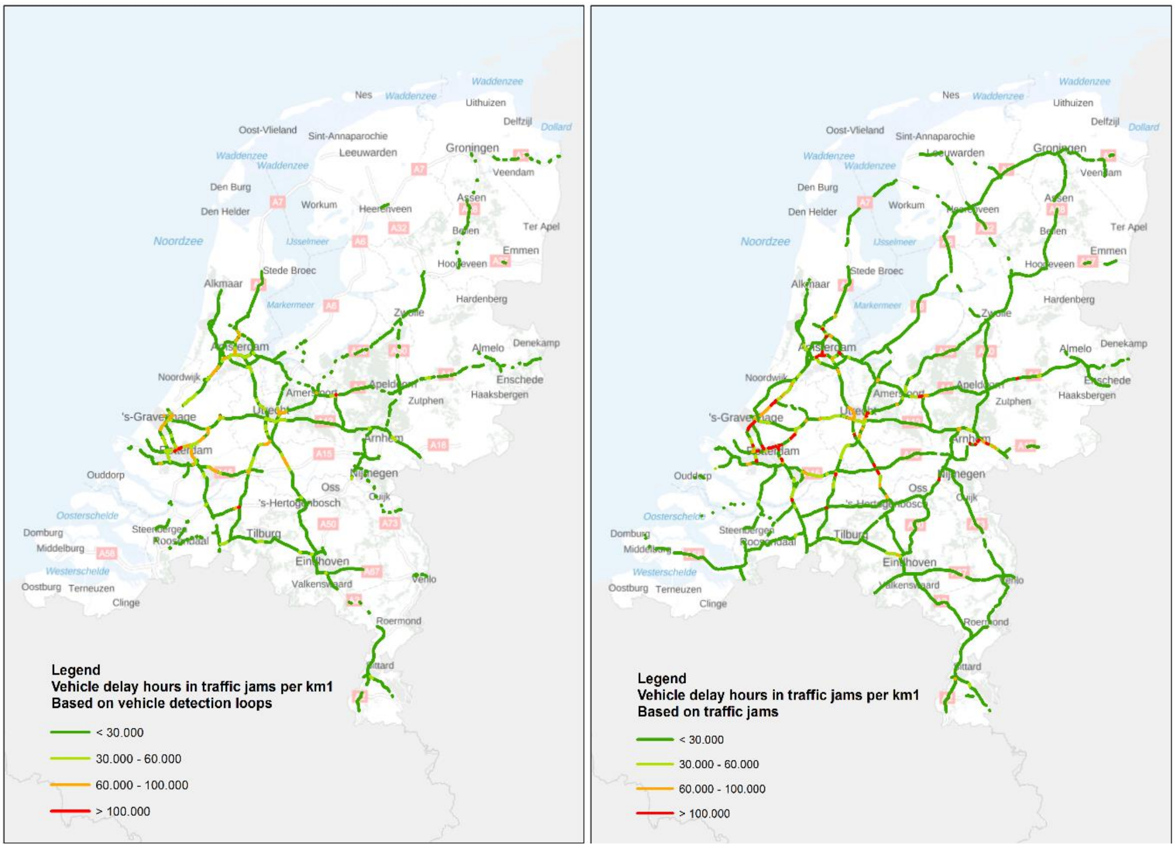


Figure F.1: Vehicle delay costs based on two datasets: data originating from vehicle detection loops (left) and data from traffic jams, with all causes (right). Note that unreliable (left) and null (both) results are excluded from the visualization.

Road sections with zero vehicle delay hours are excluded from both visualizations in the maps of Figure F.1. It is apparent from this figure that the shapefile with vehicle delay hours based on traffic jams contains more road sections with high values (>100.000 hours). A logical explanation for this is that the dataset based on vehicle detection loops is limited to working days in 2018 (255), the dataset based on traffic jams includes traffic jams during weekends and holidays as well. Another aspect that stands out is that the coverage is significantly larger in the visualized data based on traffic jams. This is especially visible in the Northern parts of the Netherlands. This is caused by the great number of null values in the dataset based on vehicle detection loops. The impact of unreliable values on the coverage of the dataset is relatively limited. Additionally, it is easier and more accurate to calculate the user delay costs based on the VDH dataset that is based on traffic jams. This dataset can be linked directly to the INWEVA dataset with the percentages of trucks and cars. Based on the larger coverage and the fact that user delay costs can be calculated more easily and accurately, the choice has been made to use the dataset with VDH based on traffic jams.

Appendix G – Calculation of the value of time for cars

This Appendix will show how the average value of time has been calculated for cars. This is for example dependent on the travel motive. First, the percentages per travel motive, divided into 'between home-work', 'business' and 'other' have been calculated, based on numbers from CBS (2016). This has been done for weekend/public holidays and regular working days and shown in Table G.1.

Table G.1: Percentages per travel motive.

Travel motive	Amount of trips (Weekend/public holidays)	%	Amount of trips (Working days)	%
Between home and work	3016	**12,22**	34922	**44,28**
Business trip	829	**3,36**	15048	**19,08**
Other	2774	11,24	7611	9,65
Other	202	0,82	2489	3,16
Other	17867	72,37	18803	23,84
Total other	20843	**84,43**	28903	**36,64**
Total	24688		78873	

These percentages are then used to calculate the weighted average based on the value of time and the travel motive, which is shown in Table G.2 and Table G.3. The value of time for each travel motive originates from Jonkers and Berne (2019).

Table G.2: Weighted average for the value of time (VoT) for weekend and public holidays.

Weekend and public holidays			
Travel motive	Value of time	Weighting	Score
Between home and work	€ 10,42	0,12	€ 1,27
Business trip	€ 32,08	0,03	€ 1,08
Other	€ 8,45	0,84	€ 7,13
Weighted average VoT working days:			**€ 9,48**

Table G.3: Weighted average for the value of time (VoT) for working days.

Working days			
Travel motive	Value of time	Weighting	Score
Between home and work	€ 10,42	0,44	€ 4,61
Business trip	€ 32,08	0,19	€ 6,12
Other	€ 8,45	0,37	€ 3,10
Weighted average VoT working days:			**€ 13,83**

The last step is to take the ratio of working days versus weekend and public holidays into account. There are 255 working days and 110 weekend and holidays, thus 70% working days and 30% weekend and holidays. Based on this, the weighted average for the value of time for cars can be calculated in Table G.4. The VoT for cars is €12,53; this is a little bit higher than the value obtained by KiM (2013). This can be explained by using a higher value of time for the different travel motives.

Table G.4: Weighted average for the value of time for cars.

	VoT	Weighting factor	Score
Working days	€ 13,83	0,70	€ 9,68
Weekend and public holidays	€ 9,48	0,30	€ 2,85
Weighted average VoT for all days:			**€ 12,53**

Appendix H – Links to used open datasets

1. RDW dataset, used for the height of viaducts: inspire.rdw.nl/www/download/data/Beperkingen_voor_Voertuigen_28992.zip
2. L_{den} dataset, not used directly but it gives an impression of the data: http://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/9b583730-e750-485a-9c0c-39bf9be72cf8
3. Geluidregister, used for the location of reference points for noise emissions: http://www.nationaalgeoregister.nl/geonetwork/srv/dut/catalog.search#/metadata/asjkqr40-2n54-rc8s-wlr9-92peqgr7r28q

Appendix I – Combination of the two datasets used for noise emissions

This section describes how two datasets are combined into one dataset, used for the noise emissions. The two datasets are:

- Noise model from 2016;
- Noise production limits in reference points.

The location and the noise production limit of the reference points have been used as a starting point. To this dataset, the noise emissions from the noise model from 2016 have been added. This is executed using a spatial join in Arcmap, where the L_{den} value of a point in the 2016 dataset that is closest to the reference point is added to the reference points dataset. The spatial join also adds the distance between the reference point and the 2016 dataset. The two datasets are shown in Figure I.1.

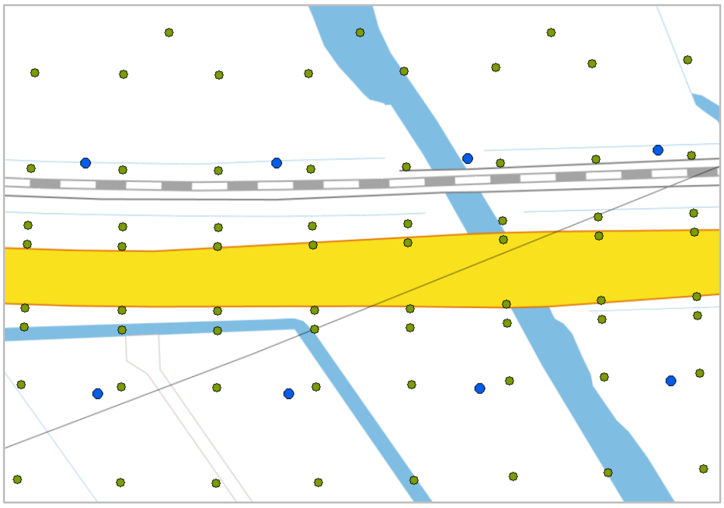


Figure I.1: The two datasets used for noise emissions. The blue points indicate the reference points, the green points indicate the large dataset of 2016.

In general, the points are located close to each other, but for some, the distance is quite significant. In most of these cases, the route of the road changed due to projects that finished between 2016 and 2019. An example is the construction of the new N18 to Enschede. To partly tackle this issue, the values in the dataset with a distance larger than 40 meters are excluded from the dataset. Also, reference points that have missing values are deleted from the dataset. The end result is a dataset containing the noise emissions of roads at reference points. Table I.1 shows the descriptive statistics of the noise model from 2016.

Table I.1: Descriptive statistics of noise emissions at reference points.

Variable	N	Mean	StDev	Minimum	Median	Maximum
24HOUR (dB)	58705	64,260	4,735	11,700	65,230	126,480

The minimum and maximum values in Table I.1 call for further analysis of these values. They are very high and low and may indicate errors in the dataset. The scatterplot in Figure I.2 confirms that there are a lot of reference points with relatively high and low values.

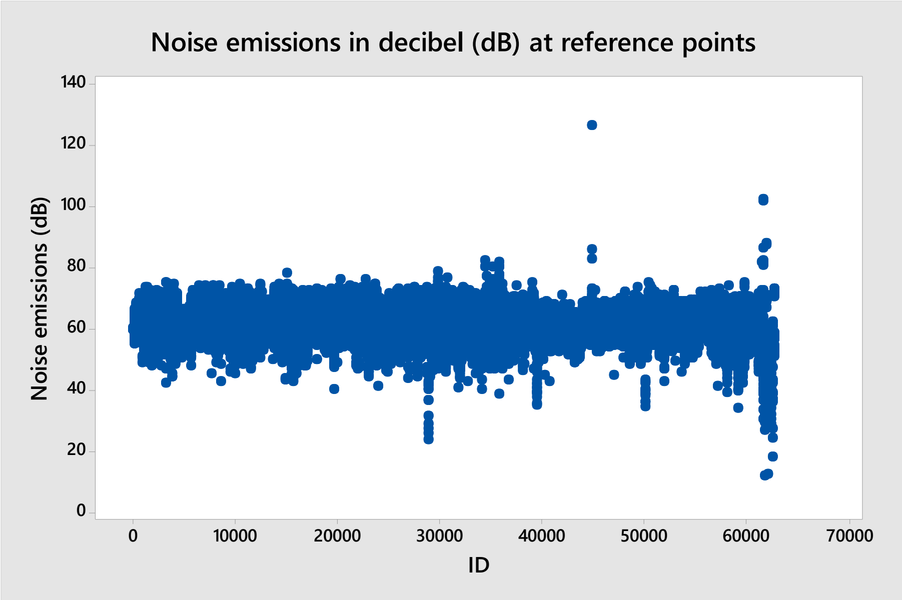


Figure I.2: Scatterplot of noise emissions at reference points.

After a short analysis of these points, these high and low values are explained by two situations when linking the data:

- Reference points are located in the middle of the old route of a road that has been reconstructed. This is often the case when the new road is located parallel and close to the old road. This causes very high noise emissions which do not correspond with the situation at this moment (left side of Figure I.3).
- Reference points are accidentally located close to a point of the 2016 dataset that is very far away from the old route of the route. Therefore, these values have very low noise emissions (rights side of Figure I.3).

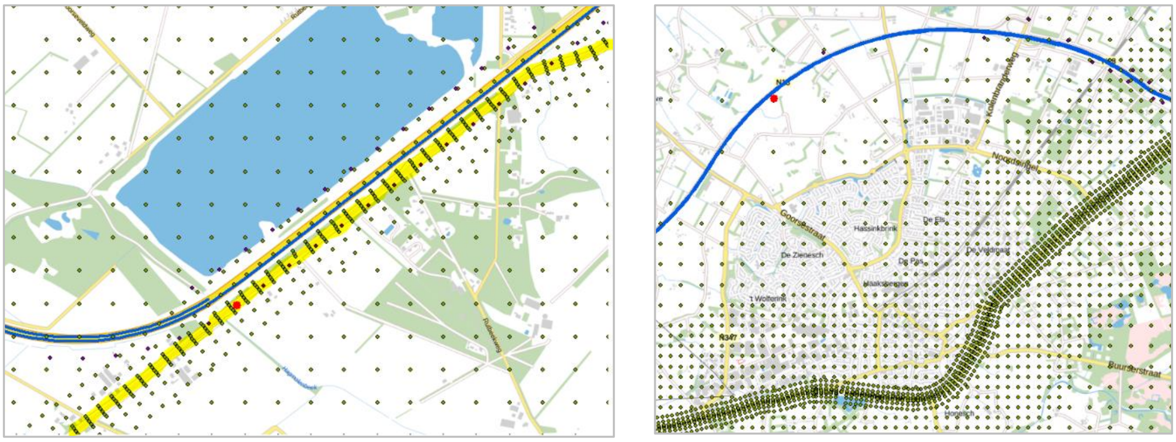


Figure I.3: Two situations where linking of the data does not provide valid results. The new route of the road is indicated in blue, the old route of the road indicated in yellow (left) and green (right). The reference points are indicated with a red dot. Very high noise emissions occur on the left, where the reference point is located in the middle of the old road. Very low noise emissions occur when the reference point is close to a point in the 2016 dataset, but very far away from the old route.

To filter out the situations where the trace of a road has been changed between 2016 and 2018, an additional shapefile has been used. This shapefile contains the location of roads in 2016 and can be compared with the reference point dataset. Normally, reference points are located 50 meters from every road. Their position sometimes slightly differs, because of objects that are in the way, such as buildings. Again, the two situations occur when a reference point is located extremely close or far away from an old road that changed. Therefore, the reference points are reduced to include only reference points that are located at a distance larger than 30 meters and smaller than 70 meters. In this way, reference points that are located very close or far away from a road section that changed between 2016 and 2018 are filtered out. The descriptive statistics of the noise emissions based on the model from 2016 are shown in Table I.2.

Table I.2: Descriptive statistics of noise emissions at reference points.

Variable	N	Mean	StDev	Minimum	Median	Maximum
F24HOUR	56594	64,322	4,515	23,600	65,230	81,830

This final manipulation of the data does not rule out all cases of non-valid data. Another way to solve this issue is to leave out viaducts and road sections that are reconstructed between 2016 and 2020 in the workshops. It is also expected to be not very relevant to analyze the functional performance of assets that are reconstructed only 4 years ago.

Appendix J – Linking of the datasets to individual assets

This appendix describes how the datasets that are used for each sub-indicator are linked to individual assets (viaducts and road sections).

Traffic flow

Traffic flow is indicated by user delay costs (UDC), which is saved in the dataset as a line geometry and contains UDC for road sections. So the data has been already linked to road sections. There is no separation between UDC in road sections and viaducts, so data for road sections are directly linked to viaducts. The objective is to link the road section with the most UDC to the viaduct. This can be a road section on top of the viaduct or a road section that passes underneath. However, DISK (used for viaducts) does not specify the road sections that cross the viaduct. Therefore, two other datasets have been used:

- A dataset that contains the viaducts as a line geometry;
- National roads file (in Dutch: NWB).

The advantage of the first dataset is that the geometry of the viaduct is saved more precisely. However, the first dataset does not contain data for every asset, especially where a road of a province or municipality crosses a viaduct of Rijkswaterstaat. This is the advantage of the second dataset, which contains a road section for every viaduct in the Netherlands. The difference in the precision of the two datasets is shown in Figure J.1.

