DEVELOPMENT OF GEOMETRIC QUALITY INDICATOR FOR RAILWAY SWITCHES

Bachelor thesis

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Management summary

The motivation of the research is the insufficient insight into the geometric quality of railway switches at ProRail. The proposed solution is the development of a performance indicator for the geometric quality. Therefore, the research focuses on the following main research question:

How can a performance indicator be designed to evaluate the geometric quality of railway switches at ProRail?

The Design Science Research Method (DSRM) is used to develop an artefact which is a methodology for the development of a quality indicator. Based on this approach the following research questions are defined:

1. How is the geometric quality of railway switches currently evaluated?
2. What role should the quality indicator fulfil at ProRail?
3. How can a quality indicator based on several measurements be developed?
4. How can a quality indicator be implemented at ProRail?
5. How can the quality scores be evaluated?

Based on literature research a framework is identified for creating a composite indicator. For each step suitable techniques and methods are incorporated into a methodology for creating a quality indicator. These steps include:

- **Selection of indicators:** The selection of indicators is based on the exploration of data, correlation analysis and the judgement of experts. The selected indicators are modelled into a hierarchy to identify the different relationships between the indicators. After selecting the indicators, the criteria measurements need to be normalised.
- **Normalisation:** Criteria values most likely have different scales and unit of measurements and therefore need to be normalised in order to be comparable. A distinction is made between two types of criteria values; criteria values that are expressed numerically are normalised by a value function and criteria values that are labelled ordinally are assigned a certain score.
- **Weighting:** The AHP-method is used to determine the weighting for each indicator. The AHP-method is a subjective weighting method and used the judgement of an expert to determine the weights.
- **Aggregation:** The simple additive weighting function is used due to it transparency and simplicity with the assumption that the indicators are independent from each other.
- **Robustness analysis:** The robustness of the indicator is tested by using uncertainty and sensitivity analysis. In addition, the indicator is validated by comparing the results with the judgement of an expert.

The methodology is implemented at ProRail to create a quality indicator for the geometry of railway switches. The geometric parameters are used as indicators and they are grouped by segment and entry. The normalisation is based on the current threshold values. The Alert Limit (AL), Intervention Limit (IL) and nominal values are used as parameters for the value function. In addition, the judgment of a railway switch expert is used to determine the weights with the AHP-method. After that, the quality scores of the railway switches are calculated for the railway switches. As a result, the overall quality scores can be analysed based on their distribution and sub-indicators can be used to evaluate the quality of the segments, entries or geometric parameter of a certain railway switch.

Finally, the quality indicator is evaluated based on evaluating uncertainties, sensitivity analysis and validation by expert judgement. The uncertainties relate to how certain decisions and input affect the rankings of the quality scores. For example, the AHP method is used in this case, however, another subjective weighting method could also be used which could result in different quality indicators.

Due to time restrictions, the sensitivity analysis is limited to analysing the effect of different parameter values for the normalisation function. This showed that the curvature of the normalisation function did not have a huge impact on the average rankings of railway switch quality scores, however, when looking at the extreme cases we see that it can have a considerable impact on the score.

In addition, weights for each geometric parameter are compared with the importance of each parameter according to a railway switch expert. These two showed different results which could be explained by how the geometric parameters are presented to the railway switch expert. Based on this, a new grouping for the geometric parameters is recommended and more research could be done on whter two separate quality indicators could be created for the safety and the sustainability of a railway switch. Furthermore, the rankings of ten railway switches were compared with the judgement of a railway switch expert. This validation showed promising results and discrepancies could be explained by the quality indicator being more consistent. However, the sample used is small and more validation is needed in the future.

In conclusion, a methodology is created for the development of quality indicators. The methodology could also be used by other situations with the same requirements and restrictions. By using own data and expert judgement the same methodology could be implemented to create other kinds of performance indicators. In case of ProRail, the same methodology could be used to improve the implementation of the current quality indicator for the railway switches or by creating the same king of indicator for the railway crossings.

In addition, the methodology showed promising results during the implementation at ProRail. Still, the implementation could be improved more and more research should be done on the credibility of the quality scores. Therefore, future research is recommended for more validation and sensitivity analysis by changing uncertain factors of the current model and then testing the quality scores by a railway switch expert. In addition, more research should be done on the meaning of the quality indicators by, for example, determining when a score is sufficient or insufficient. Also, the relationship between the quality indicator and degradation and restoration factors could be explored to get mutual insights.

Acknowledgements

This thesis would not be possible without the help of my colleagues at ProRail and my supervisors from the University of Twente.

I want to thank Monique Voorderhake for arranging my internship at ProRail and welcoming me to the company. In addition, I want to thank Frank Vermeulen for helping me get familiar with the data environment and being available for my questions. Moreover, I am grateful for the input and ideas provided by Gerbert Brouwer. His input was of great importance for the results of the research and I want to thank him for his time discussing my ideas. Furthermore, I want to give my thanks to Theo Kruze for setting up my project and offering guidance in the first weeks of my research.

In addition, I want to give my special thanks to Ingmar Bolderink who took on the job of supervising me on behave of ProRail. I really enjoyed discussing my ideas with him and his insights were of great value for shaping my research. His support, feedback and ideas helped me make my bachelor assignment a success.

Furthermore, I want to express my gratitude to my supervisor Asad Abdi. He gave me the critical feedback necessary to make my research and thesis fulfil the academic standards and making it more professional. I learned a lot from our Friday meetings, and I want to thank him for his patience, guidance, and feedback.

Finally, I want to thank Engin Topan for being my second supervisor. His feedback helped me improving the thesis making it clearer and more complete.

Table of contents

Chapter 1: Introduction

The bachelor assignment has been done in collaboration with ProRail, the company responsible for the railway network in the Netherlands. Together with the asset management department a suitable assignment has been formulated. In this chapter the company, the problem statement, the research approach and research design are described.

1.1. ProRail

ProRail is the company responsible for managing the construction, maintenance and safety of the railway system in the Netherlands. Together with the transporters they make sure that goods and passengers can safely travel over the railway without hindrance. Furthermore, ProRail is responsible for managing the traffic on the railways and the control of train stations.

ProRail strategy focuses on the three objectives: "Verbindt, Verbetert en Verduurzaamt" (Connect, Improve and Enhance Sustainability). Firstly, ProRail wants to increase the capacity of the railway infrastructure, so that future demand can be met. Due to the climate goals imposed by the government, ProRail expects an increase in the usage of trains. Secondly, ProRail focuses on improving the reliability of the railways, so that trains can safely transport goods and people without hindrance. The third objective focuses on making ProRail more sustainable by reducing energy consumption and stimulating the reuse of materials.

The research is done with the asset management department. The asset management focuses on the maintenance of their assets which is the railway infrastructure. They make sure that the railway tracks are in good condition, so that passengers can safely travel by train.

1.2. Problem context

Two times a year the quality of all the railway switches in the Netherlands are measured. These measured consists of different geometric dimensions which are measured on different points on the railway switch. Based on these measurements the geometric quality of a railway switch is evaluated. These geometric measurements are assessed by a railway switch expert based on whether they exceed a certain threshold value. Depending on the state of several of these geometric parameters the according actions are taken, so that the safety and life duration of a railway switch can be guaranteed.

However, the number of measurements per railway switch is too overwhelming for a railway switch expert too take all measurement into account. As a result, a lot of data is not incorporated into the judgement and the assessment is not always consistent. Therefore, a solution is needed which could use the geometric data to create more insight into the overall quality of a railway switch.

1.3. Problem identification

In this section, the problem cluster is worked out in order to find the core problem at ProRail. Then, a solution is proposed to solve this problem. Finally, the current situation and expectation have been compared to justify the value of solving the core problem.

1.3.1. Problem cluster

Figure 1 shows the problem cluster in which the causal relations between the different problems related to switch failures are displayed. The problem cluster shows how low quality of railway switches is caused by degradation of the rail tracks and insufficient maintenance. In addition, the problem cluster shows which problems switch failures cause to their customers which are the transports.

1.3.2. Core problem

Methods provided by the Managerial Problem-Solving Method (MPSM) of Heerkens and van Winden (2017) are used to identify the core problem. The problem cluster in figure 1 shows the different problems and their causal relationships.

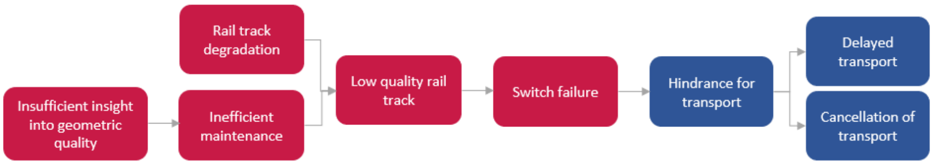


Figure 1: Problem cluster

According to Heerkens and van Winden (2017) the core problem is a problem which has no direct causes themselves. The problems without a direct cause are the rail track degradation and the insufficient insights into the geometric quality.
In addition, the core problem must be influenceable, because otherwise the situation cannot be improved. Therefore, rail track degradation is not a core problem, because damage to rail tracks is inevitable when trains are using the rail tracks for transport. This only leaves the insufficient insight into the geometric quality as possible core problem.

1.3.3. Proposed solution

The proposed solution is to develop a quality indicator which would create more insight into the geometric quality of the railway switches. Such a performance indicator would give a more consistent assessment on the state of all the railway switches. In addition, by aggregating all the measurement into a single indicator evaluating the quality becomes easier and enables the possibility for comparing contractors and predicting future quality.

1.3.4. Norm and reality

The gap between norm and reality is identified to determine how the proposed solution will improve the current situation. Currently, insight into the geometric quality is based on the judgement of railway switch experts. As a result, only a few critical geometric properties can be considered. In addition, these geometric properties are assessed based on a few limits. This means that geometric dimensions which exceed the same limit are considered the same. The norm should be that all the geometric data is incorporated into the assessment of the quality of a railway switch. Therefore, a performance indicator is proposed as a solution because this would create more insight into the quality.

1.4. Research approach

In this section, the research approach is explained. Firstly, the main research question is introduced. Then the research methodology which will be used for the research is explained. For each step of the methodology, the activities, research questions, data gathering methods and deliverables are explained. Finally, the scope of the research is described.

1.4.1. Main research question

To solve the core problem mentioned in the previous section, the following main research questions is formulated:

How can a performance indicator be designed to evaluate the geometric quality of railway switches at ProRail?

1.4.2. Research methodology

The Design Science Research Methodology (DSRM) will be used for conducting the research. The DSRM consists of six steps which are shown in figure 2. Pfefferst, Tuunan, RotheBerger and Chatterjee (2007) give a clear description of the DSRM: “Design Science involves a rigorous process to design artefacts to solve observed problems, to make research contributions, to evaluate the designs, and to communicate the results to appropriate audiences”.

The DSRM is chosen, because it focusses on the design of artefact as a solution of a problem. To solve the main research question, a method needs to be created which could be used to create a quality indicator for ProRail. This method is the artefact which will make research contributions and will be evaluated and communicated.

The MPSM proposed by Heerkens and van Winden (2017) was not chosen, because it focuses on generating different solutions for solving the problem and eventually choosing the best option. In this research, a method for developing a quality indicator is the proposed solution, therefore analysing different solutions is not relevant for this research. Instead, the focus on the requirements and feedback of the end-user to improve the proposed solution is of greater importance. Therefore, the DSRM is a more suitable approach for this research.

For each step the research questions, data-gathering methods and deliverables are described. In table 1 an overview is shown of all the steps and in which chapter they are described.

Figure 2: Design Science Research Methodology

1. Problem identification and motivation

The first step focuses on the defining the research problem and motivating the value of solving that problem. Although the DSRM is used for the research approach, the methods provided by the MPSM are used for the problem identification step, because the MPSM provides a clear systematic method for identifying the core problem. Based on the core problem, the research questions and the research approach are defined.

2. Definition of the objectives for a solution

The second step of the DSRM focuses on the formulation of objectives of solving the research problem. During this step it is important to research how a quality indicator for the railway switchers will create more insight into the geometric quality of railway switches. In order to do this, the current situations at ProRail are analysed.

- How is the geometric quality of railway switches currently evaluated?
  - How is the geometric performance of railway switches measured?
  - How is the performance assessed based on these measurements?
  - How is the decision-making regarding maintenance determined?

In addition, by analysing the current situations and conducting unstructured interviews with employees the role of the quality for ProRail is identified.

- What role should the quality indicator fulfil at ProRail?
  - What are the requirements for such an indicator?
  - What are the restrictions based on the current situation?

3. Design and development

During the design and development phase, the artefact, in this case the methodology for developing quality indicators, will be designed. This step includes gaining knowledge of theory for solving the problem. By analysing literature, existing methods and cases are used to develop a methodology which meets the requirements and restrictions at ProRail to develop a quality indicator.

- How can a quality indicator based on several measurements be developed?
  - Which steps have to be executed in order to develop such an indicator?
  - What methods are suitable to create a quality indicator?
  - What activities need to be executed?
  - How can a methodology be developed for the creation of quality indicators?

4. Demonstration

During the demonstration step, the artefact will be implemented at ProRail. This means that the methodology developed in the previous step is implemented at ProRail, so that the quality indicator of the railway switches can be calculated.

- How can a quality indicator be implemented at ProRail?
  - How can the methodology for developing quality indicators be implemented at ProRail?
  - How can the quality indicator be calculated?
  - What are the quality scores of the railway switches?

5. Evaluation

After the demonstration, step the dashboard will be evaluated to see if it fulfils the requirements. This includes identifying if there are any uncertainties present with the calculations, performing sensitivity analyses and validating the quality scores.

- How can the quality scores be evaluated?
  - What kind of uncertainties are there in the methodology?
  - How could sensitivity analysis be used to analyse these uncertainties?
  - How can the quality scores be validated?
  - How could the quality indicator be improved?

6. Communication

The final step focuses on the communication of the artefact and the research to the relevant audiences which are ProRail and the University. The artefact is communicated through this thesis. This step focuses mainly on the conclusions and recommendations that can give based on the whole research.

- What conclusion can be drawn from the research?

- What is the contribution of the research?
- What recommendation can be made?
- What further research is required?

Table 1: Overview research approach

Overview of research approach			
Step	**Research questions**	**Chapter**	**Deliverables**
Definition of the objectives for a solution	How is the geometric quality of railway switches currently evaluated? What role should the quality indicator fulfil at ProRail?	2. Current situation	Analysis of the current situation and a list of requirements and restrictions for the development of a quality indicator
Design and development	How can a quality indicator based on geometric measurements be developed?	3. Literature research	A methodology for the development of a quality indicator based on literature research
Demonstration	How can a quality indicator be implemented at ProRail?	4. Implementation at ProRail	Implementation for the calculations of the quality indicator for the railway switches and the results
Evaluation	How can the quality scores be evaluated?	5. Evaluation	Evaluation of the quality indicator
Communication	What conclusion can be drawn from the research?	6. Conclusion	List of recommendations and conclusion

1.5. Research design

The according research is designed based on the research approach. In this section, the variables, theoretical perspective, the theoretical relevance, the research method, and its limitations are described.

1.5.1. Key variables and operationalisation

The key variables of the research are the geometric parameters and the quality. These geometric parameters are measured on different points on a railway switch. The research focuses on the relationship between the geometric parameters the quality of a railway switch. The quality of a railway switch is operationalised by creating an indicator which is calculated based on the geometric measurements. The relationship between the geometric parameters and the quality of railway switches are quantified by weights which determines the importance of the geometric measurements on the total quality.

1.5.2. Theoretical perspective

Theories about Multi-Criteria Decision Analysis (MCDA) are used to research the development of a quality indicator. MCDA focuses on the evaluating alternatives based on several attributes to come up with the best decision. Using MCDA techniques, a composite indicator could be created to reflect the geometric quality of a railway switch. MCDA provide methods for normalisation, weighting and aggregation, which can be used to integrate many attributes in a single indicator. Chapter 3 gives an elaborate description on the theories used.

1.5.3. Theoretical relevance

In the literature there are several methods for assessing the geometric quality of railways. These methods include indices such as the J Synthetic Coefficient and the Track Geometry Index (TGI) (Berawi et al., 2010). These methods only focus on parameters related to normal railways, but not the geometric parameters of railway switches. In addition, there exist cases which implement a composite indicator in a maintenance context. However, these approaches mainly focus on the process of obtaining weights and not all the different steps for creating a composite indicator.

Therefore, the theoretical relevance of this research is derived from providing a general approach for creating quality indicators. Even though, the approach is developed in the problem context of ProRail, the method could also be implemented in different situations in with similar requirements and restrictions. By implementing and evaluating the quality indicator at ProRail, the suitability of certain techniques from the literature are explored.

1.5.4. Research method

The research requires explanatory quantitative analysis. The research is quantitative, because the variables are measured in numerical values. Both the geometric parameters and the geometric quality are expressed in numbers. In addition, interviews with rail system experts will be conducted. The results of the interviews will be transformed into weights which can be used for the composite indicator.