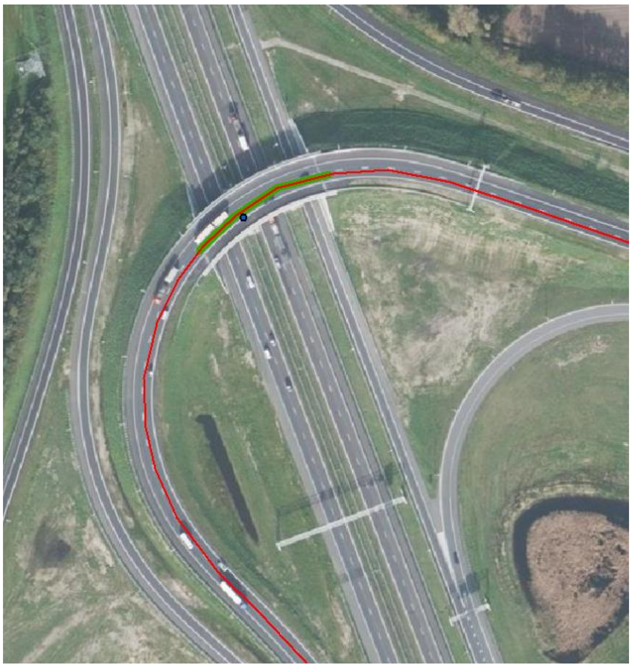


Figure J.1: Difference between the two line geometry datasets. The viaduct in DISK is indicated by the blue dot as a point geometry. The dataset that contains the line geometry of viaducts is indicated with the thick green line, while the NWB dataset is indicated with the thin red line. Note that the location of the viaduct span is indicated more precisely by the green line than the red line.

The more precise location of the first dataset is a clear advantage, especially when linking the data in a later stage. First, all viaducts that were possible to link are linked to the first dataset. When this was not possible, the remaining viaducts were linked to the NWB dataset. Because DISK and the two datasets with the line geometry do not have a common field like an object ID or name, this link has been made using a spatial join in ArcMap. A spatial join combines data from two datasets based on spatial location. DISK has been used as the target feature and the viaducts as a line geometry (first dataset) as the join feature. The road section ID has been selected as the field that needed to be added to the DISK dataset. The match option 'closest' has been used, which picks the line geometry that is closest to the point geometry from DISK. Additionally, a search radius of 5 meters has been used, to prevent that the join would pick the closest value when the line geometry would be missing. The NWB dataset (second dataset) has been used where the line geometry was missing and used the same spatial join as the first dataset. Before this second join, a check has been made if the road section that is part of the deck of the viaduct (and not the road that goes underneath) is indeed the nearest one. A lot of viaducts have been checked randomly and it turned out that in all situations, the road section on top of the deck is the nearest one. An example is shown and explained in Figure J.2.

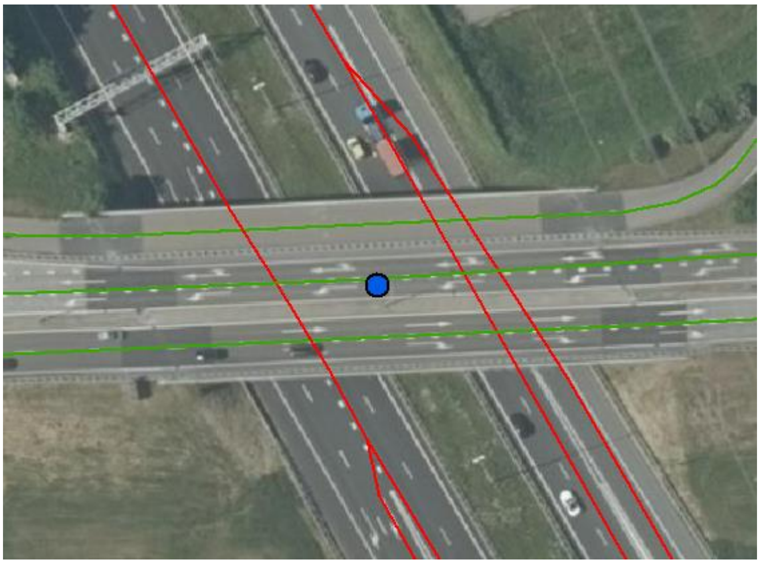


Figure J.2: An example of linking a road section ID to a viaduct in DISK (blue dot). The road sections that go over the deck of the viaduct are indicated with green lines. The road sections that cross the viaduct underneath are indicated with the red lines. Note that the blue dot is closer to a green line than the closest red line. Therefore, the spatial join will select the correct closest road section that is on top of the viaduct.

The end result of these two spatial joins is that the road section that goes over the deck of every viaduct has been joined. The next step is to link this road section ID to the user delay costs (UDC) dataset in order to obtain the UDC on top of the viaduct. This has been done using an attribute join.

Furthermore, the user delay costs of the road that goes underneath the viaduct are relevant as well. These are obtained by a spatial join between the line geometry or the NWB dataset and the user delay costs. The line geometry of the viaducts or NWB dataset has been used as the target feature in ArcMap and the UDC dataset as the join feature. Within the UDC dataset, we asked to retrieve the field containing the user delay costs per km[1]. In most cases the line geometry crosses multiple lines of the user delay costs, so the road section with the highest UDC has been selected by using the merge rule 'maximum'. This time, the used match option within ArcMap is the 'crossed_by_the_outline_of' command. This option will match lines that cross at a point, but will leave out lines that share a line segment. This means that a line geometry of a viaduct that is part of a road section will not be matched to that road section. An example is the situation in Figure J.1. The limited precision of the NWB dataset produces, in a certain situation, mistakes in the dataset. This situation is shown in Figure J.3, where the viaduct (blue dot) that is part of the road section indicated with the red line. The viaduct actually crosses the thin green line, but because the road section (red line) also crosses the orange line (with a higher amount of UDC), the join selects the value from the orange line, which is not valid. This is a limitation of the dataset, but the effect is quite limited, because in almost all situations the spatial join provides valid results. Additionally, the original data from the UDC from road sections will be kept in the tool so users can validate the data.

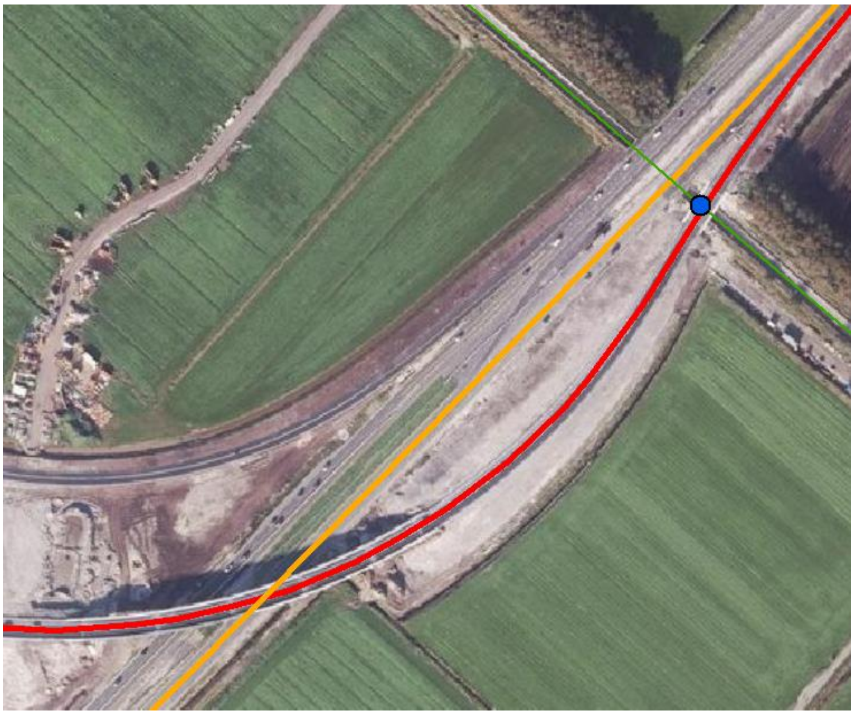


Figure J.3: Situation where the dataset produces mistakes. The blue dot indicates a viaduct, the red line indicates the road section that the viaduct is linked to. The viaduct actually crosses the green line, but the dataset takes the UDC from the orange line, which is actually a different viaduct.

The last step is to link the exact value of the UDC from the road that goes underneath the viaduct to other details about the road section. Examples of other details are the highway number and the side of the highway (left or right). The end result is a dataset with viaducts that contain the UDC of both the road that is on top of the viaduct as the road that goes underneath the viaduct. The taken steps to produce this dataset are summarized in Figure J.4. This dataset is not complete, sometimes values for the UDC are missing. Examples are roads of a province or municipality, which are not included in the UDC dataset. To link the dataset to the categories, the highest amount of UDC are used, either from the deck of the viaduct or the road that goes underneath. In the end, the data could be linked to 2045 of the total amount of 3521 viaducts. For 2809 of the total of 16345 road sections data is available. This is explainable by the fact that the UDC are only available for the main traffic lane and not for merging or other lanes.

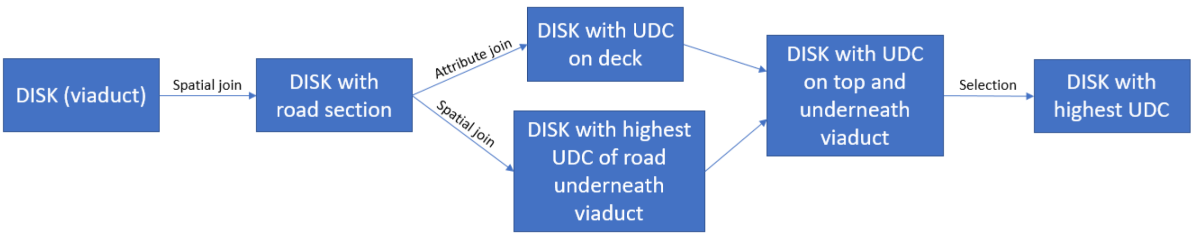


Figure J.4: Process steps to link UDC to viaducts.

Geometry

The geometry is only relevant for viaducts and is indicated by the height of the deck of viaducts. The dataset that contains the height of viaducts originates from the RDW and is saved as a point geometry, similar to the viaducts that originate from the DISK dataset. The objective is to link the data from the RDW to the DISK dataset. The major limitation of the RDW dataset is that there is not a common field like an ID that matches with the DISK dataset. Hence, a spatial join in ArcMap is used. Firstly, all zero values in the dataset from the RDW are replaced by '99999' to indicate missing values. Secondly, the spatial join has been executed, where DISK has been used as the target feature. The RDW dataset has been used as the join feature, and the match option has been set at 'within a distance'. The distance has been set at 30 meters, and the match option 'minimum' has been used to select the lowest value for the height when multiple points are within 30 meters. This spatial join basically searches for every point within the RDW dataset, within a distance of 30 meters of the DISK dataset, and joins the lowest value. When there are no points within a 30 meters distance, the join returns the value '0'. By firstly replacing all zero values with '99999', a distinction can be made between assets that could not be linked to points in the RDW dataset (0), and assets that are linked to points, but these points have missing values (99999). In the end, 1280 out of 3521 viaducts could be linked to a non-missing value for the height. This data has the largest proportion of missing data for viaducts.

Load class

The load classes are only linked to viaducts because they are not relevant for roads. They are retrieved from DISK together with the specific code for each asset. By linking this code to the ones available in the shapefile of DISK, the load classes have been added to the viaducts. In total, 2893 viaducts have a value for the load class.

Safety to users

Safety to users is reflected by the safety score based on accidents causing injuries and accidents with fatal consequences. Accidents are saved as a point geometry and can be linked to both viaducts (point geometry) and road sections (line geometry). Both types of accidents are first linked, if possible, to viaducts. Here, a spatial join has been used to identify the viaducts which are closest to an accident, with a search distance of 10 meters. This results in a list of accidents that are within 10 meters of a viaduct and contains the ID of each viaduct. These ID's are linked to DISK and counted, because sometimes multiple accidents occurred on one viaduct. This results in a list of viaducts with their ID from DISK and the number of accidents causing injuries and with fatal consequences. It must be noted that the amount of accidents that could be linked to viaducts is very limited. The remaining accidents are linked to road sections by using the same spatial join (closest, within a 10-meter distance). Some accidents could not be linked to a road section, this is the case when the trace of a road changed between 2016 and 2018. Also for the road sections, a list has been made with the number of accidents, divided by their consequences. The end result is an overview where for each viaduct and road section the number of accidents with fatal consequences and accidents causing injuries are listed. These are used to calculate the safety score in section 3.2.4.4.

Noise emissions

Noise emissions are originating from the exceedance of the noise production limit in reference points and are linked both to viaducts and road sections. The reference points are a point geometry and relatively easy to link to individual assets (road sections and viaducts) with the use of a spatial join. Again, for viaducts, the DISK dataset has been used and for the road sections the NWB dataset. In both cases, these datasets have been used as the target feature and the reference points as the join feature. The match option within a distance has been used and the distance has been set at 200 meters. The merge option 'mean' has been used for the exceedance of the noise production limit. These settings for the spatial join serve to select all reference points that are within 200 meters of each viaduct or road section, and then take the average exceedance of the noise production limit of these reference points. A small number of viaducts are further away than 200 meters from the closest reference point, so it is not possible to link these with the defined spatial join. In most cases, this happens when viaducts are located in larger intersections or crossings, as shown in Figure J.5.

Figure J.5: Situation where it is not possible to link a viaduct (blue dots) to reference points (small red dots) with the defined spatial join within 200 meters. The distance between the closest reference point is around 260 meters.

A solution to this would be to increase the distance of 200 meters of the spatial join. However, one could argue that the reference point is then too far away from the viaduct and the question arises if the reference point really reflects the viaduct, because it is also influenced by other road sections located more closely (see Figure J.5). In total, data could be linked to 3358 viaducts and 16345 road sections.

Appendix K – Applications for exemptions due to vehicle heights

For the division into score categories of the height dataset, also the applications for exemptions have been analyzed. This provides insight into the limitations of above categories for exceptional transportations and is based on a dataset with 18.975 applications from the year 2019. From these, 13.084 have data about the height of transports or trucks. The remaining applications are based on the maximum weight, width or length. The applications are linked to the heights in Table K.1 and the percentage of applications that are smaller than this value are calculated and shown in the second column. The values mean that a viaduct that has a perfect score (1) will not have a limitation for 96,3% of the applications, and this percentage can even be higher (when the viaduct has a height larger than 4,45 meters). Thus, a viaduct with a perfect score will in most cases, not hinder traffic that needs an exemption. Lastly, it must be mentioned that this data concerns data about applications with a limited time-span. The RDW also distributes yearly exemptions, which are often for vehicles with a limited height.

Table K.1: Percentages of applications linked to heights dataset.

Height (m)	Percentage of applications that are smaller than or equal to the corresponding height
4,45	96,3%
4,05	0,8%

Appendix L – Overview of score categories per indicator

Table L.1: Overview of score categories for each sub-indicator.

Indicator / Score	User delay costs (UDC) per km[1] (€/km[1])	Height (m)	Load class	Safety score	Exceedance of noise production limit (dB)
1: Perfect	0 - 2.000	$H \geq 4{,}45$	A, 60, NEN-EN-1991, NEN-6706	$0 \leq s < 5$	$\Delta < -0{,}5$
2: Good	2.000 - 36.000	$4{,}05 \leq H < 4{,}45$	B, 45	$5 \leq s < 10$	$-0{,}5 < \Delta < 0$
3: Fair	36.000 - 347.000	$3{,}85 \leq H < 4{,}05$	C, 30	$10 \leq s \leq 15$	$0 \leq \Delta < 0{,}5$
4: Poor	> 347.000	$H < 3{,}85$	D	$s > 15$	$\Delta \geq 0{,}5$

Appendix M – Manual for the tool

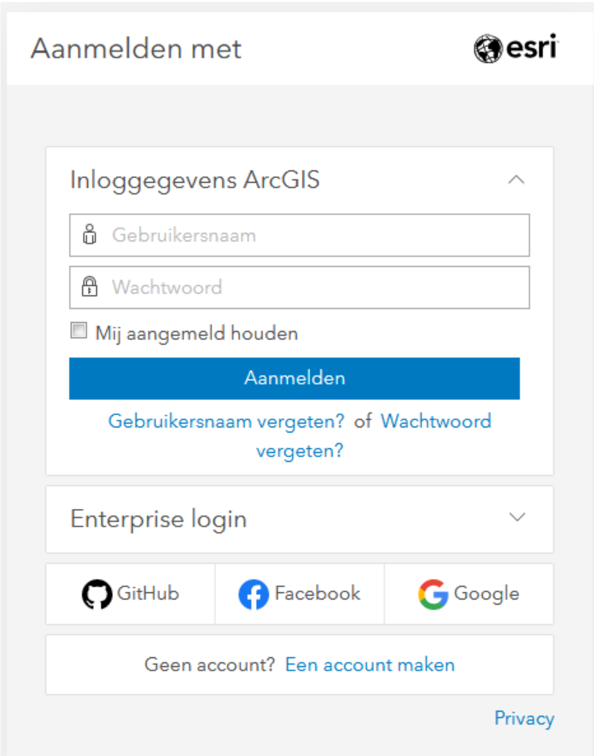
The manual of the tool has been written in Dutch, because employees of Rijkswaterstaat work with it. It also presents the final design of the tool, after verification and validation.

1. Toegang tot de tool

Eerst dien je de tool te openen, dit kan gewoon in je internetbrowser.

1. Klik op deze link (control inhouden): LINK

Je komt dan op een inlogscherm voor ArcGIS online die er als volgt uit ziet:

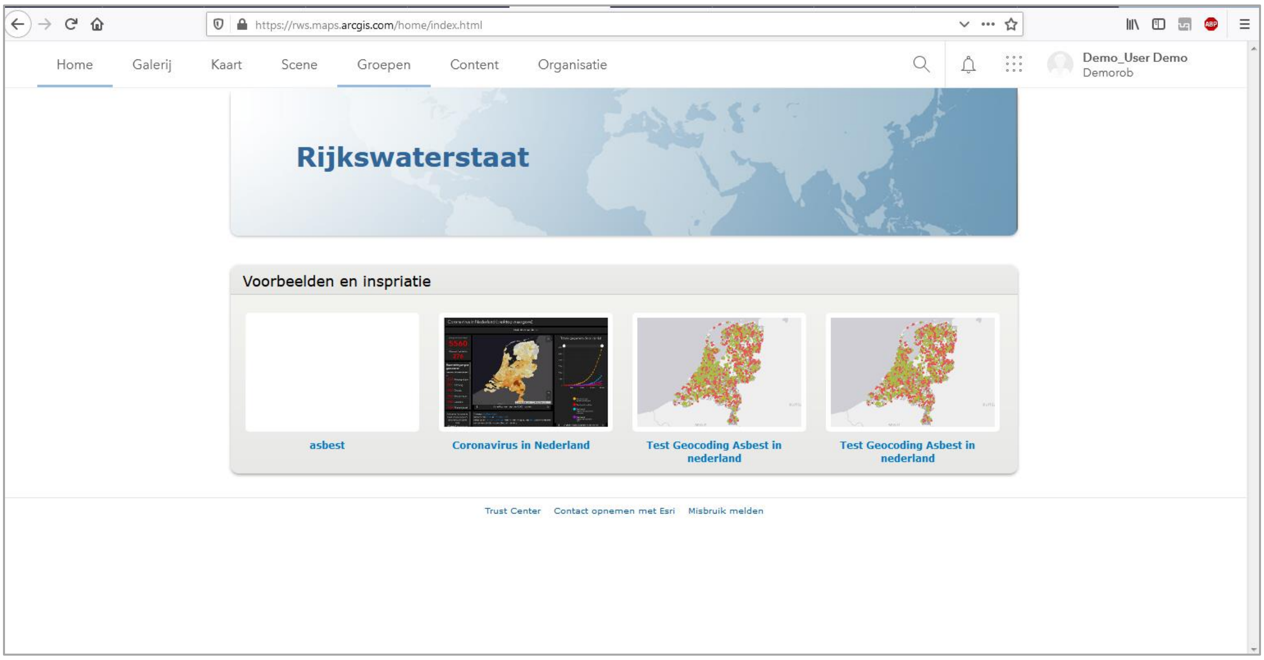


2. Log hier in met de volgende gegevens:
    a. Gebruikersnaam: Demorob
    b. Wachtwoord: Demorun1!

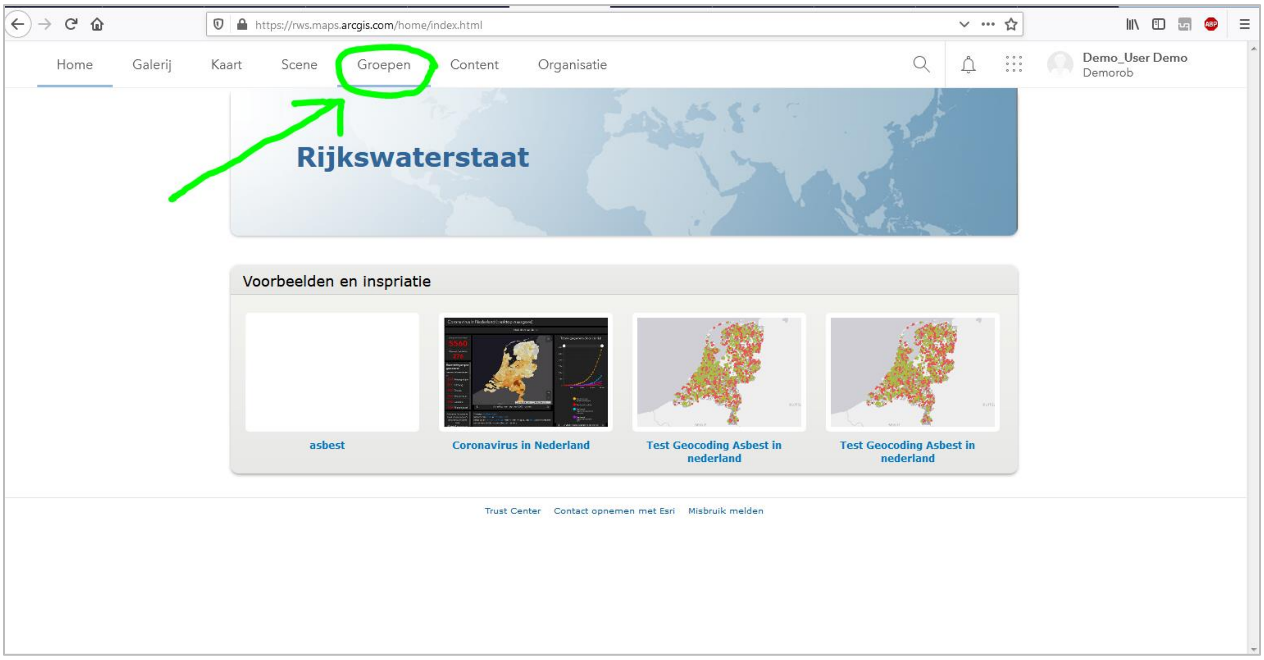
Let op het gebruik van hoofdletter ‘D’ en voor het wachtwoord de toevoeging van ‘1’ en het uitroepteken ‘!’

3. Druk op ‘aanmelden’

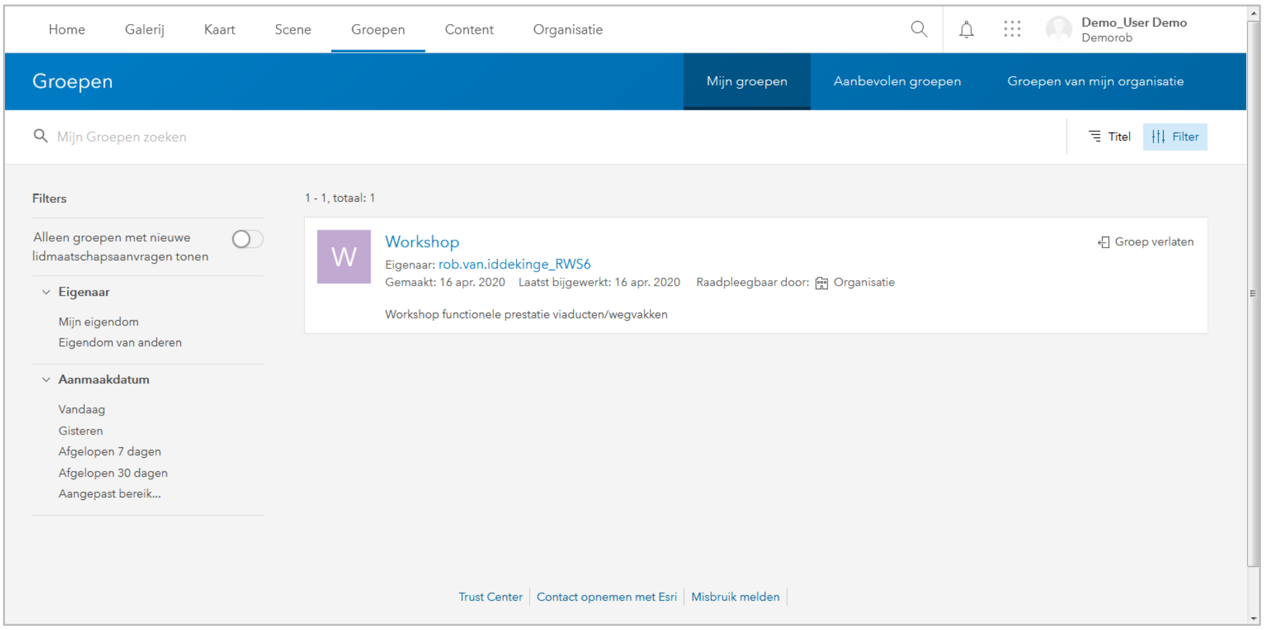
Je bent nu ingelogd, en ziet nu het volgende scherm:



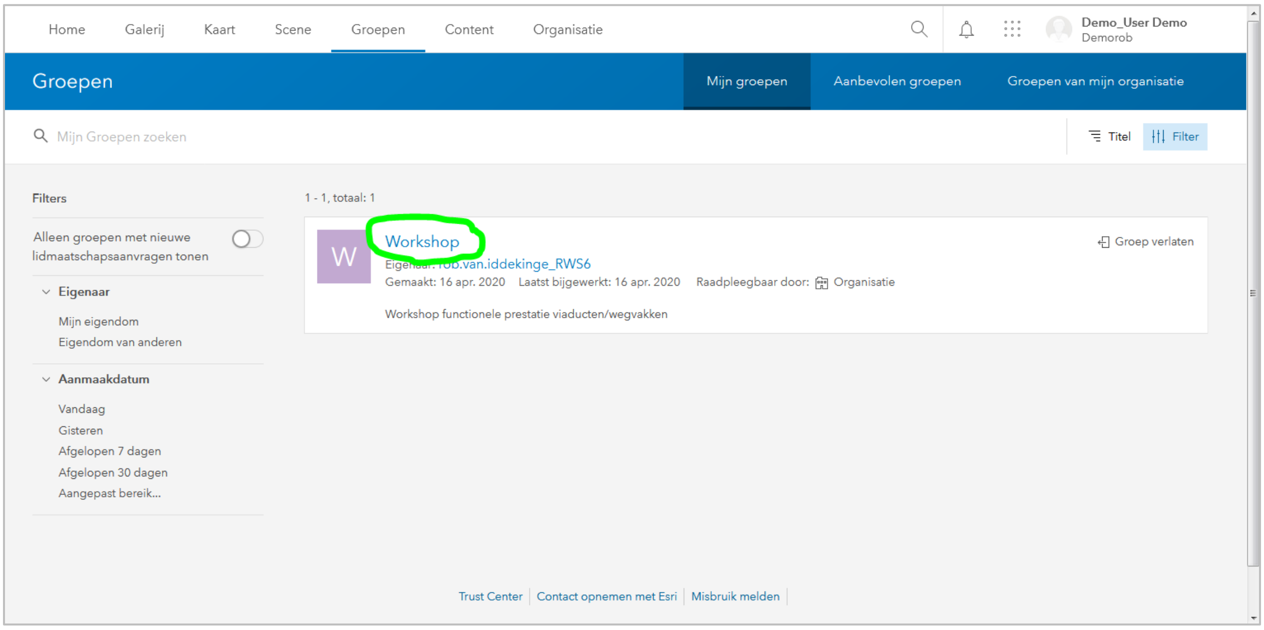
4. Klik hier bovenin in de rij op 'Groepen'



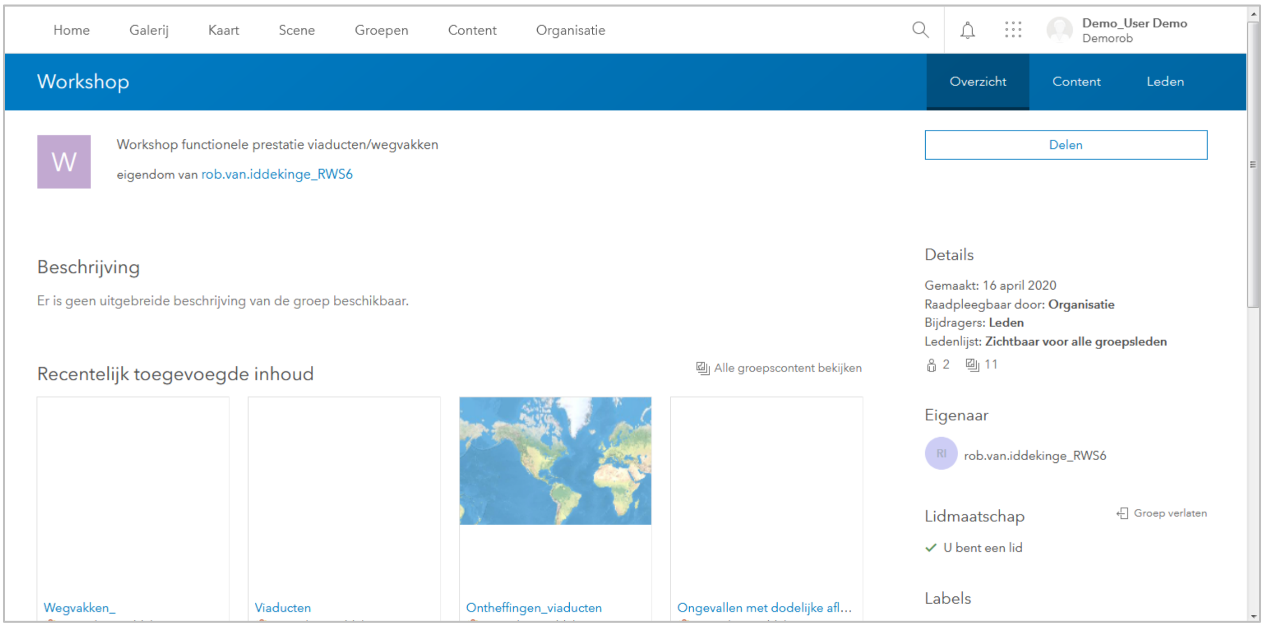
Je komt nu op het volgende scherm



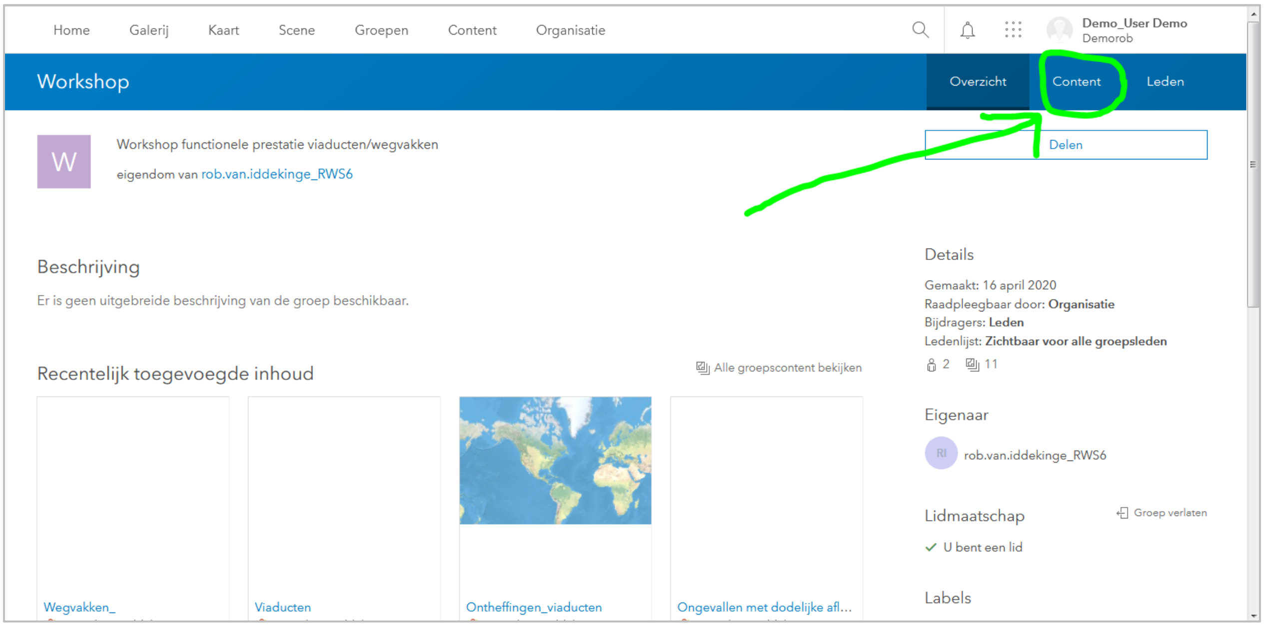
5. Klik hier op de groep ‘Workshop’