The research is explanatory, because it focuses on the relationship between the geometric parameters and the quality. By researching what weights should be assigned to each parameter, the relationship between the variable becomes clear.

The research population are the railway switches, because these objects are the main focus of the research. The geometric data of the railway switches are collected and analysed to create insights into their geometric quality.

The data-gathering methods are both quantitative and qualitative. The measurement data of the geometric parameters are numerical, therefore quantitative data-gathering is required. In addition, qualitive data-gathering methods are used to obtain more knowledge about the geometric properties and their impact on the quality. This requires interviews with experts and literature research which are descriptive.

1.5.5. Reliability and validity

The reliability of the composite indicator can be evaluated by testing the robustness. Sensitivity and uncertainty analysis are performed to identify uncertainties in the methods used and analyse how the value of the composite indicators changes with small changes in the input. This gives an indication on how robust the quality indicator is.

The validity of the geometric quality indicator will be judged by rail system experts. Interviews will be conducted with rail system experts to gather their judgement on how well the composite indicator represent the geometric quality.

1.6. Thesis overview

The following chapters focus on answering the research question. Is small description is given on the content of each chapter.

Chapter 2 gives a description of how railway switches are currently evaluated and how this results in decisions for maintenance. In addition, based on the current situation the role of a composite indicator and its requirements and restrictions are discussed.

Chapter 3 describes theories that are used to develop a method for development of a quality indicator. A framework for creating a composite indicator is discussed. Based on this framework suitable methods for the developing a quality indicator are selected and integrated into a single methodology.

Chapter 4 focuses on the implementation of the method in the problem context of ProRail. The recorded data and expert judgement of ProRail are used to implement the quality indicator for the geometry of railway switches.

Chapter 5 evaluates the results of the implementation at ProRail. The uncertainties and assumptions of the implementation and method are discussed. In addition, sensitivity analysis and validation by expert judgement are done to test the credibility of the quality indicator. Based on the evaluation improvements for the implementation of the method are discussed.

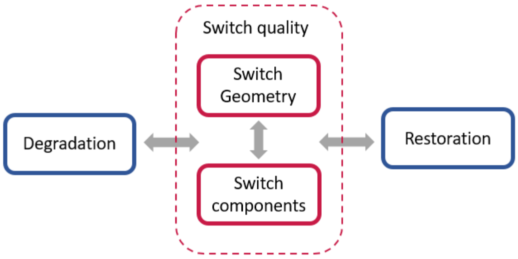


Figure 3: Railway switch quality

Chapter 2: Current situation

This chapter focuses on how the quality of railway switches are currently evaluated and what factor should be taken into account when developing a quality indicator. Firstly, the degradation and restoration of railways are described. Secondly, the monitoring and evaluation of the quality is explained. After that, the decision-making of maintenance is discussed. Finally, the role of a quality indicator is described.

2.1. Degradation and restoration

During the years, the quality of railway switches will decrease due to degradation. This degradation is caused by forces exerted by train traffic. Local factors such as the amount of load that crosses the rail switch and the subsoil affect the degradation rate.

Degradation can be described in means of the geometry of the rail track and the state of the components (Zwanenburg, 2008). The geometric quality focuses on the measurements of the shape of the rail tracks while the quality of the components focuses on the state of the materials in terms of wear and damages. The geometric quality and the quality of components mutually influence their degradation rate. A bad geometric quality will increase the degradation rate of the components and vice versa.

To guarantee the functionality and safety of the railway switch the rail switch geometry and switch components have to be restored. The restoration includes the maintenance and the renewal of railway switches when they do not meet the standards. By analysing the rail switch quality and the degradation rate, decisions can be made on what and when maintenance is needed and how safety can be guaranteed.

2.2. Railway switch measurement

The state of the geometry of the railway switches are monitored by a special measuring train. Every railway switch in the Netherlands is measured twice a year to measure the dimensions of certain

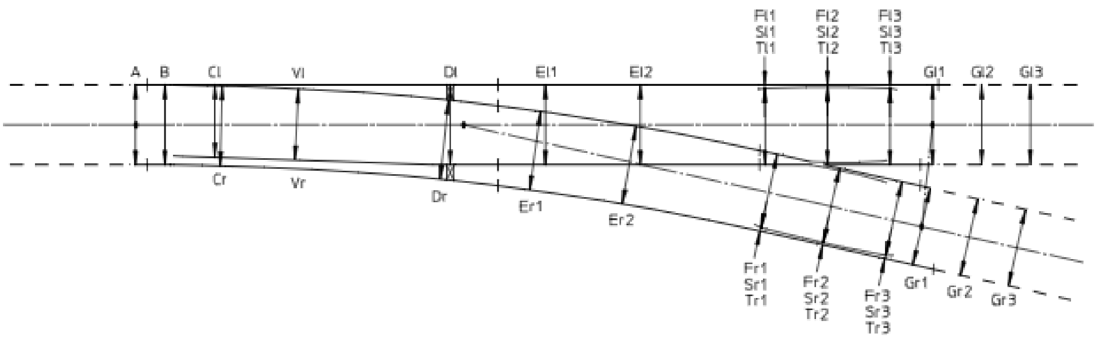


Figure 4: Sketch measuring points

geometric properties. These measured geometric properties are also called geometric parameters and include, for example, the gauge (distance between two rail tracks), the alignment and the profile of rail tracks. A full list of all the geometric properties can be found in Appendix A. The geometric parameters are measured at a certain point on the railway switch and most geometric parameters can be measured on multiple points. Figure 4 shows a sketch of a railway switch on which some of the different measuring points are marked.

Furthermore, the rail switch splits into two entries. One of the entries keeps going straight while the other entry diverges to the other side. Therefore, a railway switch is always measured twice for the left and the right entry.

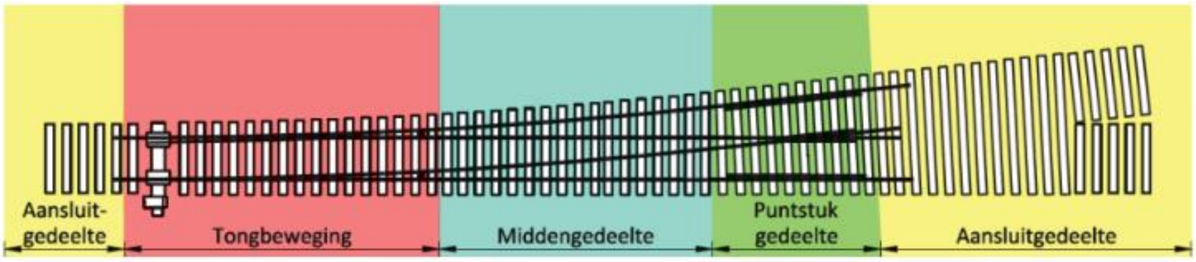


Figure 5: Rail switch segments

In addition, a rail switch can be divided into five different segments. A railway switch consists of a connection section ("aansluitgedeelte"), tongue section ("tongbeweging"), middle section ("Middengedeelte") and point section ("puntstuk gedeelte"). Figure 5 shows a sketch of a railway switch and its segments. On each segment a different set of geometric parameters are measured (See Appendix E.1). The connection and middle sections have similar geometric parameters, because these segments consist mainly of normal rail tracks. The tongue and point section are responsible for the machinal part of the railway switch which makes sure that the train is directed to the correct direction. Therefore, on these segments additional geometric parameters are measured to determine if a train can safely switch tracks.

2.3. Geometric quality assessment

Each geometric measurement is assessed by determining if the measurements exceeds a certain threshold limit. If a parameter measurement exceeds the threshold limit the measurement is labelled by its exceedance. Three limits are used to determine the severity of the exceedance:

- **The alert limit (AL)** or "Onderhoudswaarde"**:** the alert limit is the minimum standard for the state of the geometric parameter. The alert limit should not be exceeded in order to maintain a sustainable life duration of the railway switch.
- **The intervention limit (IL)** or "Inteventiewaarde"**:** When the intervention limit is reached, the safety of the trafficability cannot be guaranteed. An expert will analyse the situation and determines which measures should be taken.
- **The Immediate action limit (IAL)** or "Onmiddelijke actiewaarde**:** When a measurement exceeds the IAL, the parameter is in such a bad state that the train traffic should be cancelled immediately. In this case, the judgement of an expert does not matter.

These limits can be minimum or maximum values depending on the geometric value. These values of the limits can vary for the same geometric parameter depending on the type of railway switch and the speed limit at the certain railway switch. These conditions and values are recorded in the OHD and IHS document. Depending on the contractor of a certain area a version of one of these documents apply.

In addition, there is also a nominal value defined for each geometric parameter. This geometric parameter is the ideally preferred value a geometric measurement can have. The more the measurement deviates from the nominal value the worst the state of that parameter is.

2.4. Decision-making

Based on the encroachments, a rail system expert will assess the situation and determine which measures have to be taken. The rail system experts analyse the exceeding parameter in combination with other relevant parameters which may not exceed any limits to assess the severity of the problem. For example, geometric parameter with an intervention limit may be less dangerous when other related parameters are in a decent state.

In addition, specific factors related to the region of the railway switch are taken into account by the expert judgement. The local degradation rate influences the urgency of the situation. Because of this, the track load and the environmental factors such as the subsoil have to be taken into account in the analysis.

The rail system expert will determine which action should be taken. Firstly, the rail expert can decide to decrease the maximum speed limit of the rail system experts. The threshold limits of the geometric parameter depend on the speed limit. By decreasing the speed limit, the rail switch can fulfil the standards, so that it does not exceed the limit. Secondly, the rail system expert can decide that maintenance should be performed on the railway switch. Finally, in the worst-case scenario traffic on the railway switch should be cancelled, so that maintenance can be performed immediately. Otherwise the situation might lead to dangerous situations.

2.5. Role of a quality indicator

A quality indicator would support the decision-making regarding the maintenance, because it can take into account all the information and aggregate that into a single indicator. Such an indicator provides more insight into the overall geometric quality of railway switches, because it enables quantitative analyses on a railway switch level. For instance, the quality indicator makes it possible to compare the geometric quality of railway switches with respect to each other. As a result, problem regions could be identified and improved.

By analysing the current situation and conducting unstructured interviews the requirements and restrictions for developing a quality indicator are identified. These requirements and restriction are considered when developing a method for the construction of a quality indicator.

2.5.1. Expert judgment

Firstly, the development of a quality indicator is restricted by the lack of objective indicators for the quality of railway switches. There is no data available about, for example, the life durations or safety issues with railway switches that could be used as output variable to determine the relationships between the geometric parameters and the quality. Therefore, expert judgement has a crucial role in developing and validating the quality indicator. As a result, quantifying the relationship between the geometric parameters and the quality of a railway switch depends on gathering information from railway switch experts.

2.5.2. Transparency

An important requirement of the quality indicator is that the calculation of the indicator should be transparent. This means that the calculation should not be a black box which somehow creates a quality score where the intermediate calculation steps cannot be traced back. Instead, the user of the quality indicator should be able to understand and traceback how the quality indicator comes about.

For example, when a rail system expert discovers that a certain rail switch scores low on quality, then that person should also be able to know why the rail switch scores low.

2.5.3. Data input

For most of the geometric parameters, the exact measurement of the dimensions is available in the data. However, for a few geometric parameters only the exceedance of the threshold limits is known. Therefore, the method for determining the quality indicator should be able to handle attributes which are numerical and an ordinal scale.

In addition, the relation between the measurement of the geometric parameter and the quality is not linear. The relationship is not linear, because a millimetre change in measurement when the value does not meet the intervention limit is less critical than when the measurement changes a millimetre and it exceeds the intervention limit. For example, when the track gauge changes from the nominal value of 1435 mm to 1436 mm is less severe than when the track gauge changes from the intervention limit of 1452 mm to 1453 mm.

2.6. Conclusion

In conclusion, the quality of railway switches is currently monitored by measuring their geometric properties. These measurements are evaluated based on the three threshold values: the AL, the IL and the IAL. A railway switch expert analyses these measurements and decides if necessary what actions should be taken in order to guarantee the safety and trafficability.

A quality indicator would improve the maintenance of railway switches by making decision-making faster, more consistent and more accurate. Expert judgement, transparency and the data input are considered when developing a method for the construction of a quality indicator.

Chapter 3: Literature research

In this chapter, literature research is conducted to determine how a quality indicator can be created based on measurements of several geometric parameters. By identifying the required steps and methods for developing an indicator, a methodology is created which can be used to create a quality indicator at ProRail.

In the first section, the concept composite indicator is explained. Then, a framework to create a composite indicator is constructed based on the literature. After that, the different methods for executing each step of the framework are identified and the suitable methods for the implementation at ProRail are discussed. Finally, a methodology is constructed which is used to implement a quality indicator for the railway switches.

3.1. Composite indicator

Developing a composite indicator is a suitable concept for assessing quality of railway switches at ProRail. Greco, Ishizaka, Taisou and Rorisi (2019) describe a composite indicator as: "a composite indicator might reflect a 'complex system' that consists of numerous 'components', making it easier to understand in full rather than reducing it back to its 'spare parts'. A composite indicator makes it possible to aggregate information of several components into a single indicator. Femurewa, Berges, Stenström and Kumar (2014) also mention that composite indicators are a suitable tool for "benchmarking and strategic decision making and can be used for monitoring maintenance and renewal in a capacity enhancement programme". Therefore, creating a composite indicator for the quality of railway switches is useful because it can support the decision-making regarding maintenance of railway switches.

Methods used in Multi-Criteria Decision Analysis (MCDA) can be used to develop such a composite indicator. "The MCDA methods' task is to support a decision-maker in choosing the most preferable variant form many possible options taking into account a multitude of criteria characterizing acceptability of individual variants" (Watróbski et al., 2019). MCDA are used to select decisions based on different criteria. In the case of composite indicators, the criteria are the sub-indicators which you use to determine the composite indicator which can be used to rank different options.

3.2. Theoretical framework

A framework is formulated to give a structural approach for the construction of composite indicators. Using a clear framework is important, because it is responsible for the usefulness and integrity of the composite indicator (S.M. Famurewa et al., 2014). In the literature there exist multiple frameworks for developing such an indicator. Based on the existing frameworks, a suitable framework is created which could be used to develop a composite indicator for the quality of railway switches.

Femurewa, Berges, Stenström and Kumar (2014) have created a framework for the construction of composite indicators. They define four core issues for their framework which are: selection of indicators, selection of aggregation technique, selection of weighting method, aggregation process. A composite indicator is calculated as an aggregate of multiple sub-indicators. Therefore, a selection should be made on which indicators are relevant to be incorporated into the composite indicator. The weighting step determines what impact each indicator should have on the calculation of the composite indicator. MCDA provide many methods that can be used to determine these weights. Furthermore, there are many aggregation functions that can be used to calculate the composite indicator.

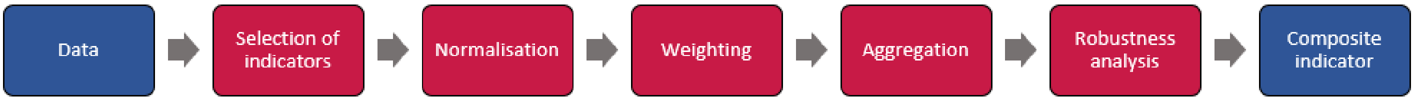


Figure 6: Framework composite indicator

Next to weighting and aggregation, Gibari, Gómez and Ruiz (2018) identify normalisation as one of the three main processes for constructing a composite indicator. The selected indicators may not have the same unit of measurement. Therefore, normalisation is needed before the aggregation to measure each indicator on the same scale, so that they can be compared with each other.

Finally, the robustness of the composite indicator should be analysed. According to the OECD (2008), "Uncertainty and sensitivity analysis should be undertaken to assess the robustness of the composite indicator". The sensitivity analysis provides insight on how reliable the model is by analysing how differences in inputs affect the calculation of the composite indicator.

These six steps are integrated into a single framework which is shown in Figure 6. This framework gives the general structure for the development of a composite indicator. For each step of the framework, relevant methods for executing the steps are identified and the most suitable methods are incorporated into the methodology for creating a quality indicator.

3.3. Selection of indicators

Firstly, the relevant indicators which need to be incorporated into the composite indicator and their relationships need to be identified. In this section, literature about how these indicators can be selected and how their relationships can be modelled in a hierarchy are discussed.

3.3.1. Selection criteria

Galar, Berges-Muro and Kumar (2014) argue there are three steps which should be taken into consideration for selecting indicators. Firstly, the data should be analysed to determine the possible indicators. After that, correlations between the different possible indicators should be analysed to see if there are any indicators which could be eliminated. If an indicator has a high correlation with another indicator, then the indicator may be substituted for that indicator, since they provide the same information. However, correlation on its own does not provide sufficient insight into substitutability of an indicator because the indicator might still provide other relevant information. Therefore, "the analyst considers the balance between policy relevance and statistical integrity". (Galar, Berges-Muro & Kumar, 2014). So, for the final step an expert should be consulted to consider the relevance of the list of indicators.