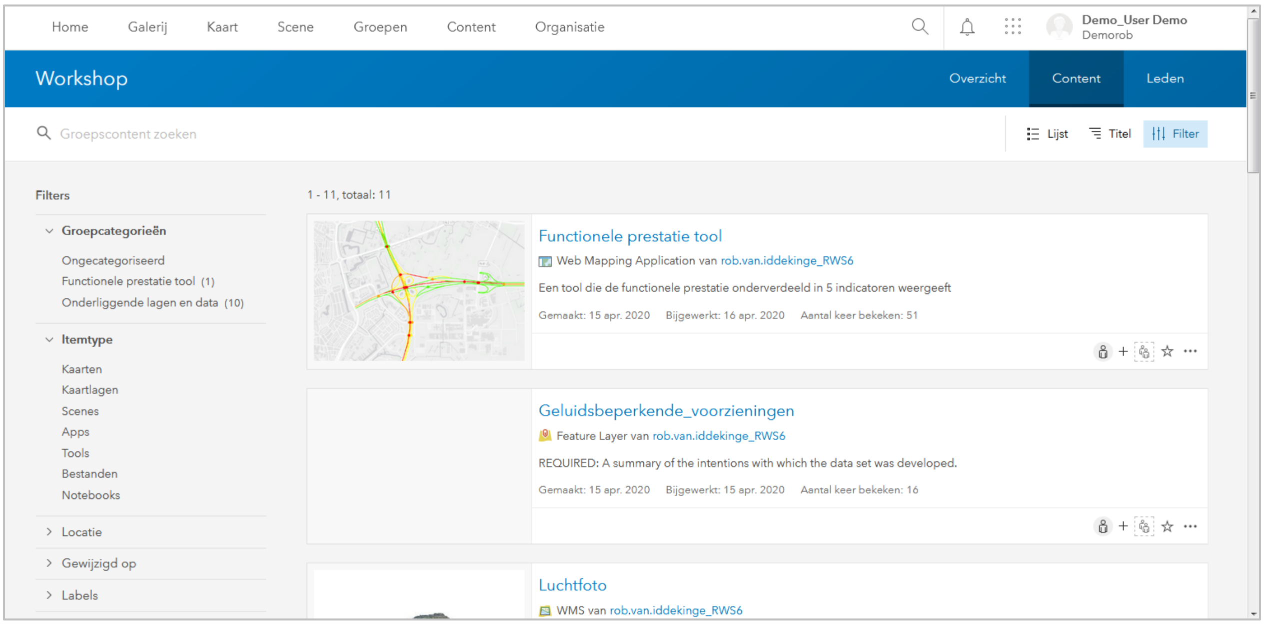
Vervolgens kom je op dit scherm:



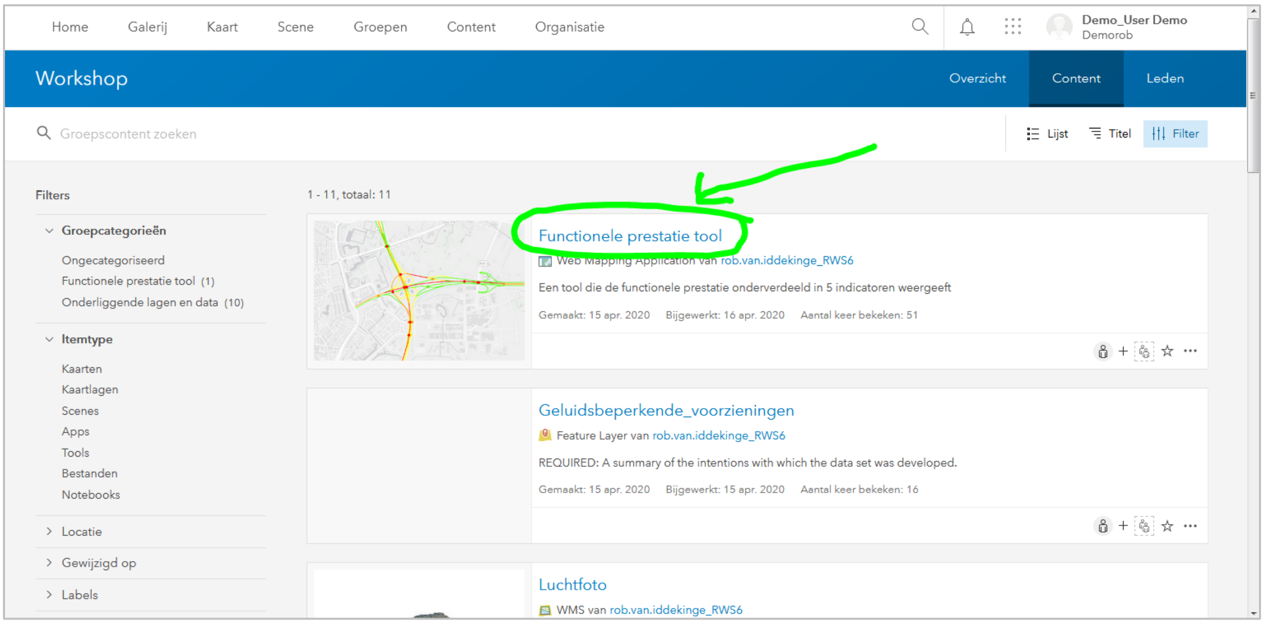
6. Hier druk je rechtsboven, in de blauwe balk op de knop ‘Content’



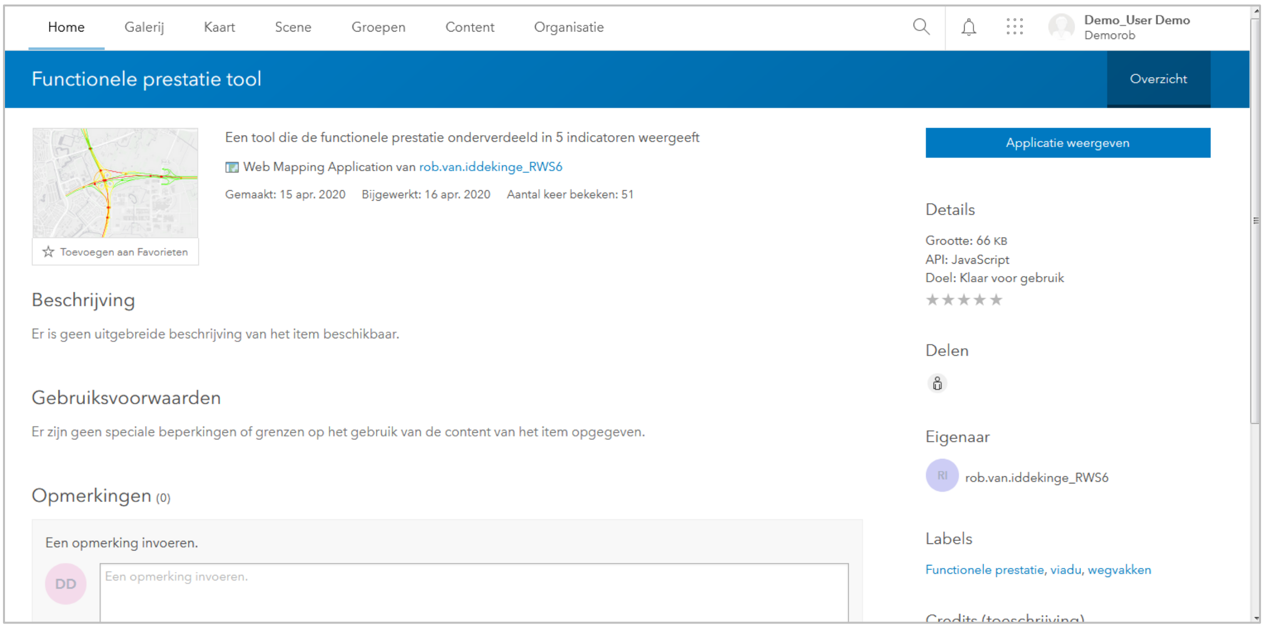
Dan kom je op het volgende scherm:



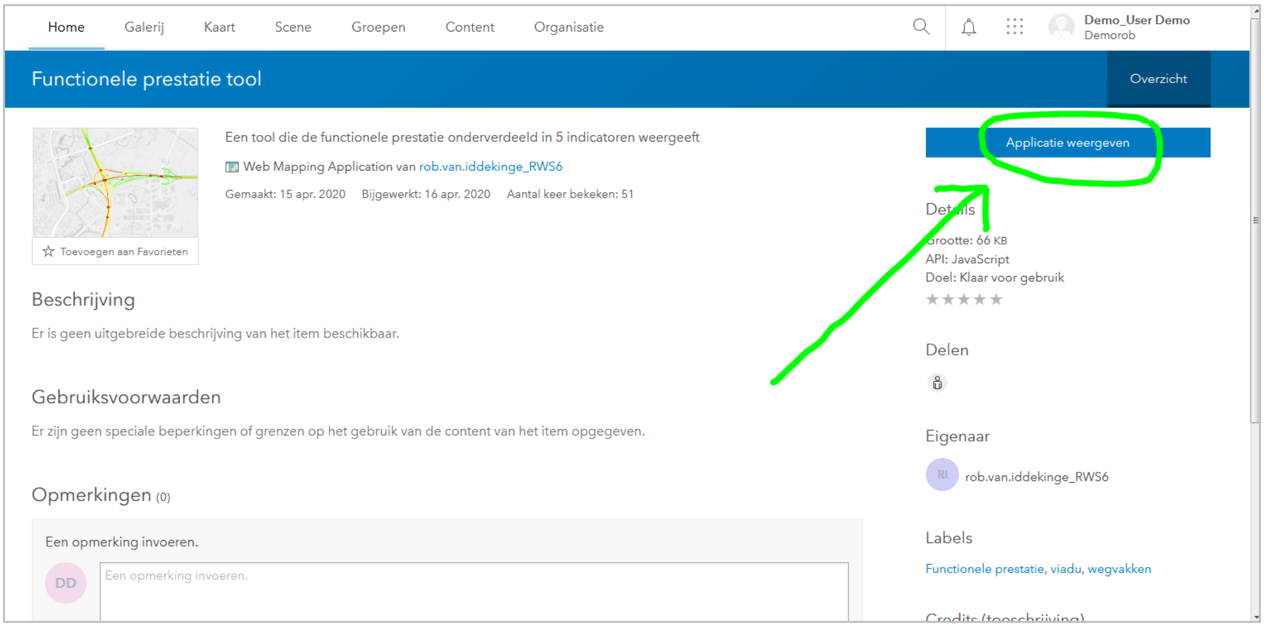
7. Klik hier op de titel van de tool ‘Functionele prestatie tool’. Indien hij niet bovenaan staat, scroll je naar beneden.



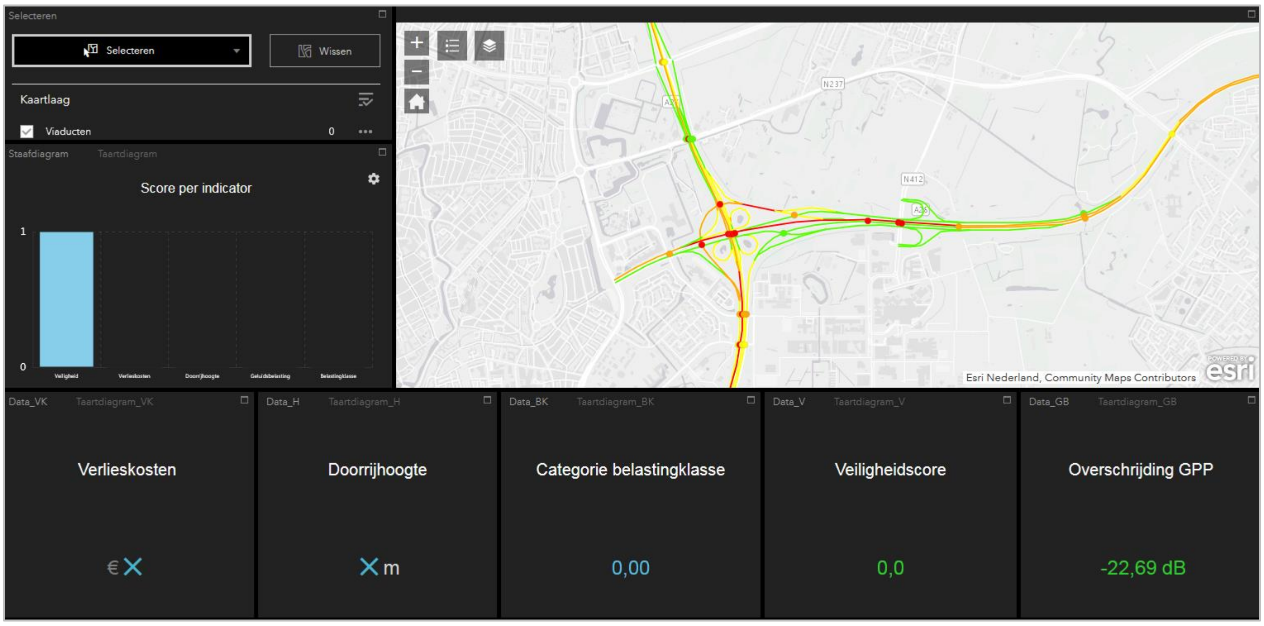
Je komt nu op een pagina met wat details over de tool:



8. Klik hier rechtsboven op de blauwe knop 'applicatie weergeven'



Nu opent zich een nieuw tabblad met de tool, die er als volgt uit ziet:


Selecteren
Selecteren
Wissen
Kaartlaag
Viaducten
0
Staafdiagram
Taartdiagram
Score per indicator
1
0
Esri Nederland, Community Maps Contributors
Data_VK
Taartdiagram_VK
Verlieskosten
€
Data_H
Taartdiagram_H
Doorrijhoogte
m
Data_BK
Taartdiagram_BK
Categorie belastingklasse
0,00
Data_V
Taartdiagram_V
Veiligheidscore
0,0
Data_GB
Taartdiagram_GB
Overschrijding GPP
-22,69 dB

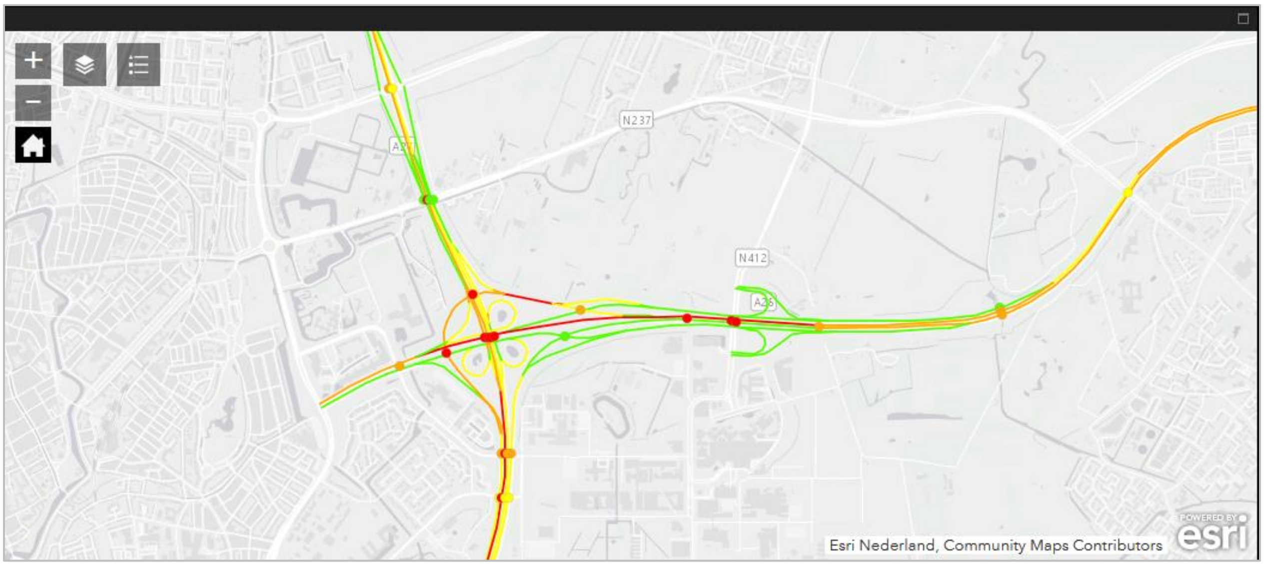
2. Gebruik van de tool

2.1. Algemeen gebruik van de tool

Het startscherm ziet er als volgt uit en kan onderverdeeld worden in verschillende elementen:

- Geel, rechtsboven: Kaart
- Rood, linksboven: Selectie tool
- Groen, onderkant en linkerkant: Indicatoren en data

We beginnen met het toelichten van de kaart, deze ziet er als volgt uit:

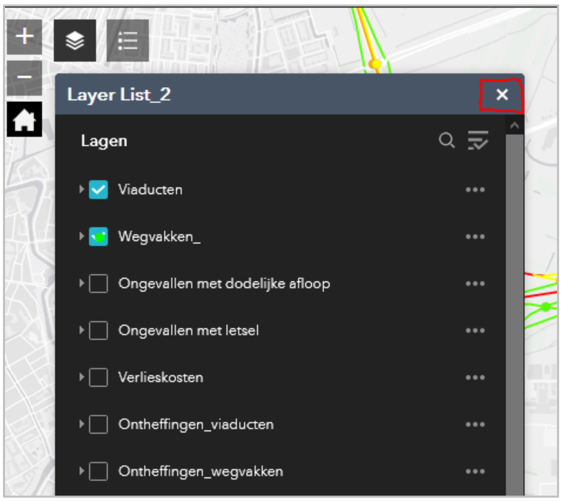


De basis principes van de kaart werken hetzelfde als google maps: verplaatsen van je locatie kan door met je muis te slepen (klikken en verplaatsen van je muis), in- en uitzoomen is mogelijk door te scrollen met het wiel op je muis.

Links bovenin zijn enkele knoppen te vinden:

1. Plusje: inzoomen.
2. Minteken: uitzoomen.
3. Huisje: hiermee ga je terug naar een standaard locatie, in dit geval de oostzijde van Utrecht, nabij de Uithof. Deze knop kun je gebruiken als je verdwaalt in de kaart.
4. Een knop om de lagenlijst te openen (deze wordt hierna verder toegelicht).
5. Een knop om de legenda te openen (deze wordt hierna verder toegelicht).

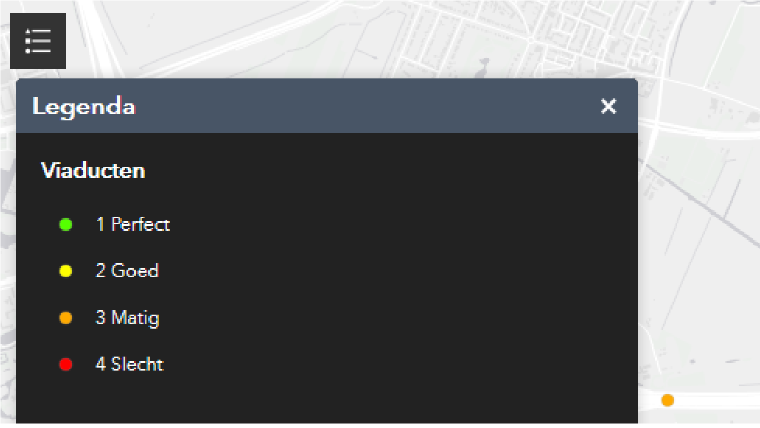
Door op de knop van de lagenlijst (4) te drukken, opent zich een pop-up scherm waarin de lagen in de tool zijn weergegeven:



Deze kunnen aan en uitgezet worden door respectievelijk in de vierkantjes of op de vinkjes te klikken (gemarkeerd met een groene stip voor de laag ‘wegvakken_’.

- ➢ Zet een aantal lagen aan/uit en kijk wat er toegevoegd wordt aan de kaart (eventueel moet hiervoor uitgezoomd worden).
  - De laag ‘Wegvakken_’ geeft bijvoorbeeld de functionele prestatie van wegvakken weer, op basis van 3 indicatoren: verlieskosten, veiligheid en geluidsbelasting.
- ➢ Laat alleen de laag ‘viaducten’ aanstaan, zet de andere lagen uit.
- ➢ Sluit het scherm, dit kan op 2 manieren:
  - Door opnieuw op de knop van de lagenlijst te klikken.
  - Door in de pop-up rechtsboven op het kruisje te klikken (met rood gemarkeerd in bovenstaande afbeelding).

Vervolgens kan de legenda geopend worden door op de laatste (5) knop te drukken. Opnieuw opent zich een pop-up scherm, waarin de legenda verschijnt.



Als het goed is, is bovenstaande legenda te zien. Mocht dit niet zo zijn, controleer dan of je alleen de laag 'viaducten' hebt aanstaan. Deze legenda geeft de uitleg voor de verschillende kleuren stippen (viaducten) op de kaart weer. Een stip met een felgroene kleur is een viaduct met een perfecte functionele prestatie, een rode kleur geeft een viaduct weer met een slechte functionele prestatie.

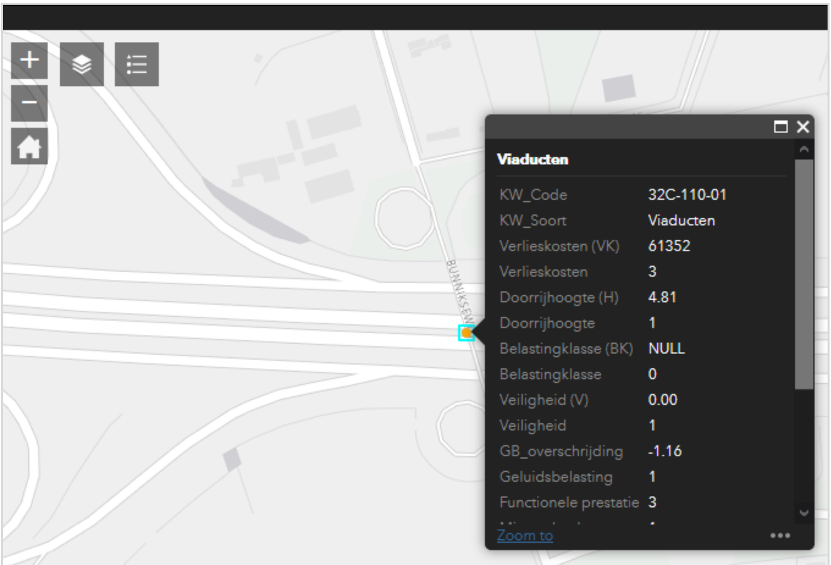
Als je de legenda erbij wil houden, kun je hem eventueel naar rechts slepen via de bovenste rand van de pop-up. Je kunt hem weglaten door opnieuw op de legenda knop te drukken of op het kruisje rechtsboven in de pop-up.

Nu we de basis functionaliteiten hebben behandeld van de kaart, wordt nu de functionaliteit van de selectie tool en de indicatoren/data uitgelegd. De selectie tool is linksboven te vinden (rood gemarkeerd) en de data/indicatoren onderaan en aan de linkerkant (groen gemarkeerd).

De selectietool wordt gebruikt om een viaduct of meerdere viaducten te selecteren. De selectie werkt samen met de schermen van de data: als een viaduct wordt geselecteerd zullen de schermen van de data veranderen. Omdat nu nog niks geselecteerd is, zie je nu nog weinig data onderin en aan de zijkant.

We beginnen nu met het analyseren van een specifiek viaduct. Vanuit de legenda kunnen we zien wat de algemene functionele prestatie is van een bepaald viaduct. Echter kunnen we hieruit niet opmaken welke van de 5 indicatoren hiervoor leidend is en hoe de score per indicator is. Hiervoor hebben we de selectie tool en de data schermen nodig.

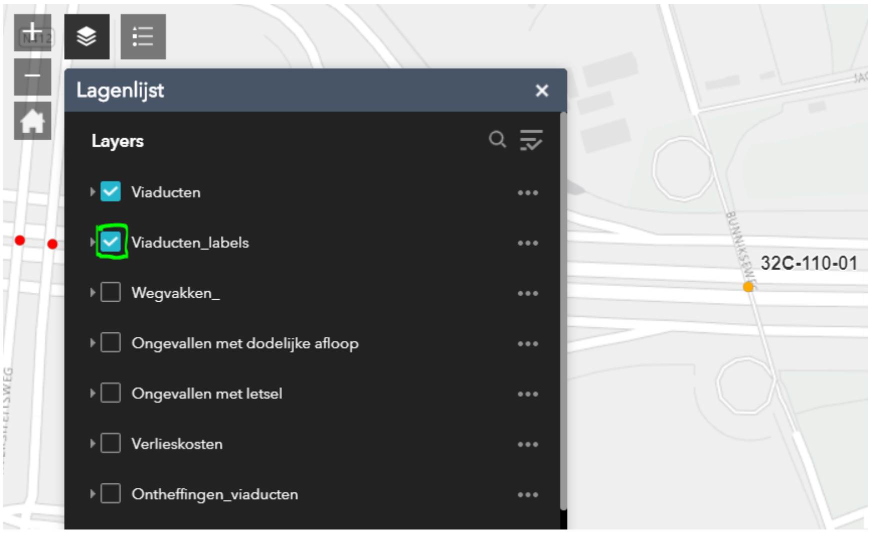
Voordat de selectietool uitgelegd wordt, moet nog 1 opmerking gemaakt worden: de kaart heeft ook een selectie mogelijkheid, deze kan gebruikt worden door simpelweg op een viaduct te klikken. Vervolgens opent zich een pop-up scherm als volgt:



Hier is wat informatie zichtbaar die in de specifieke laag staat. Het nadeel van deze standaard selectie mogelijkheid in de kaart is dat het selecteren enigszins lastig is en dat deze niet gelinkt is aan de tools aan de onderzijde: deze veranderen niet bij het selecteren van een viaduct. Hiervoor zijn we de selectie tool linksboven nodig.

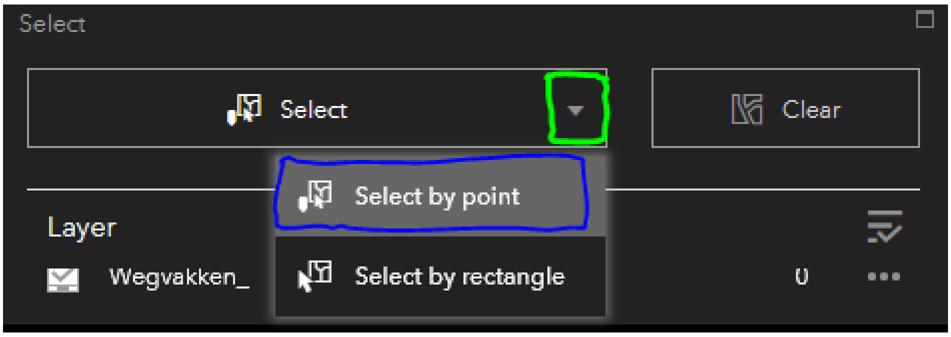
2.2. Analyse van individuele viaducten

➢ Zet de laag 'Viaducten_labels' aan (de laag 'Viaducten' kun je ook aanlaten)



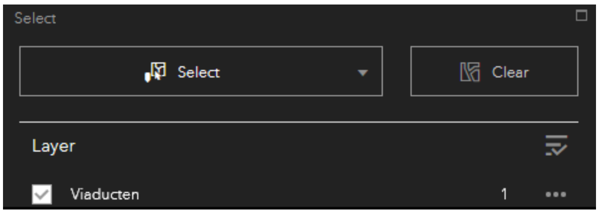
Nu zie je de kunstwerkcodes van de viaducten in de kaart, deze komen overeen met DISK. Op sommige locaties waar veel viaducten dicht op elkaar staan moet je flink inzoomen om de code per viaduct te zien.

- Sluit de lagenlijst
- 1. Navigeer naar een viaduct naar keuze die je wilt analyseren
    - Enige voorwaarde is dat dit viaduct een matige of slechte functionele prestatie heeft, dus oranje of rood kleurt op de kaart. Dit kun je controleren met behulp van de legenda.
- 2. Klik linksboven in de selectie tool op het pijltje naar beneden (groen gemarkeerd in onderstaande afbeelding) en klik daarna op 'Select by point' (in blauw gemarkeerd).



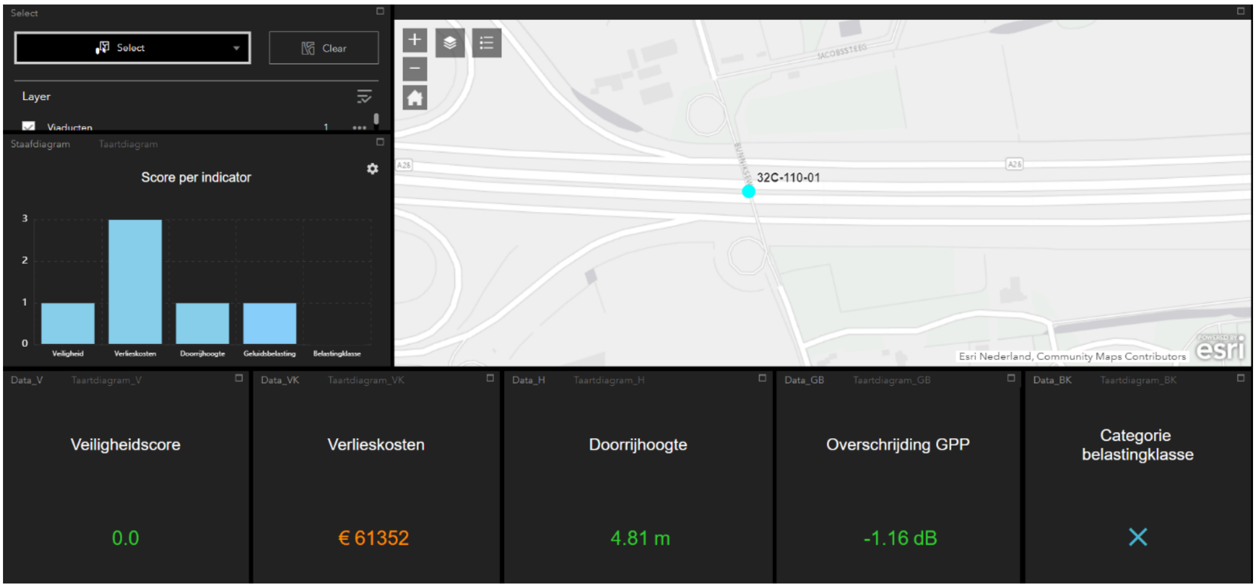
- 3. Je kunt nu een viaduct selecteren door op een stip op de kaart te klikken. Het kan zijn dat je hier een aantal pogingen voor moet doen. Controleer tijdens het selecteren of de selectie tool aanstaat:

Figuur 0.2: Selectie tool is actief.