Based on these requirements, the relevant indicators will be selected for the quality indicator for ProRail. Firstly, the data will be explored to identify potential indicators which could be incorporated into the quality indicator. Then, correlation analysis and expert judgement will be used to determine the relevance of each indicator, so that a final selection can be made.

3.3.2. Indicator hierarchy

A composite indicator is composed of several different indicators. However, these indicators can also be a composition of several sub-indicators. Consequently, there exist a hierarchical network of indicators with different groups and clusters.

The first step of the Analytical Hierarchy Process (See section 4 for a description of the AHP weighing method) is the modelling of the problem into a hierarchy model (Buksh et al., 2017). The developer of the AHP model described the process of creating a hierarchy as follow: "The elements of a hierarchy are grouped in clusters according to homogeneity and a level may consist of one or several homogeneous clusters" (Saaty, 1987). The sub-indicators can be divided into groups which in itself are also indicators. These groups can be grouped again into clusters which can be aggregated to calculate the composite indicator.

Diamantini et al. refer to the "calculation formula by which an indicator is calculated as a function of other indicators". In our case, each group represents an indicator which can be calculated by an aggregation function (see section 6) of its sub-indicators. The lowest indicators in the hierarchy are, however, are not composed of several indicators. These indicators are based on the value of a measured criteria value (See section 3).

Figure 7, shows a general model of a hierarchy tree. This hierarchy model could be extended by adding more levels of clusters and groups. To determine the hierarchy at ProRail, the groups and clusters are identified first. For example, the different railway segments could be several different, which are used to determine the total quality of a railway switch. Section 5.1. describes the implementation of the hierarchy in more detail.

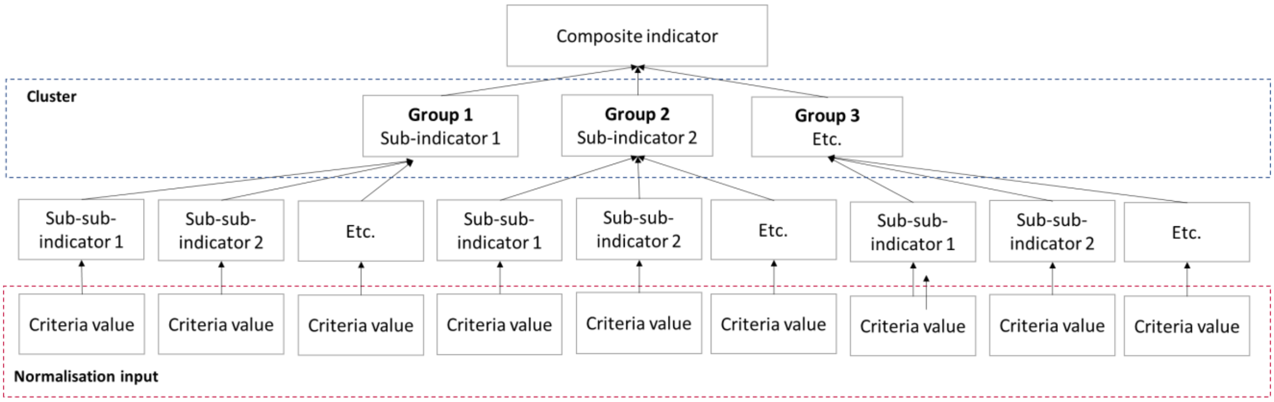


Figure 7: Hierarchy model

3.4. Normalisation methods

The lowest sub-indicator in the hierarchy need to be calculated by a criteria value. The scales and unit of measurement of these criteria values can vary. Therefore, normalization is needed to make the criteria comparable. `

The selection of a normalization method has impact on the overall calculation of the composite indicator. Tofallis (2014), for example, showed how different normalization methods can result in different outcomes for the composite indicator. Therefore, one should carefully consider which normalization method is suitable for the given criteria. In addition, "robustness tests might be needed to assess their impact on the outcomes" (OECD, 2008). In the literature there are several normalisation methods described by the OECD and Gibrari et al. An overview of these normalisation methods is found in the literature are found in Appendix B.1.

A distinction is made between two types of criteria values. Firstly, there are measurements which are expressed in numerical value. For these values a value function can be used to normalize these values. Secondly, there are values which are not expressed in a numerical value, but instead are labelled by an ordinal value. For example, some parameters at ProRail do not have measurement of their geometry, but instead they are labelled with an AL, IL or IAL (see section 2.3). Therefore, these labels are normalized by assigning a number between zero and one based on the data and expert judgement.

3.4.1. Value function

The value function mentioned by J. Maczewski and C. Rinner (2015) is used to normalise criteria with a numerical value. They use the value function for the normalisation of the criteria of MCDA problems regarding geographic information systems (GIS). However, this normalisation technique is also suitable for the normalisation of the geometric measurement. Firstly, the minimum and maximum scores of the value functions can be defined by this method. In addition, the normalisation does not have to be linear depending on the parameters. Linear normalisation assumes that each change in the measurement should result in the same relative amount of change in the quality score. However, in the case of railway switches, the worse the state of a geometric measurement is the more impactful a change in measurement is on the quality of the railway switch. Therefore, the normalisation is should not be linear.

The scores can be calculated with one of the following two value functions:

$$v(a_{ik}) = \left(\frac{\max_i\{a_{ik}\} - a_{ik}}{\max_i\{a_{ik}\} - \min_i\{a_{ik}\}}\right)^{\rho}, where\ i = 1,2,\dots,n\ and\ k = 1,2,..,m \qquad \textit{Equation 1}$$

$$v(a_{ik}) = \left(\frac{a_{ik} - \min_i\{a_{ik}\}}{\max_i\{a_{ik}\} - \min_i\{a_{ik}\}}\right)^{\rho} where\ i = 1,2,\dots,n\ and\ k = 1,2,..,m \qquad \textit{Equation 2}$$

a_{ik} is the criteria value which you want to normalise into a quality score. n is the number of criteria values and m is the number of objects you want to determine the quality score for. In the case of ProRail, n is the number of measurements for one railway switch and k is the number of railway switches for which a quality score is determined. Equation 1 should be used when a higher criteria value should result in a higher quality score, while Equation 2 should be used when a lower criteria value should result in a higher quality score.

The shape of the function depends on three points. Firstly, the minimum and maximum value need to be determined. The minimum value has the lowest score of zero and the maximum value has the highers score of one. These values determine the range of the criteria scores.

Secondly, the curvature of the function depends on the parameter ρ. If ρ = 1 then, the normalisation is linear. When ρ > 1, the function becomes convex. This means that a higher value will score relatively higher on the quality score. Conversely, when 0 < ρ < 1, the function becomes concave which means that changes in lower scores will have a bigger impact on the quality score.

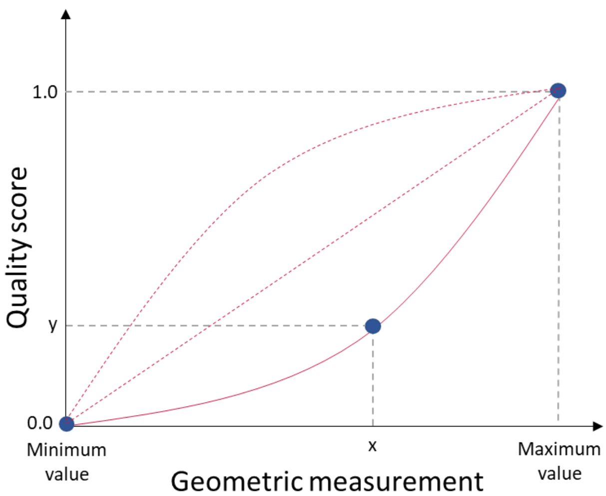


Figure 8: Min-max value function

The ρ value could be calculated by determining the values of a third point. This point could be a specific criteria value which has a quality score assigned by an expert. The value of ρ could then be calculated based on the criteria value and the quality score with Equation 3 or Equation 4 depending on whether a higher criteria value should result in a higher quality score:

$$\rho = \frac{log\ (y)}{log\left(\frac{x - \underset{i}{min}\{a_{ik}\}}{\underset{i}{max}\{a_{ik}\} - \underset{i}{min}\{a_{ik}\}}\right)} \qquad \textit{Equation 3}$$

$$\rho = \frac{log\ (y)}{log\left(\frac{\underset{i}{max}\{a_{ik}\} - x}{\underset{i}{max}\{a_{ik}\} - \underset{i}{min}\{a_{ik}\}}\right)} \qquad \textit{Equation 4}$$

In this case, x is the criteria value and y are the assigned quality score. Figure 8 shows a sketch of the possible shapes of the value function.

3.5. Weighting

Next, the importance of each indicator should be determined by assigning weights to every indicator. Firstly, different types of weighting methods are discussed. After that, the most suitable weighting methods are selected and described.

3.5.1. Weighting methods

Zardari, Ahmed, Shirazi and Yusop (2015) classify weighting methods into two categories: objective and subjective weighting methods.

Subjective weighting methods determine weights based on the judgement of decision-makers. These methods use, for example, pairwise comparison (AHP) or allocation of points (BAP) by experts of a certain field to determine the weight of each criteria. However, the problem with subjective weighting methods is that the indicator might become more biased (Greco et al., 2019). Consequently, the composite might not properly measure the performance.

Objective weighting methods use algorithms or models instead of decision-makers to determine the criteria weights. Most of these methods make use of regression, optimization of objective functions or correlation analyses to calculate the criteria weights. An advantage of objective weighting is that it is not affected by bias created by the decision-maker. However, this also means that it neglects subjective judgement information of the decision-makers which may have been important (Zardari et al., 2015). In addition, objective weighting requires more data which might not be always be available.

Next to objective and subjective weighting methods there exist mixed methods and methods which do not assess the different weights. The mixed methods use both the input of decision-makers and mathematical function to determine weights. In addition, equal or no weights could be used (Greco et al., 2019). These models although simple to construct can result in arbitrary composite indicators.

In the literature many subjective and objective weighting methods have been identified by the OECD, Greco et al., Gibrari et al. and Zardari et al. These weighting methods can be found in Appendix B.2.

Finally, a combination of the equal weighting and AHP weighting method are chosen to determine the weights for a quality indicator.

3.5.2. Equal weighting

The equal weighting method distributes equal weights for the chosen indicators. The equal weighting method is used due to its simplicity. The equal weighting method assumes that the chosen indicators should have the same impact on the calculated quality indicator. If the sub-indicators have the same importance, equal weighting is the preferred method, because it requires less time and information. However, if this assumption cannot be made the AHP weighting method is used to determine the impact of each sub-indicator.

3.5.3. AHP weighting

The Analytic Hierarchy Process is used to determine weights for each parameter in the geometric quality indicator calculation.

The AHP method is a subjective weighting method, because it uses the judgement of experts to determine weights. A subjective weighting method is chosen, because at the moment there is not enough data to support an objective weighting method. An objective weighting method would require historical information about the performance of a railway switch which could be used to determine the importance of each parameter, but this data is not available. In addition, the AHP method takes the expertise of railway experts into account, which may lead to insights which might not be taken into account when using a data-driven approach.

The AHP method was specifically chosen, because it offers a structural way of quantifying expert judgement into weights. The AHP has "the ability to reflect the way people think and make decisions by simplifying a complex decision into a series of one-on-one comparisons" (Jiaqi, Ma & Zhou, 2014). Experts can fill in a pairwise comparison matrix in which they score each parameter compared to another parameter. These scores can then be used to determine the weights for each parameter. In addition, the AHP method has been used for similar situations in the literature. For instance, J. Ma, X. Ma and F. Zhou (2014) used the AHP method to prioritize maintenance of rail tracks and Z. Buksh et al. (2017) used it to measure the performance of bridges.

Buksh et al. (2017) uses the following four steps to implement the AHP-method:

1) Model problem into a hierarchy
2) Implement pairwise comparison matrix
3) Calculate weights
4) Check consistency

3.5.4. Hierarchy structure

The modelling of the hierarchy structure is key to structuring the indicators for the pairwise comparison matrices. In this methodology, the hierarchy has already been discussed in the indicator selection step. (Section 3.3.2)

Table 2: Importance scores pairwise comparison matrix

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	Experience and judgement slightly favour one activity over another
3	Moderate importance	
4	Moderate plus	Experience and judgement strongly favour one activity over another
5	Strong importance	
6	Strong plus	An activity is favoured strongly over another; its dominance demonstrated in practice
7	Very strong or demonstrated importance	
8	Very, very strong	The evidence favouring one activity over another is of the highest possible order of affirmation
9	Extreme importance	

3.5.5. Pairwise comparison matrix

Using the hierarchy structure, the pairwise comparison matrices can be constructed. In appendix G, the pairwise comparison matrices for ProRail can be found. A pairwise comparison matrix is constructed for each group to determine the importance of each parameter within the group. In addition, a pairwise comparison is constructed to determine the weights used to determine the final quality indicator. The parameters are scored based on the Table 2 which has been constructed by Saaty (1987). Three rail system experts will eventually fill in the pairwise comparison matrices.

When filling in the matrix, one should take into account that when comparing the parameters in the opposite side the value should be the inverse of the value (See Equation 5).

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1j} \\ a_{21} & a_{22} & \dots & a_{2j} \\ \dots & \dots & \dots & \dots \\ a_{i1} & a_{i2} & \dots & a_{ij} \end{bmatrix}, where\ a_{ji} = \frac{1}{a_{ij}}$$ *Equation 5*

Weight calculation

When the pairwise matrix has been filled in, the weights for each parameter can be calculated. The weights are calculated with the following two steps (Winston, 2004) Firstly, each value in the matrix has to be normalized by dividing each value by the sum of its column. Equation 6 shows the formula for the normalized matrix.

$$\overline{\boldsymbol{A}} = \begin{bmatrix} \bar{a}_{11} & \bar{a}_{12} & \dots & \bar{a}_{1j} \\ \bar{a}_{21} & \bar{a}_{22} & \dots & \bar{a}_{2j} \\ \dots & \dots & \dots & \dots \\ \bar{a}_{i1} & \bar{a}_{i2} & \dots & \bar{a}_{ij} \end{bmatrix},$$ *Equation 6*

$$where\ \bar{a}_{i,j} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}\ with\ i,j = 1,2,\dots,n$$

Secondly, the weights are then calculated by taking the average of each column. As a result, you will have the weighting for each geometric parameter. The weight calculation is shown in Equation 7.

$$\boldsymbol{w} = (w_1, w_2, \dots, w_n), where\ w_i = \frac{\sum_{k=1}^{n} a_{ik}}{n}$$ *Equation 7*

Consistency check

For the final step, the consistency of the pairwise comparison matrix needs to be checked. This is necessary, because the pairwise comparison matrix allows rail system experts to fill in values which may be inconsistent or contradictory.

Therefore, the consistency index (CI) of the comparison matrix will be calculated. This can be calculated with Equation 8, 9 and 10

$$\boldsymbol{b} = \boldsymbol{A}\boldsymbol{w}^{\boldsymbol{T}} \quad \textit{Equation 8}$$

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{b_i}{w_i} \quad \textit{Equation 9}$$

$$CI = \frac{\lambda_{max}-n}{n-1} \quad \textit{Equation 10}$$

To determine if the comparison matrix is consistent enough, the consistency index is compared with the random index (RI). The random index is the average consistency index if the pairwise comparison matrix was scored at random (Winston, 2004). The consistency ratio (CR) is the ratio between the consistency index and the random index (See Equation 11). The value of the consistency index depends on the number of parameters you want to evaluate. They can be found in Table 3. The weights obtained from the pairwise matrix is only useful when the CR is higher than 0.1 (Winston, 2004).

$$CR = \frac{CI}{RI} \quad \textit{Equation 11}$$

If the consistency ratio does not fulfil this criterion, the rail system expert will be asked to revise their comparison matrix.

Table 3: Random index

n	RI
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

3.6. Aggregation methods

There are several aggregation functions which can be used to calculate the composite indicator with the normalized variables and weights. Selecting an aggregation method depends on the method used to normalise the data and whether compensability should be allowed (OECD, 2008). Tofallis (2019) showed how simple additive weighting (SAW) can result in different outcomes depending on the normalisation method used. In addition, compensability should be considered, because for some situations it is not desirable that very low criteria values can be compensated by other higher criteria values. An overview of the aggregation methods identified by the OECD and Tofallis is found in Appendix B.3.

For the implementation at ProRail, the additive weighting methods is used, because it is the most intuitive method. The calculation of the additive weighting method can be understood more easily due to the simplicity of the function. However, a disadvantage of this method is the compensability. But the chosen normalisation makes it possible, to give certain measurement values a higher quality score. As a result, measurements with a high deviation need more compensation, then measurements with a small deviation. The robustness analysis could give more insight on how the compensability is affected by these choices. In addition, the SAW assumes that the scoring of the indicators is independent from each other. This means that the quality score of one geometric parameter should not be influenced by the quality score of another parameter.

Equation 12 shows formula of the additive weighting method, where m is the measurement of the criteria value and w is the according weight.

$$Quality\ score = \sum_{i=1}^{n} w_i m_i \qquad \textit{Equation 12}$$

3.7. Robustness analysis

The robustness of the composite indicator should be analysed to determine in what extent different inputs and methods affect the calculation of the composite indicator. Uncertainty and sensitivity analysis can be used to analyse the robustness of the composite indicator. Uncertainty analysis focusses on how the composite index value changes when different choices are made in the inputs while “sensitivity analysis measures how much variance of the overall output is attributed to those uncertainties” (S. Greco et al., 2018). Using these analyses will help determine how much confidence can be put in the composite indicator. According to the OECD (2014), “all potential sources of uncertainty should be addressed: selection of individual indicators, data quality, normalisation, weighting, aggregation method, etc.”. By using alternative methods are or values the robustness of the composite indicator can be tested. Due to time restrictions, only a few of these uncertainties are addressed in this research.

In addition, the quality scores need to be validated. The validation of the quality indicators is restricted by the lack of objective data, the quality scores need to be validated by an expert. Therefore, the quality scores will be validated by comparing the quality scores with the judgement of an expert.

3.8. Methodology for constructing quality indicators

Based on the framework and the identified methods from the literature, a methodology is created for the construction of quality indicator for railway switches. The activities of the methodology are visualized in Figure 9 and in Appendix C the same methodology can be found with a small description for each activity. This methodology could also be used for similar situations which have the same requirements and restrictions like ProRail. In this research, the methodology is implemented for railway switches, but it could also be used to determine, for example, the quality of crossings and rail tracks at ProRail.

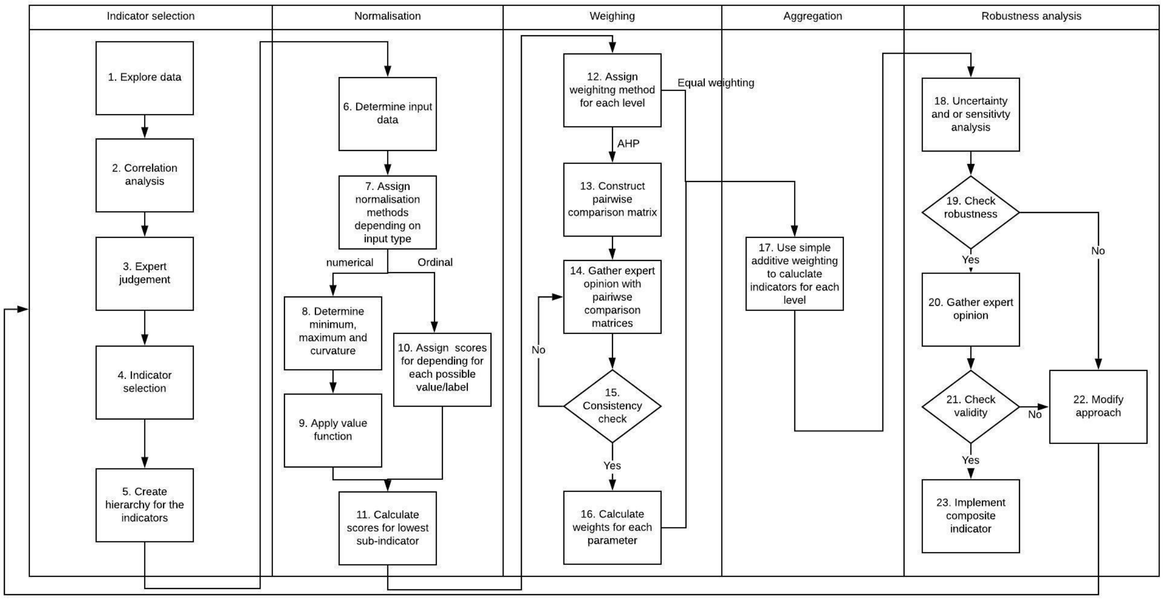


Figure 9: Methodology for constructing quality indicator

This methodology differs from other approaches in literature, because it incorporates many different techniques from MCDA methods to create a new approach for creating a composite indicator. As mentioned before there, already exist some similar composite indicators used for decisions-making regarding maintenance. However, these approaches mainly focus on the implementation of weighting methods such as the AHP, but they do not offer suitable techniques for selecting and normalizing indicators. Therefore, techniques used for the creation of composite indicators in other situations are used and incorporated into the methodology.

3.9. Conclusion

In conclusion, a composite indicator can be used to define a quality indicator for the geometric quality of railway switches. A framework for creating a composite indicator is constructed which consists of five steps: selection of indicators, normalisation, weighting, aggregation and robustness analysis. The indicators are selected based on the exploration of data, correlation analysis and the judgement of experts. Then, the min-max value function is the most suitable method for normalizing the measurements. In addition, the AHP method is chosen as the best subjective method for determining the weights and the simple additive weighting will be used to aggregate the quality indicators. Finally, robustness analysis is used to test the reliability and validity of the quality indicator. Based on these decisions, a general methodology is developed which can be implemented at ProRail to develop a quality indicator for the geometry of railway switches at ProRail.

Chapter 4: Implementation at ProRail

In this chapter, the implementation of a quality indicator for the geometry of railway switches at ProRail is explained. The methodology discussed in chapter 4 is used to develop this quality indicator. Firstly, the indicators which affect the quality of the railway switches are identified. Secondly, the parameters for normalizing the geometric measurements are determined. After that, an AHP model is constructed and used to calculate the weightings. Subsequently, the data preparation and the calculation of the quality scores are discussed. Finally, the application of the geometric quality indicator is explained.

4.1. Selection of indicators

The selection of indicators is based on the different geometric parameters which are currently measured by ProRail. Firstly, the geometric parameters which could be used as an indicator are identified by exploring the available data. Then, a selection of geometric parameters is made based on the correlation analysis and the judgement of a railway switch expert. Finally, the indicators are modelled into a hierarchy.

4.1.1. Geometric parameter selection

The dataset which includes all the point measurements for the railway switches is used to identify the geometric parameters which are currently measured. A list of all the geometric parameters found in the data can be found in Appendix A. There exist more geometric parameters which are currently measured and evaluated based on the threshold values. However, the data for these geometric parameters are not readily available, therefore these geometric parameters are left out of the scope of this research.

A rough correlations analysis is done to identify any highly correlated geometric parameters. A high correlation between geometric parameters would mean that one of the geometric parameters may be redundant and could therefore be left out.

Only the correlations between the average of the geometric parameter data labels are calculated, because there are too many point measurements to analyse every correlation. Python in combination with the Seaborn library is used to generate a correlation matrix for the geometric parameters. This correlation matrix is found in Appendix D. The matrix shows the correlations between every combination of geometric parameters.

There is only a high correlation between two different point measurements for the distance flange and rail track ('Inloopmaat_sr1_1' and 'Inloopmaat_sr2_1) which is 0.8. But these measurements are actually the same geometric parameter measured on different points. Therefore, this correlation does not influence the decision on whether the geometric parameter can be left out as an indicator. The other correlations are not exceptionally high, but there are a few correlations which have a correlation around the 0.5. The positive correlations could be explained by the fact that if a certain geometric parameter is in a bad state, the degradation rate of related parameters can increase. In addition, there is a noticeable negative correlation between the groove width "Groefbreedte" and the distance between flange and rail track "Inloopmaat" parameter. These parameters should always add up to the width of the railway, therefore if the "Groefbreedte" becomes bigger the "Inloopmaat" decreases or the width of the railway has to increase. Consequently, there were not any indicators left out because of the correlation analysis.

In addition, the selection of geometric parameters was confirmed by a railway switch expert to give a good representation for the geometric quality of a railway switch. Therefore, based on this judgement and the relatively small correlations all the geometric parameters mentioned in Appendix A are used.

4.1.2. Hierarchy model

Based on section 2.2 the different groups and levels have been identified. The levels consist of the following categories:

1) Railway segments
2) Entries (Straight or diverging)
3) Geometric parameters
4) Point measurements

A railway switch consists of five segments (See section 2.2) and each segment has a different impact on the overall quality of a railway switch. The railway switch segments are chosen as a level, because this way the geometric parameters can be subdivided per segment. This way the weights for each geometric parameter can vary depending on which segment the point is measured on. For instance, the profile of railway switch might be more important at the tongue segment than at the middle segment. In addition, the aggregation of quality scores for each segment, can be used as an indicator to assess the quality of each segment. Furthermore, determining the weights of the geometric parameters is easier in smaller groups than evaluating all the fifteen geometric parameters together.

In addition, the segments consist of a diverging and a straight entry. Generally, the geometric parameters are the diverging part of the railway switch have a greater importance than the geometric parameter in the straight part. Therefore, the geometric parameter is evaluated based on their segment and entry type. A railway switch expert identified the geometric parameter for each railway switch segment and entry. These can be found in Appendix E.

Finally, most geometric parameters are measured multiple times at different points. Therefore, the quality of each geometric parameter is determined based on multiple measurements. Based on these levels a hierarchy of the indicators is modelled which is shown Figure 10. This figure shows the all the groups for the segments and the different and a few geometric parameter groups and points are shown as well.

4.2. Normalisation

The value function is used to normalise the geometric measurement values. Firstly, the different types of input data are analysed and then the parameters for the value functions are determined.

4.2.1. Input data

There are currently two attributes in the data which can be used to calculate a quality score. These include the measurement of the dimensions and a label of the exceeded threshold value. The value of

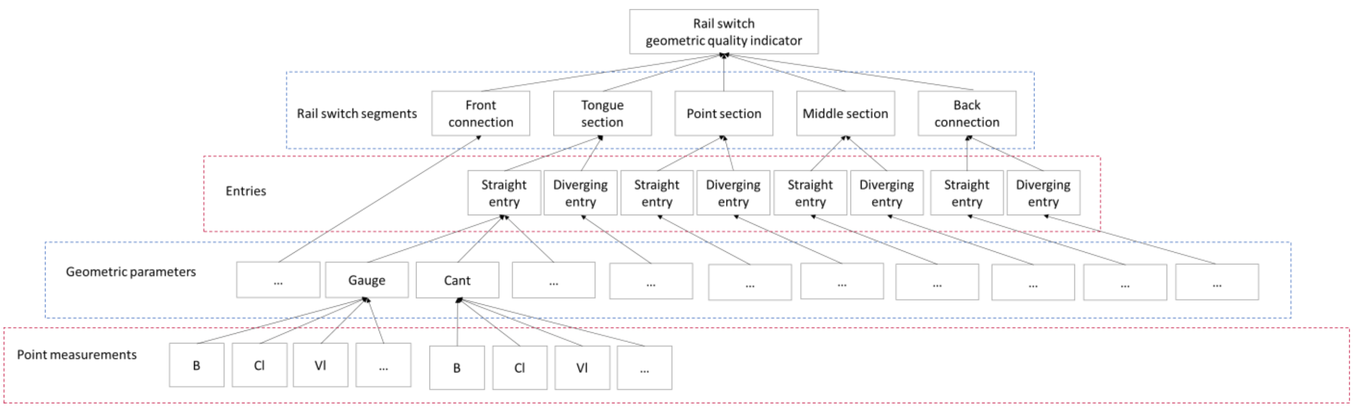


Figure 10: Railway switch hierarchy

the measurements is a continuous number in millimetres while the level of exceedance indicates whether a geometric parameter exceeds the AL, IL, IAL.

Since, level of exceedance is depended on the measurement value, therefore for all the geometric parameters where the measurements of the dimensions of the geometry are available, the measurement is used. However, for two geometric types parameter the “Mould 1” (“Mal 1”) and “Mould 2” (“Mal 2”) parameters the measurements are not available in the data set. These measurements do exist, but they are currently not readily available for this research. Instead, the data about the level of exceedance is available for these parameters and therefore these values are used as input.

4.2.2. Value function parameters

The quality scores for geometric parameters with a measurement values are calculated with the value function.

To determine the parameters of the value function, the nominal values and threshold values are used. The nominal value is the ideal dimension of a geometric parameter. So, if a measurement equals the nominal value, then the geometric parameter has the highest possible quality. Therefore, the nominal value receives the maximum quality score.

The IL is chosen to have the minimum quality score. The IL is used instead of the IAL, because there are not many geometric measurements that exceed or come close to the IAL. If the IAL would be used as minimum score, the quality scores would be skewed a lot more to the maximum score and the spread would decrease. Due to the reduced spread, the difference between quality scores would become smaller making them less distinguishable. Appendix K shows an example of how the spread changes between the IL and IAL as minimum score for a particular geometric parameter. A big disadvantage of this approach, however, is that information is lost when the measurement does exceed the IL, because these values would receive the same quality score as the IL.

Furthermore, there exist a database table with the AL and IL for every geometric parameter, but this does not include the IAL. Therefore, this data would have to be prepared first before implementing the normalisation for all the geometric parameters.

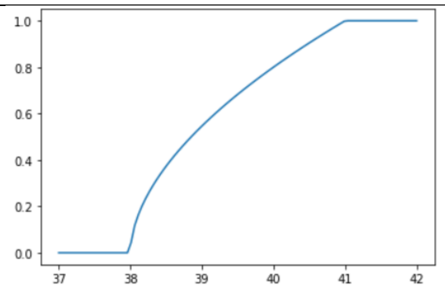
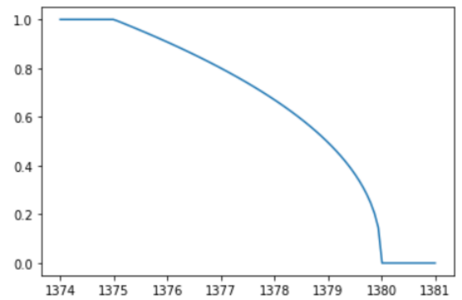
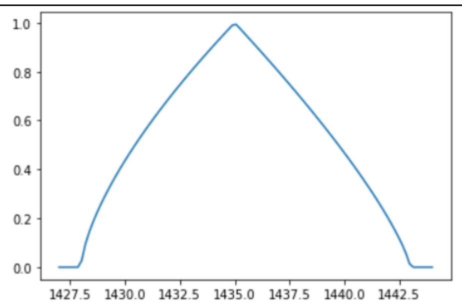
There are three types of geometric parameters which should be taken into consideration for the normalisation calculation. There are geometric parameters which only have maximum limits, there are parameters which only have minimum limits and there are parameters which have both. Depending on the type of parameter a function with equation 1, equation 2 or both need to be executed.

As mentioned before, it is possible for a measurement to exceed the IL. In this case, the quality score will be the same as the score of the IL, because the IL has the lowest possible score. This also holds for when a measurement value is higher than the lower value for only maximum limits and higher than the nominal value for only minimum limits. In this case the quality score will be the same as for the nominal value. Table 4 shows three examples of three possible geometric parameters and their value function based on the threshold values.

Finally, the curvature of the function needs to be determined. The AL is used as a reference point to determine this parameter. By defining a quality score for the AL, the parameter ρ can be calculated using the equations 3 and 4 depending on whether you want to maximize or minimize the value. The AL is chosen to have a quality score of 0.75. This score is based on the fact that a concave function is needed, so that measurement which deviate more from the nominal value also score relatively lower.

Therefore, the quality score of the AL should be relatively high. However, it should not be too high as well, because otherwise most values will result in very high scores. Choosing 0.75 is still a little arbitrary, but sensitivity analysis will be used in later steps to identify its effect on the total quality scores. In appendix F, a visualization of the normalisation algorithm can be found.

Table 4: Examples of normalisation functions

Parameter	Min IL	Min AL	Nominal	Max AL	Max IL	Graph
“Groefbreedte”	38	39	41	N/A	N/A	
“Inloopmaat”	N/A	N/A	1375	1378	1380	
“Spoorwijdte”	1428	1430	1435	1441	1443	

4.3. Weighting

The AHP method discussed in the previous chapter is used to determine the weight factors of the sub-indicators. The AHP method is used to evaluate the weights for the railway switch segments, the entries and the geometric parameters. For the point measurements, however, the equal weighting method is used, because applying the AHP method for each measurement point makes filling in the pairwise comparison matrices too complex. Therefore, the assumption is made that on which point a parameter is measured does not affect the importance of the measurement on the geometric quality.

4.3.1. AHP implementation

Based on the hierarchy modelled in section 5.1.2 the pairwise matrices are constructed in an Excel sheet which can be found in Appendix G.