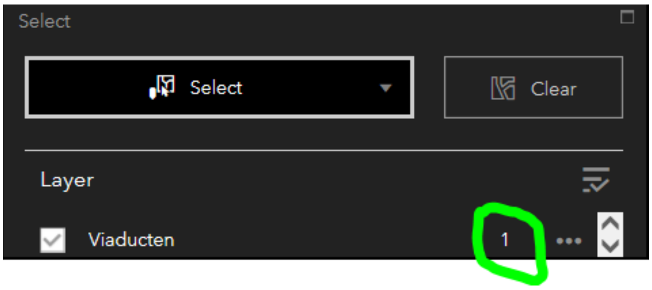


Figuur 0.1: Selectie tool is niet actief, nu kun je geen viaduct selecteren.

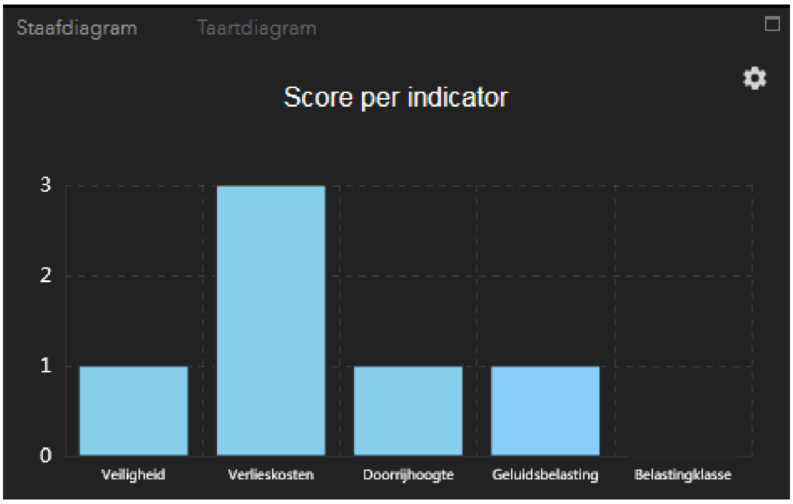
Als het gelukt is kleurt het stipje blauw, en veranderen de schermen aan de onderkant en zijkant:



Het is belangrijk bij het selecteren dat je genoeg inzoomt, anders heb je kans dat je per ongeluk 2 viaducten tegelijkertijd selecteert. Dit kun je controleren via de selectie tool, die aangeeft hoeveel viaducten je hebt geselecteerd:



Als je een viaduct hebt geselecteerd wordt aan de linkerzijde een staafdiagram weergegeven, die de score per indicator weergeeft. Deze is hieronder vergroot weergegeven:

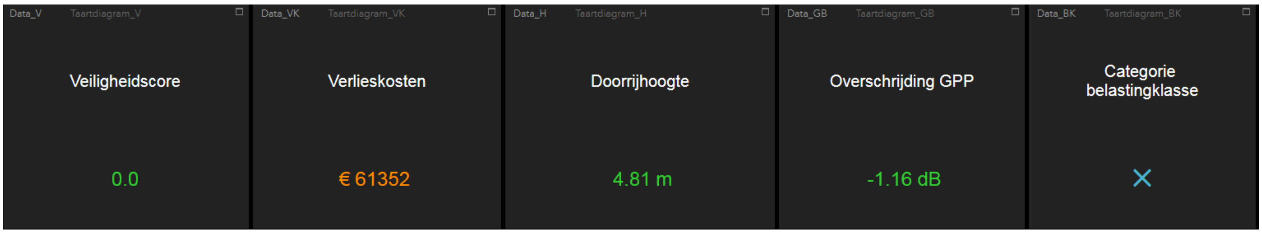


De algemene score van dit specifieke voorbeeld is ‘matig’ of ‘3’, herinner dat een hoger cijfer een slechtere score is:

0 = Missende data
1 = Perfecte score
2 = Goede score
3 = Matige score
4 = Slechte score

Vanuit bovenstaande afbeelding kunnen we voor dit voorbeeld dus concluderen dat de matige score wordt veroorzaakt doordat de indicator ‘verlieskosten’ een matige score heeft (3). De veiligheid, doorrijhoogte en geluidsbelasting hebben namelijk een perfecte score (1). Als laatste kunnen we zien dat data voor de belastingklasse ontbreekt (0).

Vervolgens kunnen de schermen aan de onderkant geanalyseerd worden, deze bevestigen de gegevens in het staafdiagram. Deze schermen geven de data weer waarop de scores zijn gebaseerd, en zien er als volgt uit:



De kleuren van de data komen wederom overeen met de verschillende scores:

Groen = Perfecte score
Geel = Goede score
Oranje = Matige score
Rood = Slechte score
Kruisje / blauw = Missende data

Dus opnieuw kunnen we zien dat de indicator ‘verlieskosten’ een matige score heeft (oranje kleur). De veiligheid, doorrijhoogte en overschrijding GPP of geluidsbelasting een perfecte score hebben (groene kleur). De data van de belastingklasse mist voor dit viaduct, dit is te zien aan het kruisje.

Ook kan de ‘leidende’ indicator geanalyseerd worden, in dit voorbeeld de indicator ‘verlieskosten’. Te zien is dat de verlieskosten €61352 per strekkende kilometer (km1) per jaar zijn. Aangezien een matige prestatie van 36000 tot 347000 loopt, duurt het dus vermoedelijk nog wel een tijdje voordat dit viaduct naar een slechte score voor de verlieskosten gaat.

- 4. Controleer voor je gekozen viaduct voor hoeveel indicatoren data mist. De tweede regel voor het selecteren van een viaduct is dat voor maximaal 1 indicator data mag missen.
- 5. Selecteer eventueel een ander viaduct, door stappen 1 tot en met 3 te herhalen. Controleer ook of je de laag ‘Viaducten_labels’ aan staat.
- 6. Zie de tabel hieronder, en vul de volgende dingen in:
    - Kunstwerkcode (zie label)
    - Algemene functionele prestatie viaduct
    - Indicator met de meest slechte prestatie
    - Indicator data voor deze indicator
    - Indicator (2*) met de meest slechte prestatie
    - Indicator (2*) score voor deze indicator
    - Indicator (3*) met de meest slechte prestatie
    - Indicator (3*) score voor deze indicator
    - *Soms kunnen meerdere indicatoren de meest slechte functionele prestatie hebben

In het voorbeeld betekent dit de volgende tabel:

De Kunstwerkcode zie je in de label, de algemene functionele prestatie is in dit geselecteerde voorbeeld 3 (matig). Dit wordt veroorzaakt doordat de verlieskosten een matige score hebben. De data die bij de verlieskosten hoort is €61352. Dit vul ik in in onderstaande tabel.

Omdat bij dit voorbeeld alleen de verlieskosten de meest slechte score hebben, hoef ik de resterende kolommen niet in te vullen. Mochten er meerdere indicatoren de meest slechte score hebben, vul je deze ook in.

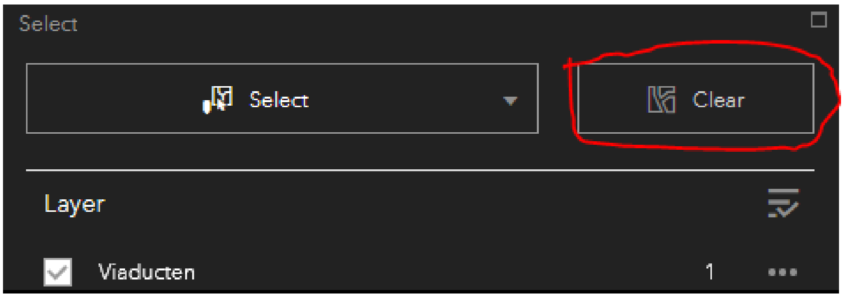
	Kunstwerk-code	Algemene functionele prestatie viaduct	Indicator (1) met meest slechte score	Score voor deze indicator (1)	Indicator (2) met meest slechte score	Score voor deze indicator (2)	Indicator (3) met meest slechte score	Score voor deze indicator (3)
Vb	32C-110-01	3	Verlieskosten	€61352	Nvt.	Nvt.	Nvt.	Nvt.
1								
2								
3								

- 7. Herhaal stappen 1 t/m 6 en vul bovenstaande tabel voor 3 viaducten in.

2.3. Analyse van meerdere viaducten tegelijkertijd

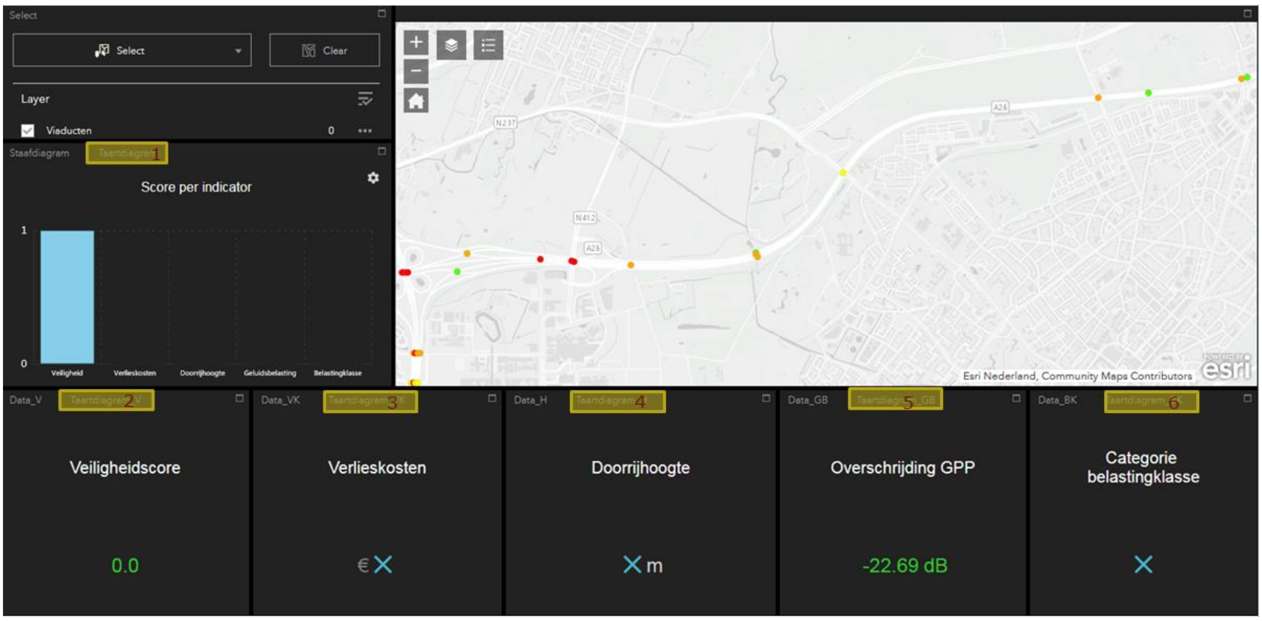
We kunnen de tool ook gebruiken om meerdere viaducten tegelijkertijd te analyseren. Hiervoor doorloop je de volgende stappen.

- 1. Zet alleen de laag ‘viaducten’ aan.
- 2. Annuleer eventuele selecties die je nog hebt aanstaan door in de selectietool linksboven op ‘Clear’ te drukken:

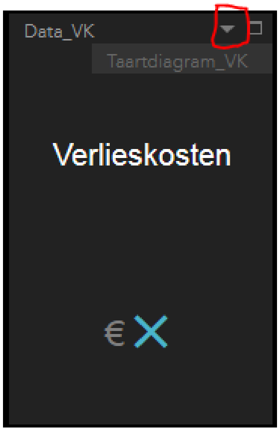


De visualisatie tools moeten ook aangepast worden, voor de analyse van meerdere viaducten gebruiken we andere visualisaties, namelijk taart diagrammen.

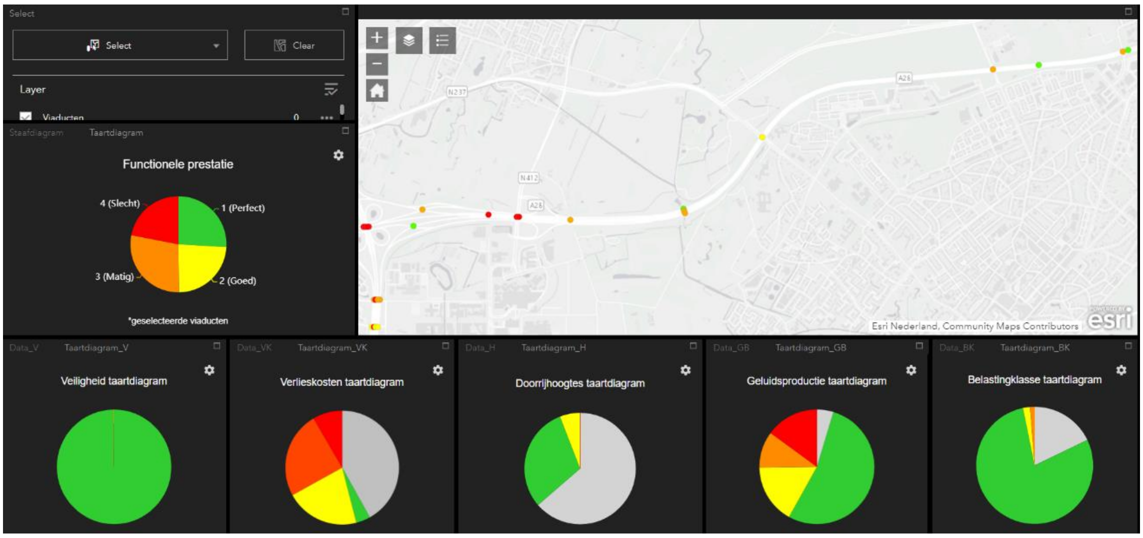
- 3. Switch de visualisaties (6x) van het staafdiagram en de data van de indicatoren naar de taartdiagrammen. Dit doe je door in elk venster linksboven op ‘taartdiagram…’ te klikken, zoals hieronder weergegeven:



Wellicht dat door een beperkte breedte van je scherm de andere data visualisaties niet zichtbaar zijn zoals hierboven weergegeven. Deze zijn dan bereikbaar via een pijltje in elk scherm, zoals hier weergegeven:



Als je alles veranderd hebt, zal je scherm er nu zoals hieronder uitzien:

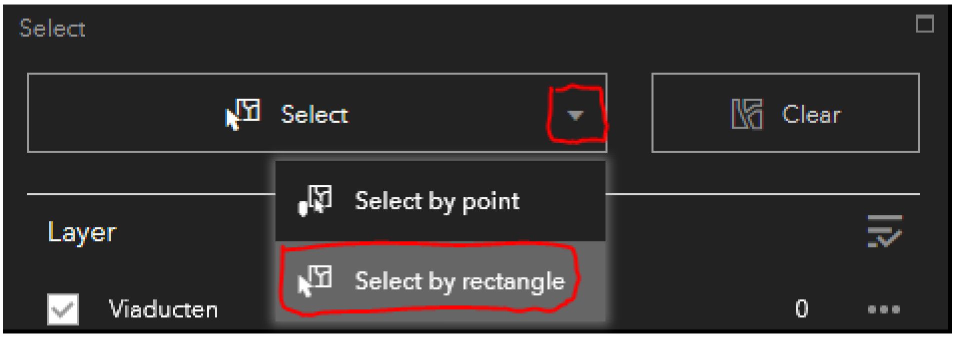


Mochten de taartdiagrammen niet zichtbaar zijn, controleer dan of je alle schermen hebt veranderd. Als je diagrammen er heel anders uitzien, controleer dan of je je selectie hebt verwijderd zoals beschreven in stap 2. Omdat we nog niks geselecteerd hebben, geven de taartdiagrammen nu een overzicht van alle viaducten weer.

- Het taartdiagram aan de linkerkant, in het midden qua hoogte, met als titel 'Functionele prestatie', geeft de algemene functionele prestatie van viaducten weer, verdeeld in de 4 mogelijke scores.
    - In het voorbeeld hierboven is de verdeling van de aantallen te zien. Elke score categorie (perfect, goed, matig en slecht) bevat ongeveer één vierde van alle viaducten.
- De 5 taartdiagrammen aan de onderkant geven een verdeling per indicator weer.
    - In het voorbeeld is bijvoorbeeld te zien:
        - Dat bijna alle viaducten voor de indicator 'veiligheid' een perfecte score hebben.
        - Er veel data mist voor de indicator 'doorrijhoogtes'.