Firstly, there is a comparison matrix for the rail segments to determine the weighting for each segment of the railway switch. Then, there are four comparison matrices to compare the importance between the diverging and straight entries. The entries of the connection sections are not evaluated, because the diverging entry turns straight at the connection sections, which means that they are virtually the same. Therefore, equal weighing factors are assigned to these entries. Finally, there are eight comparison matrices which evaluate the geometric parameters for each railway segment and entry.

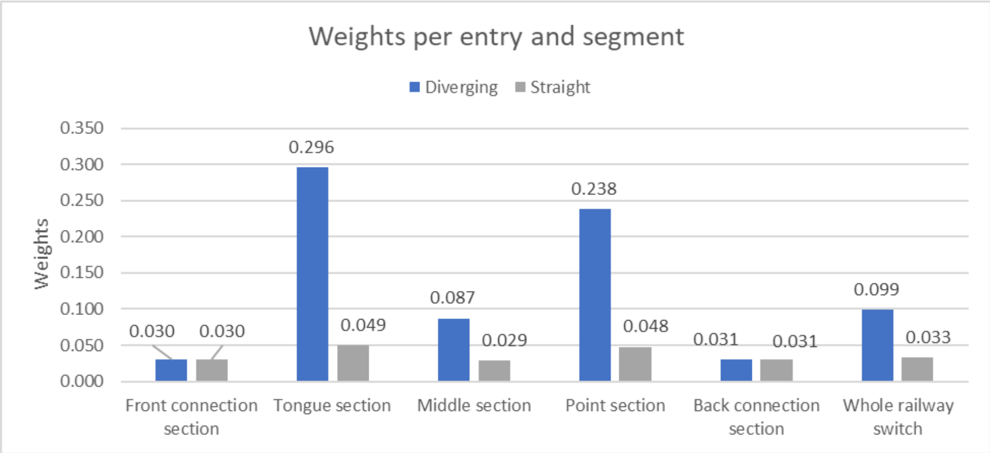


Figure 11: Weights per entry and segment

A railway switch expert at ProRail filled in each comparison and based on this judgement the weightings are calculated. As can be seen in the Excel sheet in Appendix G, the matrices have been filled in perfectly consistent, which means that the results represent the opinion of the expert very accurately. Consequently, the pairwise comparison matrices did not have to revised, because they met the consistency criteria.

4.3.2. Weighting results

The results of the weight calculations can be found in Appendix H. When looking at the weights of the entries for each segment (See Figure 11), we see that the diverging entry has a greater importance on the geometric quality of a railway switch according to the railway switch expert. In addition, the diverging part of the tongue and point section have a huge impact on the quality by making up more than 50% of the quality score. These sections are also responsible for the mechanical part of the railway switch and therefore consists of critical geometric parameters to guarantee the safety of the railway switch.

Figure 12 shows, the total weight of a geometric parameter by adding the weights of each section. According to the AHP implementation the cant difference ('Verkantingsverschil'), the gauge ('Spoorwijdte') and the distance between flange and rail ('Inloopmaat') have the biggest impact on the geometric quality. The impact of cant and gauge could be explained by the fact that these

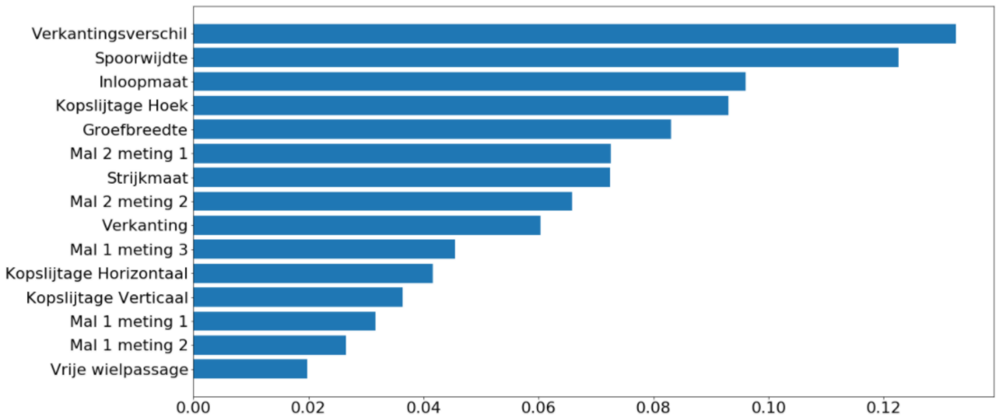


Figure 12: Total weights geometric parameters

parameters are measured over the whole railway switch while, for example, the different types of mould measurements ('Mal metingen') are only measured on one certain point.

4.4. Data preparation

To prepare the data and calculate the quality scores Python was used for programming. Python was chosen, because the company also uses Python for data analysis. Mainly the Pandas library was used for data manipulation and calculations. The code is programmed in the Jupyter Notebook. This is a programming environment where the coding and the output are displayed in blocks next after each other. This makes it possible to visualize the data next to the code which is convenient for data analysis. Screenshots of the code used can be found in Appendix I.

The data was prepared by first gathering all the relevant information. After that, the data was cleaned and the data which was still missing where inserted.

4.4.1. Data-gathering

The data needed were gathered from two sources. Firstly, the data regarding the measurements and the threshold values were obtained from the WINK database of ProRail. The WINK database contains all the data regarding the railway switches. Three tables were used from the WINK database which were the table with the geometric measurements, a table with the threshold values and a table which was used to connect both tables. The Pandasql library was used, because it makes it possible to use SQL code within Python to connect the tables into one (See Appendix I.1).

Secondly, the data regarding the weights were obtained from the expert in an Excel Sheet. The weights were calculated based on the pairwise comparison matrices. Subsequently, these weights were processed into tables, so that the weights could be easily connected based on geometric parameter, segment and entry. These tables were loaded into the Jupyter Notebook and after that they were merged with the tables from WINK using the Pandas library (See Appendix I.3). The final table could be summarised as:

- The actual measurements of geometric parameters
- The threshold values from the OHD document
- The weights per railway segment, entry and geometric parameter

4.4.2. Missing data

Some data was still missing from the tables of WINK. Firstly, the table with the threshold values did not include the values for the cant. These values were obtained from the IHS document which includes descriptions and threshold values for all the geometric parameters.

In addition, the nominal values were missing for the "Inloopmaat", "Groefbreedte", "Veraknting" and "Vrije wielpassage" parameters. These values could not be found in the HIS document. Therefore, these nominal values were obtained by asking a railway switch expert for these values. Subsequently, they were inserted into the table.

Furthermore, there are railway switches for which not all the geometric parameters are measured. These railway switches were removed from the data, because for these railway switches the weights would not add up to one which would mean that calculating these quality scores was not possible.

4.5. Quality score calculations

The calculations are also programmed using Python. The Pandas library is used to calculate the geometric quality indicators for all the railway switches in the data set. Appendix I.2 and Appendix I.4

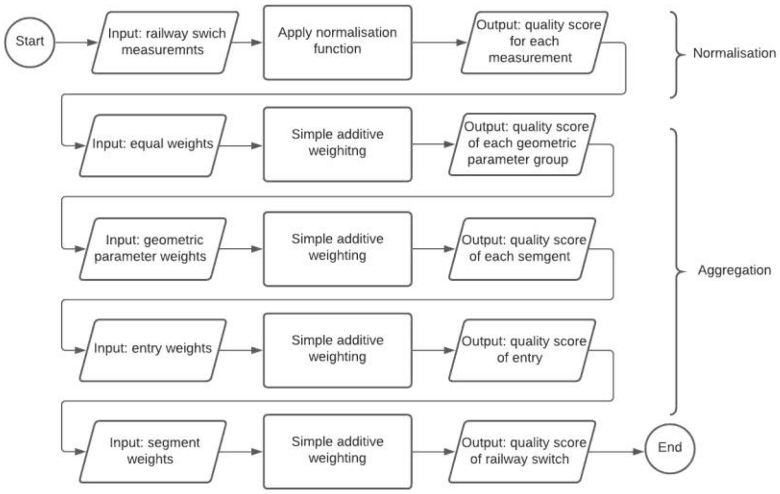


Figure 13: Flow chart quality indicator calculation

show the code used to calculate these indicators. In the following paragraphs a description and an example are given about the calculations made.

4.5.1. Calculations

Figure 13 shows a flowchart of the calculations made with their in- and outputs. Firstly, the measurements are normalised into a quality score for each measurement point by using the normalisation algorithm from Appendix F. This algorithm is programmed into a function which is applied on all the geometric measurements of the railway switches using the measurement and threshold values (See appendix I.2).

Then, these normalised quality scores are aggregated to calculate the sub-indicators for each level of the hierarchy. The simple additive weighting method is used to aggregate these values (Equation 12). The quality scores for the geometric parameter groups are calculated using the equal weighting method, which is the same as taking the average of all the quality scores for each geometric parameter. The quality scores for the segment, entries and railway switches are aggregated based on the determined weights. Firstly, the weighted average for the segments are calculated, then for the entries and finally for the total railway switch.

4.5.2. Example

An example is worked out for a certain railway switch to show how the data is processed and how the calculations are made to come up with the quality scores. Figure 14 shows a piece of the merged data used from the WINK database and the quality score. The 'BW+', 'BW'-, 'VW+' and 'VW' represent the threshold values and the column 'Nominaal' contains the nominal values of a certain geometric

Gang	Parameter	DPName	UITWBAAN	MaxValue	Level	BW+	BW-	VW+	VW-	Nominaal	Quality Indicator
Links	Groefbreedte_L	TI1	Links	66.0300	Geen overschrijding	NaN	38.0	NaN	36.0	41.0	1.000000
Links	Groefbreedte_L	TI2	Links	40.0500	Geen overschrijding	NaN	38.0	NaN	36.0	41.0	0.888099
Links	Groefbreedte_L	TI3	Links	61.8500	Geen overschrijding	NaN	38.0	NaN	36.0	41.0	1.000000
Links	Groefbreedte_R	TI4	Links	60.0800	Geen overschrijding	NaN	38.0	NaN	36.0	41.0	1.000000
Links	Inloopmaat_sr1_1	SI1	Links	1378.0800	Geen overschrijding	1380.0	NaN	1382.0	NaN	1375.0	0.609119

Figure 14: Data table with threshold values and quality indicator

parameter. These values are used as parameters for the normalisation algorithm. The 'MaxValue' column contains the measured values for the geometric parameter at a certain point and these are used as input to calculate the quality score. The output of the normalisation algorithm is inserted into the last column called 'Quality Indicator'.

The figure shows that the first, third and fourth measurement in the table have a perfect score of one, because they only have a minimum threshold limit and they do not exceed the nominal value. The second measurement, however, does exceed the nominal value (40.05 < 41.00) and therefore receives a 0.888 score according to the algorithm. The fifth measurement only has maximum threshold values and since it exceeds the maximum AL ('BW+') it receives a quality score of 0.609 (the quality score for the AL is 0.75, and since the measurement exceeds the AL, the quality score needs to be below 0.75).

These quality scores per measurement point are aggregated to calculate the quality sub-indicators for the parameter groups, the entries, the segments and the total quality of the railway switch. Figure 15 shows the second part of the table with the same geometric measurements. This part shows, the weights for the parameter group ('Parameter groep'), the railway switch segment ('Wisselgdeeldte') and the entry ('Uitwijking').

Quality Indicator	Parameter groep	Wisselgedeelte	Uitwijking	Parameter weighting	Uitwijk weighting	Wisselgedeelte weighting
1.000000	Groefbreedte	Puntstukgedeelte	Afbuigend	0.290741	0.833333	0.285423
0.888099	Groefbreedte	Puntstukgedeelte	Afbuigend	0.290741	0.833333	0.285423
1.000000	Groefbreedte	Puntstukgedeelte	Afbuigend	0.290741	0.833333	0.285423
1.000000	Groefbreedte	Puntstukgedeelte	Afbuigend	0.290741	0.833333	0.285423
0.609119	Inloopmaat	Puntstukgedeelte	Afbuigend	0.336542	0.833333	0.285423

Figure 15: Data table with weights

The quality score per parameter group is determined by using the equal weighting method. This means that the average is taken of the point measurement for each geometric parameter, segment and segment. Figure 16 shows the quality scores for each geometric parameter in the 'Quality Indicator'.

Parameter groep	Wisselgedeelte	Uitwijking	Parameter weighting	Uitwijk weighting	Wisselgedeelte weighting	Quality Indicator
Groefbreedte	Puntstukgedeelte	Afbuigend	0.290741	0.833333	0.285423	0.960402
		Rechtdoorgaand	0.292680	0.166667	0.285423	0.893653
Inloopmaat	Puntstukgedeelte	Afbuigend	0.336542	0.833333	0.285423	0.559856
		Rechtdoorgaand	0.337127	0.166667	0.285423	0.423628
Kopslijtage Hoek	Aansluitgedeelte achterkant	Afbuigend	0.234444	0.500000	0.061132	0.526548
...	...	...	...	...	...	...
Verkanting	Tongbeweging	Rechtdoorgaand	0.043095	0.142857	0.345227	0.989142
Verkantingsverschil	Gehele wissel	Afbuigend	1.000000	0.750000	0.132601	0.481266
		Rechtdoorgaand	1.000000	0.250000	0.132601	0.630703
Vrije wielpassage	Tongbeweging	Afbuigend	0.044312	0.857143	0.345227	0.506309
		Rechtdoorgaand	0.135226	0.142857	0.345227	0.896033

Figure 16: Quality scores geometric parameters

The other quality sub-indicators are calculated by taking the weighted average for each level. So, to determine the quality score for each entry the weighted average of the quality scores of the parameters is taken. These can be seen in Figure 18. In order to get the quality score each segment the weighted average of each entry is taken which can be seen in Figure 17. Finally, the weighted average of each segment is taken to get the total quality score of the railway switch which is in this case 0.73663.

Equipmentnummer	Wisselgedeelte	Uitwijking	Quality Indicator
10201095	Aansluitgedeelte achterkant	Afbuigend	0.814127
		Rechtdoorgaand	0.735890
	Aansluitgedeelte voorkant	Afbuigend	0.541296
		Rechtdoorgaand	0.539074
	Gehele wissel	Afbuigend	0.481266
		Rechtdoorgaand	0.630703
	Middengedeelte	Afbuigend	0.727943
		Rechtdoorgaand	0.721151
	Puntstukgedeelte	Afbuigend	0.691275
		Rechtdoorgaand	0.500680
	Tongbeweging	Afbuigend	0.921180
		Rechtdoorgaand	0.875011

Figure 18: Quality scores entries

Equipmentnummer	Wisselgedeelte	Quality Indicator
10201095	Aansluitgedeelte achterkant	0.775008
	Aansluitgedeelte voorkant	0.540185
	Gehele wissel	0.518625
	Middengedeelte	0.726245
	Puntstukgedeelte	0.659509
	Tongbeweging	0.914584

Figure 17: Quality scores segments

4.5.3. Results

Figure 19 shows the distribution of all the quality scores of the available railway switches and Table 5 shows the descriptive statistics of these scores. This figure and table are based on the calculated quality scores of 940 different railway switch of different periods available in the data.

The quality scores range between 0.71 and 0.94 and the standard deviation is 0.037 (See Table 5). The quality scores of the point measurements mainly had a range between 0 and 1, but due to aggregating the different sub-indicators into a single indicator, the spread of the overall quality indicator has been reduced. Still, the distribution of the overall quality scores seem to have considerable spread to distinguish the quality of different railway switches.

The distribution seems to be a plausible distribution for the quality of the railway switches. When the quality indicator has a perfect score, it means that all the measurements of all the geometric parameters equal the nominal value. However, when the railway switch scores a zero, all the

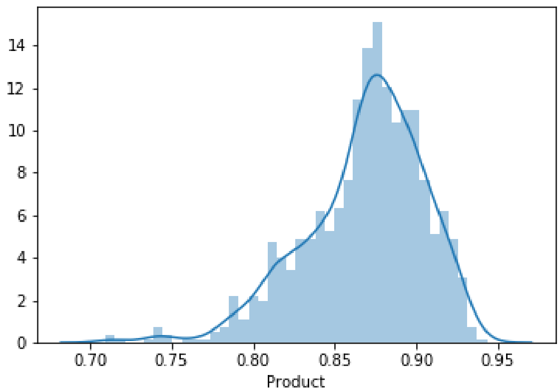


Figure 19: Distribution of quality scores

Table 5: Descriptive statistics quality scores

Count	940.000000
Mean	0.868312
Standard dev.	0.036687
Minimum	0.709523
25% (Q1)	0.847814
50% (Q2)	0.873831
75% (Q3)	0.893881
Maximum	0.943112
Median	0.873831

geometric parameters exceed the IL. This to be the case is very improbable, however for a railway switch to be in a pretty good state compared with the nominal values is more likely. Therefore, it is not surprising that the distribution is closer to the one than the zero.