Vervolgens kunnen we deze analyse uitvoeren voor een stukje van een netwerk.

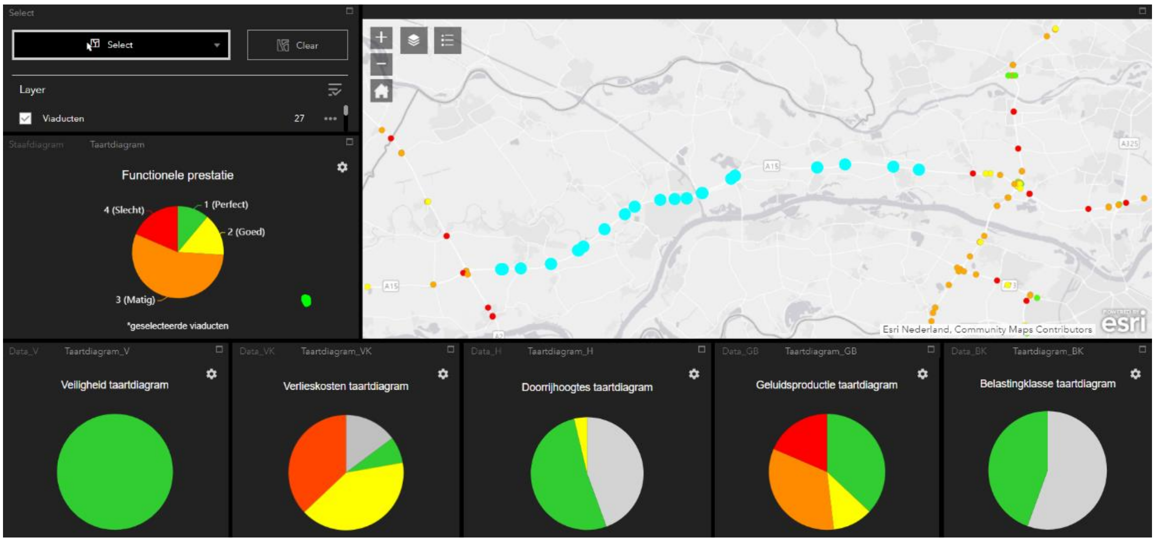
- 4. Navigeer naar een stukje netwerk die je wilt analyseren, hier zitten geen regels aan.
- 5. Gebruik de selectie tool, maar gebruik nu de optie 'select by rectangle'



Hiermee kunnen we een vierkant tekenen op de kaart, waarmee alle viaducten worden geselecteerd binnen dit vierkant.

- 6. Teken een vierkant op de kaart, waar je gekozen stukje netwerk binnen valt.

Hierna lichten de gekozen viaducten op in blauw en veranderen de visualisaties:



➢ 7. Klik vervolgens in één van de zwarte schermen van de visualisaties. Bijvoorbeeld op de plek gemarkeerd met de groene stip hierboven.

Dit zorgt ervoor dat je selectie tool uit staat, waardoor je kunt navigeren door de kaart zonder dat je selectie wordt aangepast. Ook kun je je cursor bewegen over de visualisaties om de precieze percentages en aantallen te zien.

Vervolgens kun je het geselecteerde stukje netwerk analyseren, in het voorbeeld hierboven heb ik gekozen voor een stukje van de A15. Te zien is dat:

- Aan de linkerzijde dat een groot gedeelte van de geselecteerde viaducten een matige score hebben. Een beperkt aantal (1/5e) heeft een slechte functionele prestatie.
- Aan de onderzijde, geluidsbelasting: bij de viaducten die een slechte functionele prestatie hebben, wordt dit veroorzaakt door de geluidsbelasting. De geluidsbelasting is namelijk de enige indicator die scores heeft in de categorie 'slecht'.

➢ 8. Doorloop stappen 4 t/m 7 opnieuw voor meerdere selecties. Let goed op dat je je selectie uit hebt gezet als je wilt navigeren in de kaart.

Als je weer individuele viaducten wil analyseren, switch je de visualisaties weer om zoals beschreven in stap 3, alleen nu andersom.

Appendix N – Summary of the dataset

The visualizations within the tool can be used to give an overview or summary of the dataset. Therefore, all viaducts within the dataset are selected, which are in total 3521 viaducts. These 3521 are not all named viaducts within DISK, also 'underpasses' (in Dutch: onderdoorgangen) have been included. When reviewing the differences between an underpass and a viaduct, one could spot clear differences between the appearance of the two types of structures. However, the principle is similar: they are both located at a location where a road crosses another road on a different height level. For simplicity, both types of structures are named 'viaducts' within this research. The next section will commence with the overall functional performance, where after the different sub-indicators will be analyzed.

Overall functional performance

For the overall functional performance of a viaduct, the worst score of an indicator is leading. In Figure N.1 it can be seen that the proportion per score is quite equal: every score category has around ¼ of the total amount of viaducts. The exact percentages, rounded to one decimal, of viaducts are:

- Perfect score: 25,9%;
- Good score: 23,9%;
- Fair score: 28,2%;
- Poor score: 22,0%

These percentages mean that of a total of 3521 viaducts, 25,9% have a perfect score. This translates into 913 viaducts with a perfect score.

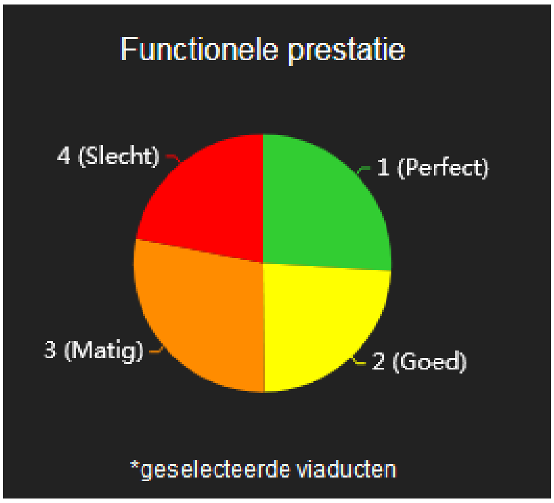


Figure N.1: Overall functional performance of viaducts and the proportion per score category.

Safety score

The proportion of scores for the safety score is shown in Figure N.2, where it can be seen that almost all viaducts fall within a perfect score. The exact percentages are, rounded to one decimal:

- Perfect score: 99,9%;
- Good score: 0,0%
- Fair score: 0,1%
- Poor score: 0,0%
- Missing data: 0,0%

This can be explained by the fact that most accidents are linked to road sections. There are simply not a lot of accidents occurring at the location of a viaduct. Additionally, the accidents that cause injuries that could be linked to a viaduct still fall within a perfect score. The fair scores can be seen as viaducts where a fatal accident occurred in 2017.

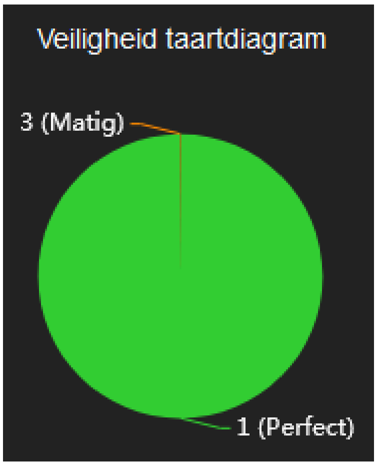


Figure N.2: Division of viaducts into the sub-indicator 'safety score'. Almost all viaducts fall within a perfect score within this sub-indicator.

User delay costs

The user delay costs give more differences between the proportions, as shown in Figure N.3. The percentages per score category are:

- Perfect score: 4,1%;
- Good score: 21,0%;
- Fair score: 24,6%;
- Poor score: 8,4%;
- Missing data: 41,9%

The significant amount of missing data can be explained by the fact that the UDC are only available for the main traffic lane and highways. So, at a location where a viaduct is located in a merging lane and crosses, for example, a provincial road, there is no data available.

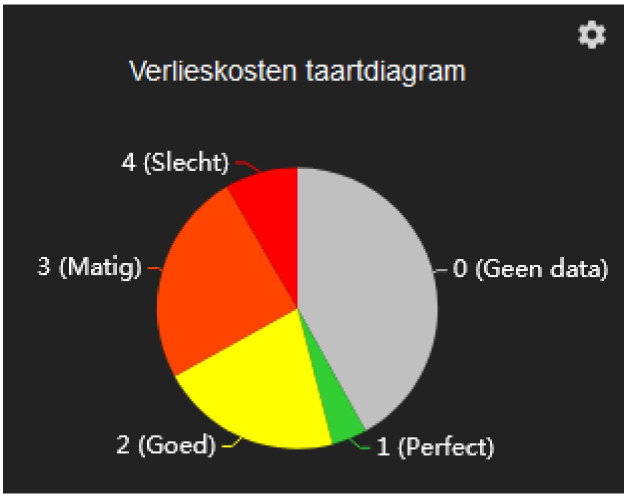


Figure N.3: Proportion of user delay costs among the score categories.

Height

The height is divided among the score categories as shown in Figure N.4. There is a large proportion of missing data, apparently, the dataset of the RDW could only be linked to a limited amount of viaducts under the management of Rijkswaterstaat. The viaducts that contain data for the heights fall almost entirely within a perfect or good score. As previously indicated, this can be explained by the original use of the dataset: to evaluate requests for exemptions, which are only needed when the height of a vehicle is higher than 4 meters. The exact percentages are:

- Perfect score: 30,5%;
- Good score: 5,9%;
- Fair score: 0,0%
- Poor score: 0,03%;
- Missing data: 63,7%

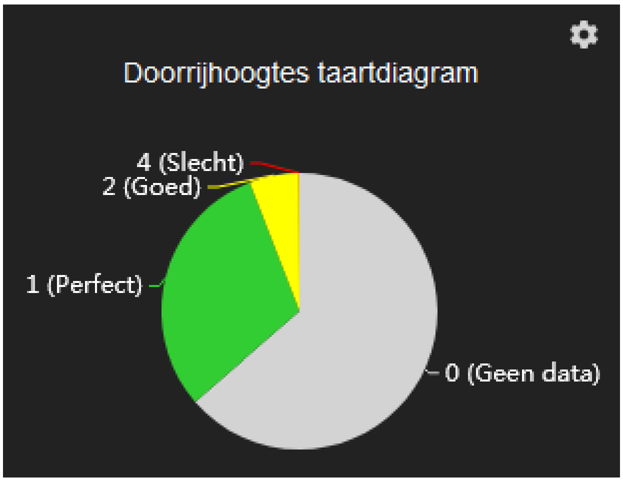


Figure N.4: Proportion of score categories for the height of viaducts. There is a large proportion of missing data (grey part).

Exceedance of noise production limit

The exceedance of the noise production limit is divided among the score categories as visualized in Figure N.5. This sub-indicator has, compared with the other sub-indicators, the largest proportion of viaducts with a poor score. Almost half of the viaducts have a perfect score and there is a limited amount of missing data. This is caused by the large coverage of the reference points across the Netherlands. The exact percentages are:

- Perfect score: 53,5%;
- Good score: 16,7%;
- Fair score: 10,3%;
- Poor score: 14,9%;
- Missing data: 4,6%

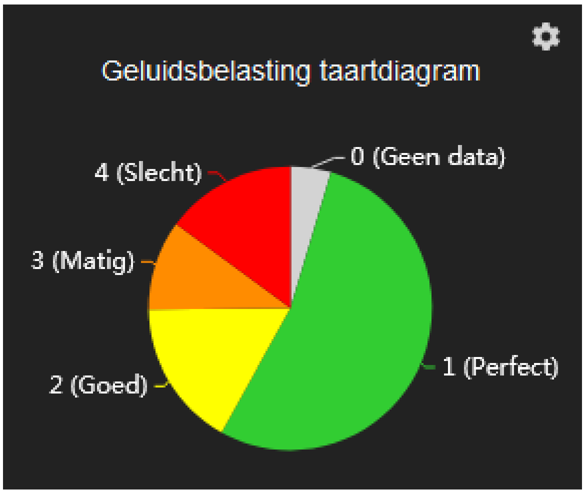


Figure N.5: Division of score categories within the sub-indicator 'exceedance of noise production limit'.

Load class

Figure N.6 shows the proportion of scores among the sub-indicator 'load class'. It can be seen that a very large part of the viaducts has a perfect score and that there is a limited amount of viaducts with a good or fair score. The exact percentages are:

- Perfect score: 79,0%;
- Good score: 1,9%;
- Fair score: 1,3%;
- Poor score: 0,0%;
- Missing data: 17,8%

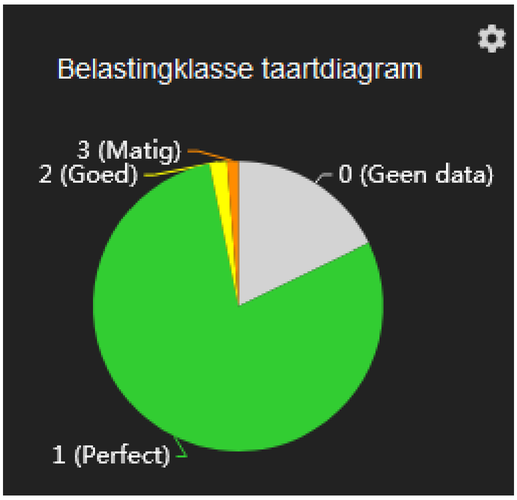


Figure N.6: Score categories for load class. A very large proportion of viaducts have a perfect score for the load class.

From these visualizations and percentages, it can be concluded that for the overall functional performance the score categories are distributed evenly. Furthermore, the exceedance of the noise production limit and the user delay costs have compared to the other sub-indicators in general worse scores. The exceedance of the noise production limit has the largest proportion of poor scores, while the user delay costs have the largest proportion of fair scores.

Appendix O – Description workshop

The workshop has been organized via skype and uses a combination of a webinar and workshop. The objectives of the workshop are the following:

1. Explain the topic of 'functional performance' and its relevance within replacement decisions.
2. Explain the methodology to determine the functional performance of viaducts and road sections.
3. Demonstrate the ArcGIS online tool.
4. Let users use the tool.
5. To evaluate the methodology and the tool and gather feedback on how to develop these further.

The first 2 objectives will be executed using a PowerPoint presentation. The demonstration of the tool will also be done within the presentation, by sharing the screen within Skype. After this, users can access the tool on their own and use the manual to follow certain steps. Lastly, the evaluation has been used using multiple ways: the questionnaire, emails or the chat function within Skype. Additionally, there will be time at the end of the session for a little discussion via Skype with participants.

Schedule Workshop

The objectives lead to the schedule shown in Table O.1, where the main parts of the workshop are:

- Introduction
- Methodology
- Demonstration online tool
- Question to participants
- Use of the tool
- Evaluation of the tool

Table O.1: Schedule workshop.

Time	Part	Topics	How?
9:10 (10 min)	Introduction	- Personal introduction - Relevance - Previous research and problem statement - Scope - Program	PowerPoint, the whole group
9:20 (40 min)	Methodology	- Used indicators - Datasets - Division in score categories - Link to individual assets (viaducts and road sections) - Overall functional performance per asset - Visualizations - Questions can be asked via the chat in Skype	PowerPoint, the whole group
10:00 (10 min)	Demonstration online tool	- Accessing the tool via a web browser - Basic functionalities map - Analysis of individual viaducts - Display of road sections - Analysis of multiple viaducts at the same time	Tool, the whole group
10:10 (5 min)	Question to participants	- Give instructions to the employees - Use the tool based on the manual - Evaluate the tool - Aspects within the context of a viaduct	PowerPoint, the whole group
10:15 (20 min)	Use of the tool	- Analysis of 3 individual viaducts, note some data of these - Analysis of multiple viaducts at the same time	Tool, manual, individual
10:35 (10 min)	Evaluation of the tool	- What do you think of the used methodology and the tool? - What kind of additional data is needed, also within the context of a viaduct?	Online questionnaire (individual), discussion (the whole group)

Participants

The participants of the workshops are employees of Rijkswaterstaat, with different roles within the organization and departments:

- Employees of the organization departments Major Projects and Maintenance, Water Traffic and Environment and the Central Information Services.
- Employees of national departments and regional departments.
- A large amount of employees is involved in the program ‘replacement and renovation’.
- People that have certain expertise for a certain sub-indicator (for example load class or noise emissions).