In addition, the median of 0.873 is a little higher than the mean of 0.868, which means that the distribution is a little skewed to the right.

This distribution gives a clear indication on the performance of railway switches compared to each other. The quality score can be compared to the mean to decide whether a railway switch performs worse or better than the average.

4.6. Application

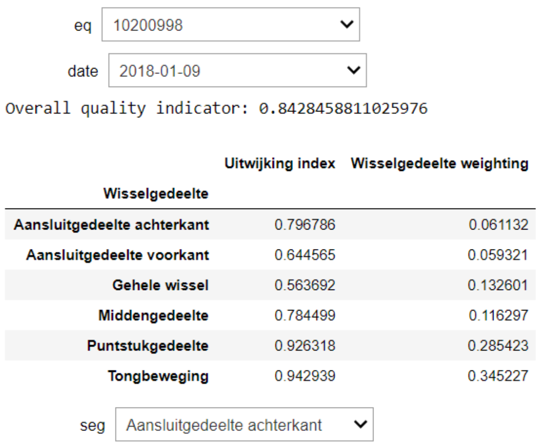
The constructed quality indicator creates more insight into the geometric quality of the railway switches for ProRail. A simple interface is created to give an overview of the calculated quality scores. In addition, the practical relevance of these quality scores is discussed.

4.6.1. Interface

A simple interface is made to give an overview of the quality indicators for each railway switch (See Figure 20 and Figure 21). The code of the interface can be found in Appendix I.5. The Ipywidgets library is used to create the interface. This library focuses on the creation of interactive elements which can be displayed within the Jupyter Notebook.

In the interface the equipment number and date of the measurement can be selected to show the quality indicators for the railway switch, the railway switch segments, entries, geometric parameters and the point measurements. The interface makes it possible to analyse which parts are performing well compared to each other. For example, when looking at Figure 20, you can see that the whole railway switch segment ("Gehele Wissel") is performing worse compared to the other segments. This segment can then be selected to analyse which geometric parameters cause the relatively low result. This way the calculations of railway switch become transparent, because one can easily track back why a railway switch receives a particular score.

The interface is currently integrated in the Jupyter Notebook, however, in the future the quality scores could be incorporated into already existing dashboards of ProRail. There already exist dashboards regarding the geometric measurements of the railway switches at ProRail, therefore these quality



eq 10200998

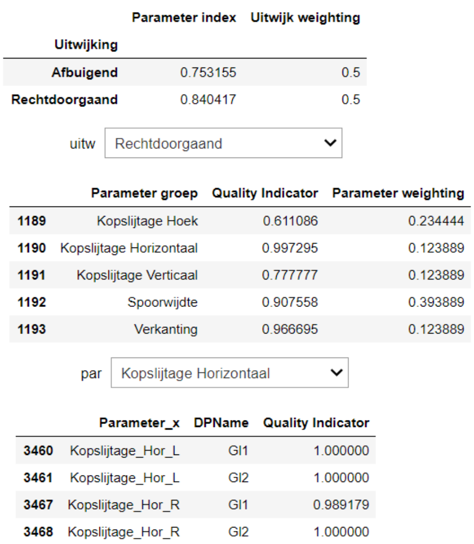
date 2018-01-09

`Overall quality indicator: 0.8428458811025976`

Wisselgedeelte	Uitwijking index	Wisselgedeelte weighting
Aansluitgedeelte achterkant	0.796786	0.061132
Aansluitgedeelte voorkant	0.644565	0.059321
Gehele wissel	0.563692	0.132601
Middengedeelte	0.784499	0.116297
Puntstukgedeelte	0.926318	0.285423
Tongbeweging	0.942939	0.345227

seg Aansluitgedeelte achterkant

Figure 20: Interface part 1



Uitwijking	Parameter index	Uitwijk weighting
Afbuigend	0.753155	0.5
Rechtdoorgaand	0.840417	0.5

uitw Rechtdoorgaand

	Parameter groep	Quality Indicator	Parameter weighting
1189	Kopslijtage Hoek	0.611086	0.234444
1190	Kopslijtage Horizontaal	0.997295	0.123889
1191	Kopslijtage Verticaal	0.777777	0.123889
1192	Spoorwijdte	0.907558	0.393889
1193	Verkanting	0.966695	0.123889

par Kopslijtage Horizontaal

	Parameter_x	DPName	Quality Indicator
3460	Kopslijtage_Hor_L	GI1	1.000000
3461	Kopslijtage_Hor_L	GI2	1.000000
3467	Kopslijtage_Hor_R	GI1	0.989179
3468	Kopslijtage_Hor_R	GI2	1.000000

Figure 21: Interface part 2

indicators could be processed and visualized in these dashboards to create more insights into the geometric quality.

4.6.2. Practical relevance

The practical relevance is derived from the fact that the quality indicator gives more insight into the overall geometric quality of a railway switch. The quality indicator makes it possible to quantify the geometric quality, so that the overall quality of a railway switch can be analysed. Before, the geometric quality of railway switches could only be analysed on a geometric parameter level. By aggregating the information of the geometric parameter into indicators, railway switches can be analysed on a railway switch, segment and entry level.

As a result, different railway switches can be compared with each other based on their quality scores. For example, the performance of different contractors could be assessed by analysing the overall quality of their railway switches. So, the quality indicator could be incorporated into the already existing dashboards for analysis.

In addition, the quality indicators can give insight into the degradation of the railway switches. By analysing how the quality scores change over time, a trend could be found which could be used to predict the future geometric quality of railway switches. Consequently, the maintenance planning of railway switches could be optimised.

In addition, the quality scores provide a more consistent assessment of the quality of railway switches. Currently, the railway switches are evaluated by a railway switch expert and based on their assessment decisions are made to guarantee the safety of the railway switches. However, a railway switch expert is not able to take into account the many measurement to come to a consistent decision. Even though, the quality indicator is also based on the judgement of a railway switch expert as well, it always uses the same weights and functions to evaluate the quality. Therefore, the quality scores always produce the same result with the inputs. The quality scores could therefore be used to support or even automize the decision-making of the railway switch experts.

4.7. Conclusion

In conclusion, based on the exploration of data, expert judgement and correlation analysis a selection of geometric parameters is made. Then, a hierarchy of the indicators is modelled with four different cluster levels: the railway switch segment, the entries, the geometric parameters and the geometric point measurements. The parameters of normalisation functions are defined by using the nominal values, the AL and the IL. Then, the hierarchy is used to create pairwise comparison matrices for the AHP method. The judgement of a railway switch expert is used to fill in the matrices, so that the weights can be calculated. Finally, the data is prepared, and the quality are calculated in Python which result in quality scores for the railway switches. A simple interface is made which displays the quality scores for every railway switch. The quality scores could be used for data analysis and supporting decision-making regarding the maintenance of railway switches.

Chapter 5: Evaluation

In this chapter the methodology and the quality scores are evaluated to determine the robustness and credibility of the quality indicators. The evaluation of the quality scores is restricted by the fact that there are currently not any other quality indicators with which the obtained quality scores can be compared. Instead, this evaluation chapter will focus on the reflection of decisions made regarding the implementation and comparing the results with the judgement of an expert.

Firstly, the uncertainties regarding the methodology and the implementation are discussed. Secondly, the main assumptions of the techniques used are discussed. After that, sensitivity analysis is used to evaluate the impact of the parameter ρ on the value function. Then, the weights per railway switch segment and geometric parameter are evaluated. Finally, railway switches are selected to validate their quality scores.

5.1. Uncertainty analysis

During the design of the composite indicator several subjective choices are made regarding the techniques and input used. "Since the quality of a model also depends on the soundness of its assumptions, good modelling practice requires that the modeller provide an evaluation of the confidence in the model, assessing the uncertainties associated with the modelling process and the subjective choices taken." (OECD, 2014). The following decisions result in the uncertainty of the quality scores:

- The selection of geometric parameters
- Choosing the AHP method and equal weighting as weighting method
- Quality of the geometric measurement data
- Using the normalisation algorithm
- Using additive weighting as aggregation function
- The current values for the weights

Uncertainty and sensitivity analysis could be implemented by analysing the quality scores of the current method where one of the decisions is changed. However, analysing the different approaches is left out of the scope of this research due to time limitations. Therefore, the evaluation of the uncertainties is limited by analysing the main assumption of the methodology, sensitivity analysis of the normalisation function and the weights of the geometric parameters.

5.2. Assumptions of the quality indicator methodology

Based on the chosen techniques and implementation decisions a number of assumptions are made for the simplicity and feasibility of the implementation of the quality indicator. The main assumptions are discussed to evaluate the credibility of the method and to discuss any possible improvements.

5.2.1. Upper and lower bound of value function

Firstly, an upper and lower bound need to be defined for the value function in the normalisation step. This assumes that a quality score cannot be infinitely better (or worse) than another quality score. In the case of ProRail, these bounds are based on the nominal value and the IL. When a geometric parameter measurement exceeds the IL, the quality score will be the same as the quality score of an IL. Consequently, the overall quality score of a railway switch is not affected by how much quality score exceeds the IL. More research could be done, to see if this assumption has a huge impact on the credibility of the quality indicator. If this is the case, research could be done on if and how an unbounded value function could be implemented.

5.2.2. Weighting based on expert judgement

Secondly, the AHP method assumes that weights can be determined based on the judgement of a railway switch experts. As mentioned before, the judgement of an expert is the only possible source for determining weights now. Therefore, this is a reasonable assumption to make. However, the AHP method also assumes, that an expert is able to rationally and consistently compare criteria in pairs. However, in section 5.3 inconsistencies are discussed which are caused by how the comparisons are presented to the expert.

5.2.3. Equal weighting point measurements

Furthermore, the assumption is made that each point measurement of geometric parameter in a certain railway switch segment have the same importance. Therefore, equal weighting is used to determine the quality score of a certain parameter. Using the AHP was not used, because this would mean that for each geometric parameter a pairwise comparison matrix needs to be constructed which makes the problem too complex.

5.2.4. Preference mutually independence

Finally, the simple additive aggregation method is used as aggregation function due to its simplicity. However, this aggregation function assumes that there exists mutual independence between the indicators (Goodwin & Wright, 2014). This means that the quality score of a certain geometric parameter should not be depended on the quality score of other geometric parameters. However, one can argue there is some dependency between the geometric parameters. When a geometric parameter exceeds the IL, the railway switch expert will take into account the state of several other relevant geometric parameters to determine the severity of the exceedance. In addition, at the point section the gauge (‘Spoorwijdte”), distance flange and rail track (“Inloopmaat”) and groove width (“Groefbreedte”) are parameters which are directly dependent on each other, since the gauge is the sum of both parameters (See section 4.1.1). Validation of the quality indicator could provide more insight on the impact of the dependencies on the final quality score.

5.3. Sensitivity analysis of the normalisation function

The curvature of the value function depends on the quality score assigned to the AL. The quality score was set to be 0.75, however, this could also be another value as long as the value function would remain concave. Therefore, sensitivity analysis is conducted on different values for the quality score of the AL, to see what impact this value has on the total quality scores of the railway switches.

Appendix J.2. shows the distribution of the quality scores for an AL score of 0.65, 0.70, 0.75, 0.80 and 0.85. The distribution shift to the right as the AL quality score decreases. This is not surprising, because railway switches which exceed the AL will have a lower overall quality score as well. Consequently, the mean of the overall quality scores decreases with the scores for the AL which is shown in Table 6. In addition, looking at the standard deviation and the minimum and maximum the spread of the distribution decreases as the score of the AL increases.

Table 6: Descriptive statistics for different AL quality scores

	AL score = 0.65	**AL score = 0.70**	**AL score = 0.75**	**AL score = 0.80**	**AL score = 0.85**
Mean	0.8243	0.8460	0.8683	0.8914	0.9154
Standard deviation	0.0428	0.0400	0.0367	0.0328	0.0282
Min	0.6472	0.6773	0.7095	0.7465	0.7896
Max	0.9190	0.9312	0.9431	0.9548	0.9664

Table 7: Rank difference between different AL quality scores

	Rank difference AL score 0.65 and 0.70	**Rank difference AL score 0.70 and 0.75**	**Rank difference AL score 0.75 and 0.80**	**Rank difference AL score 0.80 and 0.85**
Average	7.6212766	8.20212766	8.919148936	9.8808511
Standard deviation	7.68081158	9.172437653	10.87481256	12.396665
Max	69	96	113	147

Furthermore, the quality score of the AL affects the ranking order of the railway switches. All the available railway switches are ranked and then, the difference is taken between the shift of ranks when the AL changes with 0.05. As can be seen in Table 7, the rank changes on average between seven and ten places. This would not be considered significant considering there were 940 railway switches ranked. However, when taking the max difference of all the ranks, there exist railway switches which can shift a hundred places depending on which AL score is used. Therefore, further research would be required to determine which quality score would result in the most plausible ranking of the railway switches. This could be done by validating the quality scores of several railway switches by a railway switch expert. In addition, more research could be done on the relative importance of an exceedance of the AL compared to an exceedance of the IL.

5.4. Evaluation of the weights

The weights obtained by the AHP method are evaluated by firstly looking at the weights for each railway switch section. After that, the weights for each geometric parameter are discussed.

5.4.1. Railway switch section weights

The importance of each railway switch section is shown in table 8. The weights give a good reflection of the importance of each section on the quality of a railway switch. Firstly, the tongue and point section consist of many critical geometric parameters and have therefore a great importance on the overall quality. This is also reflected in the weights, since these sections score highest compared to the other sections in the same entry. Secondly, the diverging entry has a greater importance on the

Table 8: Importance of railway switch sections

Importance	**Section**	**Weight**
1	Tongue section (diverging)	0.296
2	Point section (diverging)	0.238
3	Whole railway switch (diverging)	0.099
4	Middle section (diverging)	0.087
5	Tongue section (straight)	0.048
6	Pont section (straight)	0.049
7	Whole railway switch (straight)	0.033
8	Back connection (straight and diverging)	0.031
9	Front connection (straight and diverging)	0.030
10	Middle section (straight)	0.029

geometric quality which is reflected in the weights. For each section, the diverging entry always has a higher weight factor. Finally, the back connection, front connection and straight middle section have virtually the same weight factor around the 0.030. These sections consist of the same kind of geometric parameters and they all have straight rail tracks. Therefore, they should have the same importance, which is the case.

5.4.2. Geometric parameter weights

The weights calculated by the AHP method are evaluated by analysing the total weights of each geometric parameter. Currently, the weights are determined by evaluating their importance for every pair combination per entry and segment. By adding the weights of the same geometric parameters of each railway switch segment, we can see which geometric parameters influence the quality indicator the most. These weights were shown in the previous chapter in Figure 12. To validate the distribution of the weights, a rail system expert is asked to rank the importance of the geometric parameters independently from the AHP model.

5.4.3. Discrepancy of geometric parameter weights

The results in Table 9 show a discrepancy between the importance of geometric parameters according to the AHP model and the ranking of the rail system expert. Only the most and least important parameters, the cant difference ("Verkantingsverschil"), the gauge ("Spoorwijdte") and the clearance ("Vrije wielpassage"), have the same ranking, while all the other parameters shift one to four places. This difference is noticeable, because both the AHP model and the ranking are based on the judgement of the same rail system expert.

There are three reasons why this difference could occur. Firstly, the decision-making regarding maintenance of railway switches depends on whether its trafficability is safe and the how sustainable the state of the railway switch is for the life duration. For example, the profile of the railway switch could be worn out a lot, but it could still be very safe, since the gauge is in a good state. However, the railway switch being worn out would probably result in more maintenance and lower life duration.

Table 9: Importance of geometric parameters

Most important	**Parameter importance according to AHP method**	**Parameter importance according to railway switch expert**
1	Verkantingsverschil	Verkantingsverschil
2	Spoorwijdte	Spoorwijdte
3	Inloopmaat	Mal 2 meting 1
4	Kopslijtage hoek	Mal 2 meting 2
5	Groefbreedte	Kopslijtage hoek
6	Mal 2 meting 1	Inloopmaat
7	Strijkmaat	Groefbreedte
8	Mal 2 meting 2	Strijkmaat
9	Verkanting	Mal 1 meting 3
10	Mal 1 meting 3	Mal 1 meting 1
11	Kopslijtage horizontaal	Mal 1 meting 2
12	Kopslijtage verticaal	Verkanting
13	Mal 1 meting 1	Kopslijtage horizontaal
14	Mal 1 meting 2	Kopslijtage verticaal
15	Maat voor vrije wielpassage	Maat voor vrije wielpassage
Least important		

Therefore, the importance of the geometric parameters can vary depending on whether you are focussing on the safety or the sustainability of the railway switch.

Secondly, the number of points at which a railway switch is measured depends on the geometric parameter. The gauge and cant difference are measured at points over the whole railway switch, while the mould measurements ("Mal 1 and Mal2") are only measured at one point. As a result, it is hard to determine how important one point measurement compared to the multiple measurement divided over the whole railway switch.

This leads to the third reason, which is that how geometric parameters are grouped before determining their importance can have a huge impact on the weight calculation. In the case of the AHP model, a hierarchy was modelled where all the geometric parameters are grouped per railway switch segment. Consequently, the weights of geometric parameters which are present in multiple segments are calculated multiple times. This could, for example, explain why cant ('Verkanting') has a higher importance according to the AHP model than when evaluating the geometric parameter with each other, because the cant is also measured at every railway switch segment.

5.4.4. Improvements for obtaining weights

Based on the rankings of the geometric parameters, it is for now difficult to determine which ranking reflects the true importance of the geometric parameters. Both rankings are based on the opinion of the same rail system expert, but only the method of evaluating this importance differ.

Still, recommendations could be given to improve the process of obtaining the weights at ProRail based on the previous observations. Firstly, instead of developing a general quality indicator for a railway switch, more specific indicators could be developed instead. An indicator could be developed which reflects the safety of the railway switch and another indicator could reflect the durability. By separating these two factors, the railway switch expert would not have to make a trade-off between those aspects resulting in a more consistent and accurate indicators. The same methodology could be used to create these performance indicators.

Furthermore, the weighting process could be improved by doing one of the following things:

- Use a different subjective weighting approach
- Change the hierarchy and groups of the indicators
- Change the values of the pairwise comparison matrices of the current AHP model

The AHP method still seems the best approach for determining the weights, because the argumentation provided in sections 3.5.3 still holds. However, the current model could be improved by changing the hierarchy. For further research, it is interesting to see if the weighting of the geometric parameters change depending on how the parameter grouped. A different approach would be dividing the geometric parameters in three sections: "The tongue section", "the point section" and "the whole railway switch". All the geometric parameters that are measured over the whole railway switch would be put in the same group, and the rest of the indicators are divided over the tongue and point section. This way, no geometric parameter will be evaluated several times. However, this approach assumes that the importance of a geometric parameter is the same no matter what the

railway segment is. To determine which approach would be best depends on further research regarding the validation of the indicator described in the next section.

5.5. Validation of the quality indicator

As mentioned in chapter 2, there is at the moment no objective data readily available which could be used as an indication for the geometric quality of railway switches. Therefore, it is not possible to validate the quality scores based on objective data. Instead, the judgement of a railway switch expert is compared to the results from the quality scores.

5.5.1. Validation approach

A quality score can represent a ranking, because the railway switches can be compared based on their quality score. For example, the railway switch with the highest score, has also the best quality compared to the other railway switches. To be able to compare the quality score with the independent judgement of a railway switch expert, ten railway switches are ranked based on their quality. Firstly, ten railway switches are selected in total. Six railway switches are selected by taking railway switches with each approximately 0.05 difference between their quality score. The four other railway switches are selected, because they exceeded the IL on a critical geometric parameter.

These selected railway switches are ranked by a railway switch expert based on the same geometric measurement data. The geometric measurements of these ten railway switches are collected into an Excel sheet which has been sent to the railway switch expert. The railway switch expert based his assessment by analysing the exceeded of the AL and IL and the geometric measurements themselves found in the selected data. The railway switch expert looked specifically at the exceedance of an IL and he looked globally at the geometric measurement values. The exceedance of the AL was also taken into account, but it had a lot less impact on their final judgement then the IL.

The results of the rankings by the developed quality score and the judgement of the railway expert are found in Table 10.

5.5.2. Evaluation of rankings

Both rankings seem quite similar, however, there are some small differences. The ranking of the two highest and two lowest quality scores correspond with each other and the rankings which are not similar differ no more than two ranks from each other.

Both rankings are based on the judgement of a railway switch expert, but only the method is different. The railway switch experts assessed the railway switches by evaluating the AL, IL and the geometric measurement value. The IL did have the highest impact on their assessment and the measurement values where only evaluated globally. The ranking based on the quality scores also indirectly uses the

Table 10: Railway switch ranking

Equipment number	Campaign date	Quality score	Rank by quality score	Rank by railway switch expert
10265441	28/02/2019	0.94311	**1**	**1**
11295331	15/03/2019	0.90323	**2**	**2**
10264872	15/02/2019	0.87043	3	5
10266554	24/08/2017	0.85095	4	3
10525134	01/03/2020	0.82213	5	6
10265668	24/08/2017	0.80953	6	4
11225424	30/08/2019	0.80134	7	8
10201096	15/03/2019	0.78312	8	7
10201095	06/08/2018	0.74837	**9**	**9**
10265426	15/02/2018	0.70952	**10**	**10**

same judgement of the railway switch expert because of the assigned weights. However, the quality scores are more consistent, because it will always produce the same outcome and it takes into account all the measurement values while a railway switch expert can only take into account a limited amount of information into their judgement.

The railways switch expert also mentioned that the ranking based on the quality scores was recognisable. There were a few railway switches which were close looking at their quality according to the railway switch expert. According to him the railway switches ranked 3, 4, 5 and 6 and the railway switches ranked 7 and 8 were hard to differentiate. These also happen to be the railway switches which are ranked differently by the quality scores. This means, that the ranking of the railway switch expert might be different when evaluated by someone else or by evaluating the data in more detail. Therefore, the quality indicator corresponds to the judgement of the railway switch expert, but it is more consistent especially when assessing railway switches which seem to have a closer geometric quality.

5.6. Conclusion

Decisions made based on the subjective judgement result in uncertainties for the method. Therefore, the robustness of the quality indicator can be evaluated by sensitivity and uncertainty analysis. However, experimenting with different methods and inputs is a time-consuming task, therefore, the analysis is restricted to performing sensitivity analysis on the value function. This sensitivity analysis shows that the impact of the parameter Rho does not have a huge impact on average, but in a few cases, it can affect the ranking a lot. Furthermore, analysis of the weights of the geometric parameters show that the weighting does not totally reflect the importance of each parameter. Therefore, the implementation could be improved by changing the groups in which the geometric parameters are evaluated. Finally, the ten railway switches are validated by a railway switch expert. This validation shows promising results; however, a more elaborate validation needs to be executed for more conclusive results.

6. Conclusion and recommendations

In this last chapter, the conclusions of the research are discussed. In addition, recommendations for ProRail are described and further research is suggested.

6.1. Conclusion

In conclusion, an indicator is developed for the geometric quality of railway switches at ProRail. This resulted in methodology for constructing quality indicators which is the artefact of the research. This methodology could be used in other situation with similar requirements and restrictions like ProRail. The methodology consists of a combination of different techniques from the literature which offer a structured approach for the development of a quality indicator. This approach could be implemented in different situations by using own data records and expert judgement. In addition, steps of the methodology could be adjusted by using other weighting or normalisation methods.

The theoretical contribution of this research is derived from providing a systematic approach to develop a quality indicator for railway switches. The method differs from approaches found in the literature due its combination of existing techniques used. As a result, it offers a unique solution for the development of a quality indicator in the context of railway switches. In addition, in the literature there exist indicators for the quality of railway switches, but these studies do not provide a complete approach with all the necessary steps. This research provides a detailed approach from the selection of indicators till the evaluation of the final composite indicator.

In addition, the practical relevance of the quality indicator at ProRail is that it provides more insight into the overall geometric quality of their railway switches. Quantifying the geometric quality of railways switches makes it possible for ProRail to compare the states of different railway switches with each other. This enables the possibility for further analysis by, for example, comparing different contract regions, measuring the effectiveness of maintenance strategies or by identifying trends to predict future quality scores. Furthermore, it provides a more consistent assessment of the quality of railway switches which could support the decision-making regarding the maintenance.

In addition, the implementation at ProRail showed promising results. The validation by comparing rankings created by a railway switch expert and the quality indicator showed similar results. Discrepancies in the results could be explained by inconsistencies in the judgement of the railway expert. However, the population used for validation was small (ten railway switches) and therefore, more research should be done on the credibility of the quality indicator.

Furthermore, by analysing the assumptions, weights for each parameter and the sensitivity analysis of the normalisation function showed that there is room for improvement. However, these improvements seem to mainly involve the implementation of the methodology and not the methodology itself.

The methodology has currently only been implemented in one certain way for the railway switches. This input of the railway switch could be adjusted to improve the quality indicator. For example, more geometric parameters could be included or different groups for the geometric parameters could be used to change the weighting. In addition, the same methodology could also be implemented for crossings which are left out of scope of this research. But by grouping the geometric parameters of the crossings and using according pairwise comparison matrices the quality indicator could be easily implemented.

6.2. Recommendations

The research quality indicator could be incorporated in the current decision-making regarding the maintenance of railway switches.

Firstly, the quality indicator could be used as a support tool for railway switch experts. The quality indicator could be used to help experts make more consistent decisions. In addition, the quality indicator can provide a more manageable overview of the overall quality of railway switches. Also, the sub-indicators could be used to specifically evaluate the segment, entries and parameters. A next step could even be automating decision-making based on the quality indicator.

Secondly, the quality indicator could be used to optimize maintenance planning. Together with the degradation rate the future quality of a railway switch could be predicted. This could be used to determine which railway switches need maintenance the most.

Furthermore, the quality indicator could be used for data analysis. The quality indicator enables ProRail to make comparisons based on the overall quality of railway switches. For example, the quality indicator could be used to evaluate the performance of different contractors or regions. Based on these insights strategies regarding the maintenance could be improved.

Finally, a certain quality score could be set as a target, which could be incorporated in contracts next to the current threshold limits. This way, contractors have to make sure that a certain quality score is maintained, so that the safety of a railway switch is guaranteed.

However, before implementing the quality indicators more research needs to be done to improve and validate the quality indicators

6.3. Further research

Even though, the results seem promising, still more research is needed to improve and test the credibility of the quality indicators. Therefore, the following recommendations are made for further research:

- The sensitivity analysis of quality score for the AL showed that the positions by rank of the railway switches did not change a lot on average. However, there seem to exist a few railway switches which can shift more than one-hundred positions. Therefore, more research would be needed to explain these shifts and to determine which Rho reflects reality best. In addition, more research could be done on the relative importance between exceeding the AL and the IL. This way a grounded score could be given to the AL score.
- More extensive validation could be performed for the quality indicator. Comparing rankings created by expert judgement and the quality indicator showed to be an insightful way for determining the credibility of the quality scores. However, this method is limited by the ability for a railway switch expert to distinguish the geometric quality of railway switches. Therefore, for future research it could be interesting to validate the quality scores by letting the railway switch expert make a bigger selection of extreme cases which can easily distinguished.
- More research should be done on the meaning of a quality score. At the moment the quality scores only receive meaning by comparing the quality score with each other. Therefore, research should be done to determine when the quality of a railway switch is sufficient or insufficient depending on their quality score. Consequently, decision-making could improve or even automated based on these scores.

- The relationship between degradation and restoration factors and the quality indicator should be analysed. A degradation rate could be determined, so that future quality scores could be predicted. In addition, these could be used to validate the quality scores. For example, when a maintenance is performed on a railway switch, the quality score should increase. In addition, the quality score of a railway switch with more traffic is expected to decrease more. Therefore, the degradation and restoration factors could provide more insight into the quality indicator and vice versa.
- The weighting of the geometric parameters could be improved by using other groups. Appendix E.2 shows a recommendation which could result in a weighting that reflects the importance of the railway switches better. In addition, more research could be done on creating separate indicators for the safety and the durability of a railway switch. This could maybe also improve the weighting of the geometric parameters.
- This research has only implemented one combination of techniques to determine the quality indicator. It could be interesting to try out other techniques for normalisation or determining weights. These approaches could be compared with the method proposed in this research.

Bibliography

Berawi, A. R. B., Delgado, R., Calçada, R., & Vale, C. (2010). Evaluating Track Geometrical Quality through Different Methodologies. *International Journal of Technology*, *1*, 38–47. Retrieved from https://www.researchgate.net/publication/286413084_Evaluating_Track_Geometrical_Quality_through_Different_Methodologies

Bukhsh, Z. A., Stipanović Oslaković, I., Klanker, G., Hoj, N. P., Imam, B., & Xenidis, Y. (2017). Multi-criteria decision making: AHP method applied for network bridge prioritization. *Proceedings of the Joint COST TU1402 - COST TU1406 - IABSE WC1 Workshop: The Value of Structural Health Monitoring for the Reliable Bridge Management*, 3.2-1-3.2-9. https://doi.org/10.5592/co/bshm2017.3.2

El Gibari, S., Gómez, T., & Ruiz, F. (2018). Building composite indicators using multicriteria methods: a review. *Journal of Business Economics*, *89*(1), 1–24. https://doi.org/10.1007/s11573-018-0902-z

Famurewa, S. M., Stenström, C., Asplund, M., Galar, D., & Kumar, U. (2014). Composite indicator for railway infrastructure management. *Journal of Modern Transportation*, *22*(4), 214–224. https://doi.org/10.1007/s40534-014-0051-1

Galar, D., Peters, R., Berges, L., Stenström, C., & Kumar, U. (2011). Composite Indicators in Asset Management. *Conference Paper*, 1–14. Retrieved from https://www.researchgate.net/publication/260729965_Composite_Indicators_in_Asset_Management?enrichId=rgreq-25556378f4ab8d27d7483fa3b0c4212d-XXX&enrichSource=Y292ZXJQYWdlOzI2MDcyOTk2NTtBUzo5NzAxMTczNDk0MTY5N0AxNDAwMTQwODA5NDQx&el=1_x_2&_esc=publicationCoverPdf

Goodwin, P., & Wright, G. (2014). *Decision Analysis for Management Judgment* (5th Edition). Hoboken, NJ, United States: Wiley.

Greco, S., Ishizaka, A., Tasiou, M., & Torrisi, G. (2018). On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness. *Social Indicators Research*, *141*(1), 61–94. https://doi.org/10.1007/s11205-017-1832-9

Heerkens, H., & Winden, A. (2017). *Solving managerial problems systematically* (1st ed.). Groningen, Netherlands: Noordhoff.

Ma, J., Ma, X., Zhou, F., & Ma, H. (2014). An Approach to Track Maintenance Prioritization for Urban Rail Transit. *Public Works Management & Policy*, *20*(2), 159–175. https://doi.org/10.1177/1087724x14526155

Malczewski, J., & Rinner, C. (2015). *Multicriteria Decision Analysis in Geographic Information Science*. New York, United States: Springer Publishing.

Meersman, R., Panetto, H., Dillon, T., Missikoff, M., Liu, L., Pastor, O., … Sellis, T. (2014). *On the Move to Meaningful Internet Systems: OTM 2014 Conferences*. New York, United States: Springer Publishing.

OECD, European Union, Joint Research Centre - European Commission, Union, E., & Commission, J. R. C. E. (2008). *Handbook on Constructing Composite Indicators: Methodology and User Guide*. Paris, France: OECD.

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A Design Science Research Methodology for Information Systems Research. *Journal of Management Information Systems*, *24*(3), 45–77. https://doi.org/10.2753/mis0742-1222240302

Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, *9*(3–5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Tofallis, C. (2014). Add or Multiply? A Tutorial on Ranking and Choosing with Multiple Criteria. *INFORMS Transactions on Education*, *14*(3), 109–119. https://doi.org/10.1287/ited.2013.0124

Wątróbski, J., Jankowski, J., Ziemba, P., Karczmarczyk, A., & Zioło, M. (2019). Generalised framework for multi-criteria method selection. *Omega*, *86*, 107–124. https://doi.org/10.1016/j.omega.2018.07.004

Winston, W. L., & Winston, W. L. (2003). *Operations Research* (4th ed.). Belmont, USA: Cengage Learning, Inc.

Zardari, N. H., Ahmed, K., Shirazi, S. M., & Yusop, Z. B. (2014). *Weighting Methods and their Effects on Multi-Criteria Decision Making Model Outcomes in Water Resources Management*. New York, United States: Springer Publishing.