Because of the different backgrounds of employees and the relatively new topic ‘functional performance’ it is an important aspect to explain the relevance, scope and methodology of the research extensively. In the invitation around 50 people have been invited, approximately 25 people joined during the session. The presentation and the demonstration have been recorded and sent to people that could not participate in the session so they could watch it at a later time.

Use of the tool

In this part of the session, participants are asked to use the online tool individually. In order to guide them in this process, the manual for the tool has been developed (Appendix M – Manual for the tool). Additionally, they have been introduced to the tool during the demonstration. The manual asks respondents to perform steps in a given order, from accessing the tool via the web browser to analyzing viaducts. They are also asked to analyze 3 viaducts and note the following four aspects for each viaduct:

- DISK code of viaduct;
- Overall functional performance of the viaduct;
- The sub-indicator that is leading for this functional performance (worst score);
- The data where this sub-indicator has been based on.

A viaduct is shown in Figure O.1 as an example.

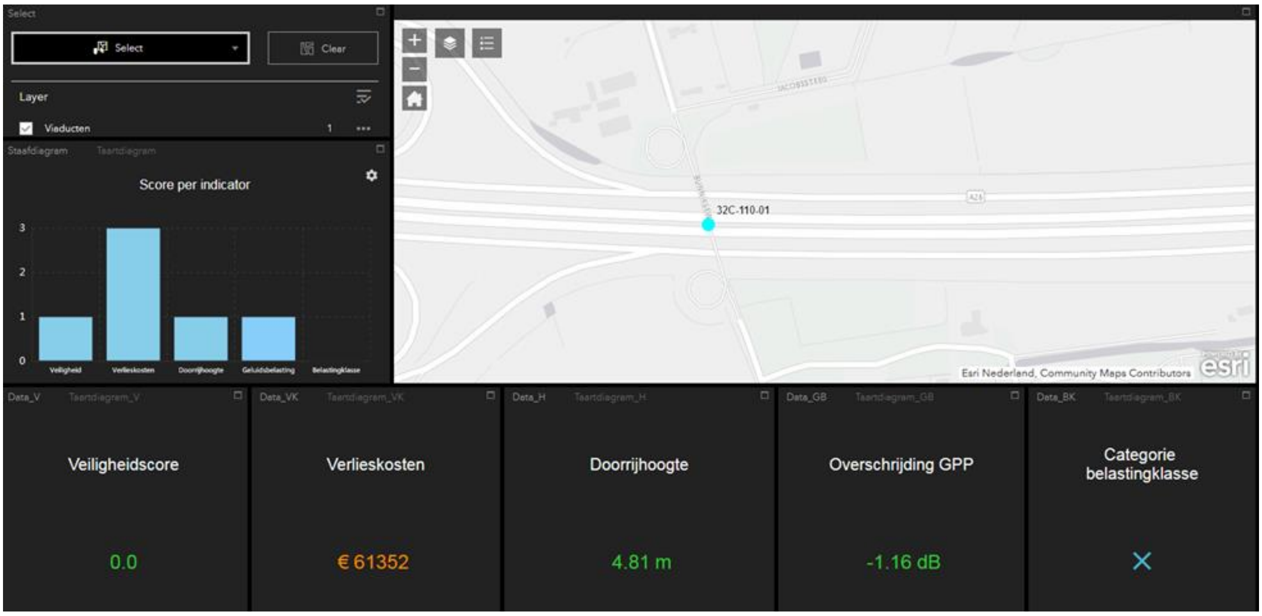


Figure O.1: Example viaduct for analysis.

If the four aspects are noted for this example, this will look like the data noted in Table O.2. When there are multiple sub-indicators that have the most worse score, people should note multiple sub-indicators.

Table O.2: Data for this specific viaduct.

DISK code	Overall functional performance	Leading sub-indicator	Data of the sub-indicator
32C-110-01	3 (fair)	User delay costs (verlieskosten)	€61352

Respondents are then asked to fill this data into the manual and send it back to the author. In this way, it can be analyzed if employees can work easily with the tool by returning the correct values from the tool and visualizations. During the use of the tool, the skype meeting will be kept intact, so employees can ask questions when they have problems when using the tool. Only a limited amount of people (3) have sent the manual filled in back.

Evaluation of the tool

As previously indicated, for the evaluation of the tool different sources have been used to gather feedback:

- Chat function within Skype;
- Emails;
- Questionnaire;
- Discussion at the end of the session via skype.

The questionnaire consists of 18 questions and has been developed using Qualtrics. The questions are in Dutch and have been added in Appendix P - Questionnaire. Respondents could fill in the questionnaire online and individually. The questionnaire has been used to steer respondents in the right direction with their feedback. It has been divided into the following elements:

- Current methodology and tool:
    - Used data and indicators
    - Score categories
    - User-friendliness
    - Visualizations
- Further development of the methodology and tool:
    - Problem and solubility analysis
    - Additional data in the tool

Six employees filled in the questionnaire, most participants preferred to give their feedback via the chat function, email or during the discussion. The results of the workshop are given in section 3.3.2.

Appendix P - Questionnaire

Link to the online questionnaire: Link questionnaire

The questionnaire has also been written in Dutch, because it has been used by employees of Rijkswaterstaat. It has been made in Qualtrics.

Evaluatie workshop

Start of Block: Default Question Block

U1 Deze vragenlijst wordt gebruikt voor de evaluatie van de huidige tool en suggesties voor verdere ontwikkeling.

In totaal bevat deze vragenlijst 18 vragen.

Hij is opgedeeld in de volgende delen:
- 1: Gebruikte data/indicatoren
- 2: Indeling van de indicatoren in de categorieën
- 3: Gebruiksvriendelijkheid
- 4: Visualisaties
- 5: Analyse van viaducten in context en verdere ontwikkeling van de tool

Wees kritisch en licht je antwoorden eventueel toe!

---

1 Wat is je naam?

____

---

2 Wat is je functie?

____

---

3 Heb je ervaring met het werken met GIS (geografische informatiesystemen)?

- ◯ Ja (1)
- ◯ Nee (2)

Page Break

U4 Deel 1: Gebruikte data en indicatoren

4 Ik begrijp goed wat de volgende indicatoren betekenen

	Helemaal oneens (1)	Oneens (2)	Neutraal (3)	Eens (4)	Helemaal eens (5)
Verlieskosten (1)	○	○	○	○	○
Doorrijhoogte (2)	○	○	○	○	○
Ontwerpbelastingklasse (3)	○	○	○	○	○
Veiligheid score (4)	○	○	○	○	○
Geluidsbelasting (5)	○	○	○	○	○

O4 Opmerkingen

____

5 Rangschik de indicatoren op basis van belangrijkheid/relevantie voor de algemene functionele prestatie van viaducten binnen vervanging en renovatie.

1 = meest belangrijk
5 = minst belangrijk

______ Geluidsbelasting (1)
______ Doorrijhoogte (2)
______ Ontwerpbelastingklasse (3)
______ Veiligheid score (4)
______ Verlieskosten (5)

5-A Heb je genoeg inzicht in de indicatoren om bovenstaande rangschikking te kunnen maken?

- ○ Ja (1)
- ○ Nee (2)

5O Opmerkingen, of zijn er nog functionele aspecten die missen?

____

Page Break

U6 Deel 2: Indeling van de indicatoren in de categorieën

U6 Zie de volgende indeling in categorieën van de verlieskosten

A6

Waarde (€/km1)	Score
0 - 2.000 (0 tot 1e deciel)	1 (perfect)
2.000 - 36.000 (1e deciel tot mediaan)	2 (goed)
36.000 - 347.000 (mediaan tot 9e deciel)	3 (matig)
> 347.000 (9e deciel en hoger)	4 (slecht)

6 Ik beoordeel de indeling van de verlieskosten in de 4 prestatie categorieën als

- ◯ Erg slecht (1)
- ◯ Slecht (2)
- ◯ Niet slecht, niet goed (3)
- ◯ Goed (4)
- ◯ Zeer goed (5)
- ◯ Weet ik niet (6)

O6 Opmerkingen

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U7 Zie de volgende indeling in categorieën van de doorrijhoogtes

A7

Doorrijhoogte (m)	Score
H ≥ 4,45	1 (perfect)
4,05 ≤ H < 4,45	2 (goed)
3,85 ≤ H < 4,05	3 (matig)
H < 3,85	4 (slecht)

7 Ik beoordeel de indeling van de doorrijhoogtes in de 4 prestatie categorieën als

- ◯ Erg slecht (1)
- ◯ Slecht (2)
- ◯ Niet slecht, niet goed (3)
- ◯ Goed (4)
- ◯ Zeer goed (5)
- ◯ Weet ik niet (6)

O7 Opmerkingen

____

U8 Zie de volgende indeling in categorieën van de ontwerpbelastingklasses

A8

Ontwerpbelastingklasse	Score
A, 60, NEN-EN-1991, NEN-6706	1 (perfect)
B, 45	2 (goed)
C, 30	3 (matig)
D	4 (slecht)

8 Ik beoordeel de indeling van de ontwerpbelastingsklasses in de 4 prestatie categorieën als

- ○ Erg slecht (1)
- ○ Slecht (2)
- ○ Niet slecht, niet goed (3)
- ○ Goed (4)
- ○ Zeer goed (5)
- ○ Weet ik niet (6)

O8 Opmerkingen

____

U9 Zie de volgende indeling in categorieën van de veiligheid score

A9

Veiligheid score per viaduct of strekkende km1 wegvak per jaar	Score
0 - 5	1 (perfect)
6 - 10	2 (goed)
11 - 15	3 (matig)
> 15	4 (slecht)

9 Ik beoordeel de indeling van de veiligheid score in de 4 prestatie categorieën als

- ○ Erg slecht (1)
- ○ Slecht (2)
- ○ Niet slecht, niet goed (3)
- ○ Goed (4)
- ○ Zeer goed (5)
- ○ Weet ik niet (6)

O9 Opmerkingen

____

U10 Zie de volgende indeling in categorieën van de geluidsbelasting

A10

Overschrijding GPP	Score
Δ < -0,5	1 (perfect)
0 > Δ > -0,5	2 (goed)
0,5 > Δ > 0	3 (matig)
Δ > 0,5	4 (slecht)

10 Ik beoordeel de indeling van de geluidsbelasting in de 4 prestatie categorieën als

- Erg slecht (1)
- Slecht (2)
- Niet slecht, niet goed (3)
- Goed (4)
- Zeer goed (5)
- Weet ik niet (6)

O10 Opmerkingen

____

Page Break

U11 Deel 3: Gebruiksvriendelijkheid

11 Gebruiksvriendelijkheid

	Helemaal oneens (1)	Oneens (2)	Neutraal (3)	Eens (4)	Helemaal eens (5)
De uitleg van de tool in de presentatie was duidelijk (5)	○	○	○	○	○
De handleiding van de tool hielp mij om de tool goed te gebruiken (6)	○	○	○	○	○
Ik had weinig problemen in het gebruik van de tool (1)	○	○	○	○	○
De algemene kaart is vrij duidelijk (2)	○	○	○	○	○
Het was makkelijk om een enkel viaduct te selecteren en de visualisaties ervan te zien (3)	○	○	○	○	○
Het was makkelijk om meerdere viaducten te selecteren en de visualisaties ervan te zien (4)	○	○	○	○	○

O11 Opmerkingen

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Page Break

U12 Deel 4: Visualisaties

12 Visualisaties

	Helemaal oneens (1)	Oneens (2)	Neutraal (3)	Eens (4)	Helemaal eens (5)
De visualisaties hielpen mij de data te begrijpen (1)	○	○	○	○	○
De visualisatie gaf mij een goed overzicht van de score van verschillende indicatoren per asset (2)	○	○	○	○	○
De vele verschillende visualisaties werkten verwarrend (3)	○	○	○	○	○

O12 Opmerkingen

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Page Break

U13 Algemene beoordeling tool

13 Wat vind je van de verschillende onderdelen van de tool?
Geef een cijfer voor elk onderdeel van de tool
1 = zeer slecht
10 = perfect

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 (7)	8 (8)	9 (9)	10 (10)
Gebruikte data/indicatoren (2)	○	○	○	○	○	○	○	○	○	○
Indeling van indicatoren in de vier prestatie categorieën (3)	○	○	○	○	○	○	○	○	○	○
Gebruiksvriendelijkheid (1)	○	○	○	○	○	○	○	○	○	○
Visualisaties (4)	○	○	○	○	○	○	○	○	○	○

O13 Opmerkingen

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Page Break

U14 Deel 5: Analyse van viaducten in context en verdere ontwikkeling van de tool

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U14 De tool bepaalt nu op een vrij globale manier de functionele prestatie van viaducten, door een methode die toepasbaar is voor alle viaducten van Rijkswaterstaat.

Echter spelen ook per viaduct aspecten mee die de functionele prestatie in de specifieke context beïnvloeden, deze worden duidelijk als meer wordt ingezoomd op een specifiek viaduct. Een voorbeeld is een overschrijding van het geluidsproductieplafond (in dezelfde mate) in 2 verschillende locaties:
- Locatie 1: Dicht bevolkt gebied.
- Locatie 2: Afgelegen gebied, de afstand tussen het viaduct en een bewoond gebied is groot.

Je zou dus concluderen dat voor locatie 2 de impact op de omgeving veel minder is dan op locatie 1.

In de volgende vraag vraag ik je om na te denken over de relevantie van de context per indicator en wat we daarvoor zouden kunnen gebruiken.

---

14 In hoeverre is de analyse van de context belangrijk voor de 5 indicatoren?

	Onbelangrijk (1)	Enigzins belangrijk (2)	Redelijk belangrijk (7)	Belangrijk (8)	Zeer belangrijk (9)	Weet ik niet (10)
Verlieskosten (1)	○	○	○	○	○	○
Doorrijhoogte (2)	○	○	○	○	○	○
Ontwerpbelastingklasse (3)	○	○	○	○	○	○
Veiligheid score (4)	○	○	○	○	○	○
Geluidsbelasting (5)	○	○	○	○	○	○

O14 Opmerkingen

____

U15 Wat voor aspecten zouden we kunnen meenemen in de analyse van de functionele prestatie in de context per indicator? De volgende voorbeelden per indicator zijn gegeven om je op weg te helpen, vul deze verder aan.

- Verlieskosten: eventuele bottleneck, bijvoorbeeld een reductie in het aantal rijstroken
- Doorrijhoogte: nabijheid alternatieve routes
- Ontwerpbelastingklasse: beperkingen maximaal gewicht of tonnage
- Veiligheid score: eventuele onveilige situatie
- Geluidsbelasting: afstand tot een woonwijk

Je hoeft niet voor elke indicator iets in te vullen, mocht je niks kunnen bedenken bij een bepaalde indicator.

	Aspecten (1)
Verlieskosten (4)	
Doorrijhoogte (5)	
Ontwerpbelastingklasse (7)	
Veiligheid score (8)	
Geluidsbelasting (9)	

O15 Opmerkingen

____

16 Welke functionaliteiten of data zijn nog handig om toe te voegen aan de tool?

____

17 Zie je nog andere mogelijke toepassingen binnen RWS voor een vergelijkbare tool, die AcrGIS online gebruikt?

☐ Ja (1)

☐ Nee (2)

O17 Zo ja, voor wat?

____

18 Heb je nog algemene opmerkingen of suggesties voor de tool?

____

End of Block: Default Question Block

Appendix Q - Preview of the development of traffic flow in the future

Figure Q.1 shows a preview of how data can be used that predicts the situation for the user delay costs in the future. A description of the figure will follow after the figure.

Figure Q.1: User delay costs in the year 2030 in a scenario where a high increase in traffic occurs.

This map is based on a report that predicts the future situation of highways in the Netherlands (4cast, 2017). The report distinguishes two scenarios: a high or low increase in traffic in the future. Based on the scenario with a high increase in traffic, the figure has been composed for the situation in the year 2030. The 50 road networks with the highest user delay costs are included in the figure and a division has been made between 3 categories of user delay costs. The prediction of user delay costs also includes new road networks that will be built in the future. Please note that this map does not take into account the different lengths of road networks.