Zwanenburg, W.-J. (2008). A model for the life expectancy of railway switches and crossings for maintenance and renewal planning in asset management systems. *Computers in Railways XI*, 765–773. https://doi.org/10.2495/cr080741

Appendix A: Geometric parameters

Parameter (Dutch)	English name	Data label
Groefbreedte	Groove width	Groefbreedte_L
		Groefbreedte_R
Inloopmaat	Distance flange and rail track	Inloopmaat_sr1_1
		Inloopmaat_sr2_1
		Inloopmaat_vl1_1
Kopslijtage hoek	Profile of the angle	Kopslijtage_Hoek_L
		Kopslijtage_Hoek_R
Kopslijtage horizontaal	Horizontal profile	Kopslijtage_Hor_L
		Kopslijtage_Hor_R
Kopslijtage verticaal	Vertical profile	Kopslijtage_Vert_L
		Kopslijtage_Vert_R
Spoorwijdte	Gauge	Spoorwijdte
Strijkmaat	Distance checker and rail track	Strijkmaat_L
		Strijkmaat_R
Verkantinsverschil/Scheluwte	Cant difference/Track twist	Verkantingsverschil_3m
Vrije wielpassage	Clearance	Vrije_wielpassage
Verkanting	Cant	Verkanting
Mal 1 meting 1	Mould 1 measurement 1	Toets_mal1_1_1
Mal 1 meting 2	Mould 1 measurement 2	Toets_mal1_2_1
Mal 1 meting 3	Mould 1 measurement 3	Toets_mal1_3_1
Mal 2 meting 1	Mould 2 measurement 1	Toets_mal2_1_L
		Toets_mal2_1_R
Mal 2 meting 2	Mould 2 measurement 2	Toets_mal2_2_BW_1
		Toets_mal2_2_VW_1

Appendix B: Normalisation, weighting and aggregation methods

B.1. Normalisation methods

Method	**Source**
Ranking	(OECD, 2008), (Gibrari et al.)
Standardisation/z-scores	(OECD, 2008), (Gibrari et al.)
Min-Max	(OECD, 2008), (Gibrari et al.)
Distance to a reference	(OECD, 2008), (Gibrari et al.)
Categorical scales	(OECD, 2008), (Gibrari et al.)
Indicators above or below the mean	(OECD, 2008)
Cyclical indicators	(OECD, 2008)
Balance of opinions	(OECD, 2008)
Percentage of annual differences over consecutive years	(OECD, 2008)
Value function	(J. Maczewski and C. Rinner, 2015)

B.2. Weighting methods

Subjective weighting methods	
Method	**Source**
Budget Allocation Process (BAP)	(Greco et al., 2019), (Zardari et al., 2015), (OECD, 2008)
Analytic Hierarchy Process (AHP)	Greco, (Zardari et al., 2015), (OECD, 2008)
Conjoint Analysis (CA)	(Greco et al., 2019), (OECD, 2008)
Multi-Attribute Utility Theory (MAUT)	(Gibrari et al.)
Multi-Attribute Value Theory (MAVT)	(Gibrari et al.)
Utility Theory Additive (UTA)	(Gibrari et al.)
Simple Multi-Attribute Rating Technique (SMART)	Gibari, (Zardari et al., 2015)
Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH)	(Gibrari et al.)
Elimination and Choice Expressing Reality (ELECTRE)	(Gibrari et al.)
Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)	(Gibrari et al.)
SIMOS weighting method	(Zardari et al., 2015)
Ranking method	(Zardari et al., 2015)

Objective weighting methods	
Method	**Source**
Principal Component Analysis (CPA)	(Greco et al., 2019), (OECD, 2008)
Factor Analysis (FA)	(Greco et al., 2019)
Correlation Analysis	(Greco et al., 2019)
Multiple Linear Regression	(Greco et al., 2019)
Data Envelopment Analysis (DAE)	(Gibrari et al.)
Goal programming method	(Gibrari et al.)
Compromise programming method	(Gibrari et al.)
Reference point method	(Gibrari et al.)
Technique for order Preferences by Similarity to ideal Solutions (TOPSIS)	(Gibrari et al.)
Grey Relational Analysis (GRA)	(Gibrari et al.)

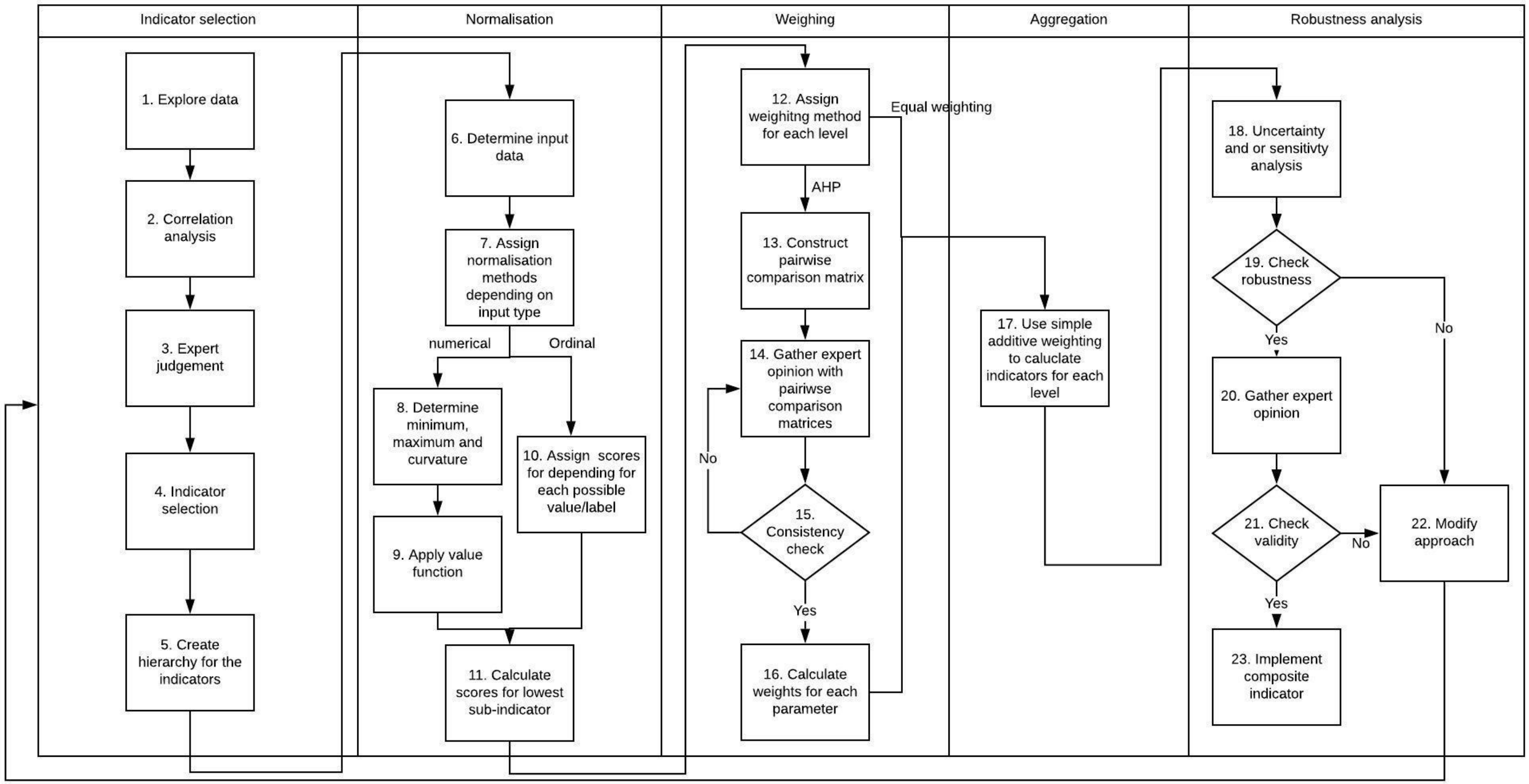
B.3. Aggregation methods

Aggregation methods	
Method	**Source**
Simple additive weighting (SAW)	(Tofallis, 2019), (OECD, 2008)
Weighted product (WP)/ geometric aggregation	(Tofallis, 2019), (OECD, 2008)
WDI_2	(Tofallis, 2019),
WDI_∞	(Tofallis, 2019),
TOPSIS	(Tofallis, 2019),
Non-compensatory multi-criteria approach (MCA)	(OECD, 2008)

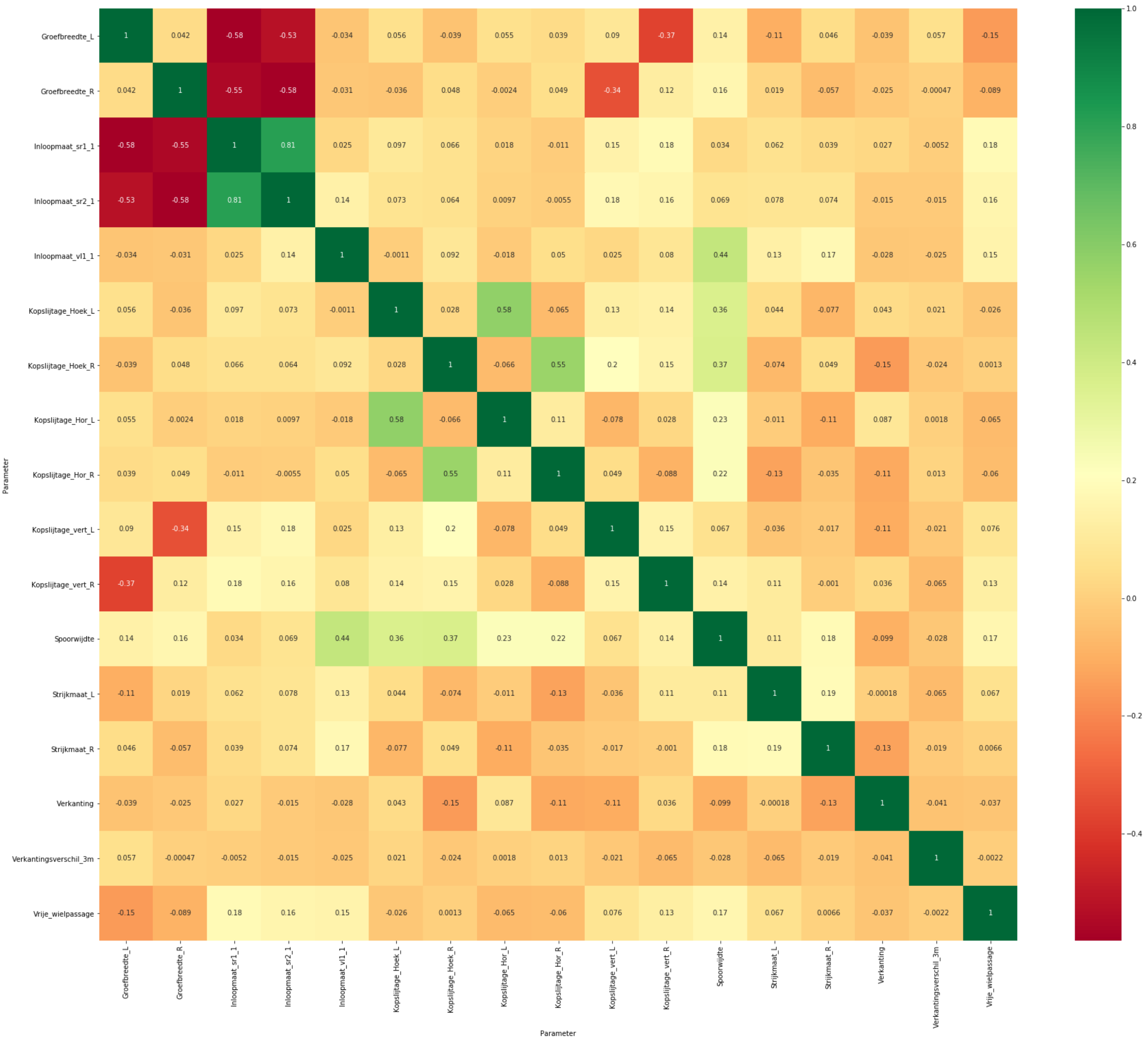
Appendix C: Quality indicator methodology

1. **Explore data:** the data needs to be explored in order to determine which indicators could be defined and incorporated into the quality indicator.
2. **Correlation analysis:** correlation analysis gives insight on which indicators are statistically relevant for the quality indicator, because some indicators might already contain enough information to make other indicators redundant
3. **Expert judgement:** an expert need to confirm which indicators are relevant for measuring the quality of an object.
4. **Indicator selection:** based on the exploration of the data, the correlation analysis and the judgement of an expert, the relevant indicators are selected.
5. **Create hierarchy for the indicators:** The indicators are clustered into groups and levels, so that a hierarchy can be created to establish relationships between the indicators.
6. **Determine input data:** the measurement data that is used to assess the lowest sub-indicators needs to be determined.
7. **Assign normalisation methods depending on input type:** the measurements are normalised depending on their data type. If the data is measured numerically, then the value function is used. If the data is not expressed in number, but instead is defined by an ordinal ranking or a classification, values are assigned depending on the label/classification.
8. **Determine minimum, maximum and curvature:** the parameters of the value function need to be determined. The measurement which result in a minimum and maximum score need to be determined and the curvature needs to be determined by using a reference measurement with an assigned score.
9. **Apply value function:** the value function (Equation 1 and 2) are used to calculate the scores
10. **Assign scores for each possible value:** for each possible classification a quality score between 0 and 1 needs to be assigned.
11. **Calculate score for lowest sub-indicators:** when the parameters and scores of both normalisation approaches are defined, the quality scores for the lowest sub-indicators can be determined.
12. **Assign weighting method for each level:** if the indicators in the same level have the same importance regarding the quality, the equal weighting method should be used. If their impact on the quality differs between indicators, the AHP method should be used.
13. **Construct pairwise comparison matrices:** for each sub-indicator group in the hierarchy a comparison matrix needs to be created.
14. **Gather expert opinion with pairwise comparison matrices:** an expert needs to give his judgement on importance of the indicators on the quality by filling in the pairwise comparison matrices.
15. **Consistency check:** the consistency of the filled in pairwise comparison matrices need be checked and if they do not meet the consistency criterium, the expert needs to revise their evaluation.
16. **Calculate weights for each parameter:** for each sub-indicator the weights are calculated
17. **Using simple additive weighting to calculate indicators for each level:** using equal weights or the weights obtained from the AHP method, the weighted average is used to calculate indicators for each level.
18. **Uncertainty and or sensitivity analysis:** the robustness of the quality indicator is tested by using uncertainty and sensitivity analysis.
19. **Check robustness:** based on the uncertainty and sensitivity analysis, one should determine if the quality indicator is robust enough.

20. **Gather expert opinion:** the quality scores need to be compared with the opinion of an expert to determine if the quality indicator reflects their judgement.
21. **Check validity:** based on the opinion of an expert the validity of the quality indicators needs to be checked.
22. **Modify approach:** if necessary, the methodology needs to be implemented differently or a whole other approach needs to be used to determine the quality indicator.
23. **Implement composite indicator:** the composite indicator can be implemented for data analysis or supporting decision-making.


Indicator selection
Normalisation
Weighing
Aggregation
Robustness analysis
1. Explore data
2. Correlation analysis
3. Expert judgement
4. Indicator selection
5. Create hierarchy for the indicators
6. Determine input data
7. Assign normalisation methods depending on input type
numerical
Ordinal
8. Determine minimum, maximum and curvature
9. Apply value function
10. Assign scores for depending for each possible value/label
11. Calculate scores for lowest sub-indicator
12. Assign weighitng method for each level
Equal weighting
AHP
13. Construct pairwise comparison matrix
14. Gather expert opinion with pairiwse comparison matrices
No
15. Consistency check
Yes
16. Calculate weights for each parameter
17. Use simple additive weighting to caluclate indicators for each level
18. Uncertainty and or sensitivty analysis
19. Check robustness
Yes
No
20. Gather expert opinion
21. Check validity
No
22. Modify approach
Yes
23. Implement composite indicator

Appendix D: Geometric parameter correlation matrix



Appendix E: Rail switch segment parameter division

E.1. Geometric parameter used in current AHP model

Railway switch segment	**Geometric parameters**
Front connection section Dutch: *“Aansluitgedeelte voorkant”*	- Spoorwijdte - Verkanting - Kopslijtage horizontaal - Kopslijtage verticaal - Kopslijtage hoek
Tongue section (Straight and diverging entry) Dutch: *“Tongbeweging (Recht doorgaand en afbuigend)”*	- Spoorwijdte - Verkanting - Kopslijtage horizontaal - Kopslijtage verticaal - Kopslijtage hoek - Mal 1 meting 1 - Mal 1 meting 2 - Mal 1 meting 3 - Mal 2 meting 1 - Mal 2 meting 2 - Vrije wielpassage
Middle section (Straight and diverging entry Dutch: *“Middengedeelte (Recht doorgaand en afbuigend)”*	- Spoorwijdte - Verkanting - Kopslijtage horizontaal - Kopslijtage verticaal - Kopslijtage hoek
Point section (Straight and diverging entry) Dutch: *“Punstukgedeelte (Recht doorgaand en afbuigend)”*	- Spoorwijdte - Verkanting - Inloopmaat - Strijkmaat - Groefbreedte
Back connection section (Straight and diverging entry) Dutch: *“Aansluitgedeelte achterkant (Recht doorgaand en afbuigend)”*	- Spoorwijdte - Verkanting - Kopslijtage horizontaal - Kopslijtage verticaal - Kopslijtage hoek
Whole railway switch (Straight and diverging Entry) Dutch: *“Gehele wissel (Recht doorgaand en afbuigend)”*	- Scheluwte

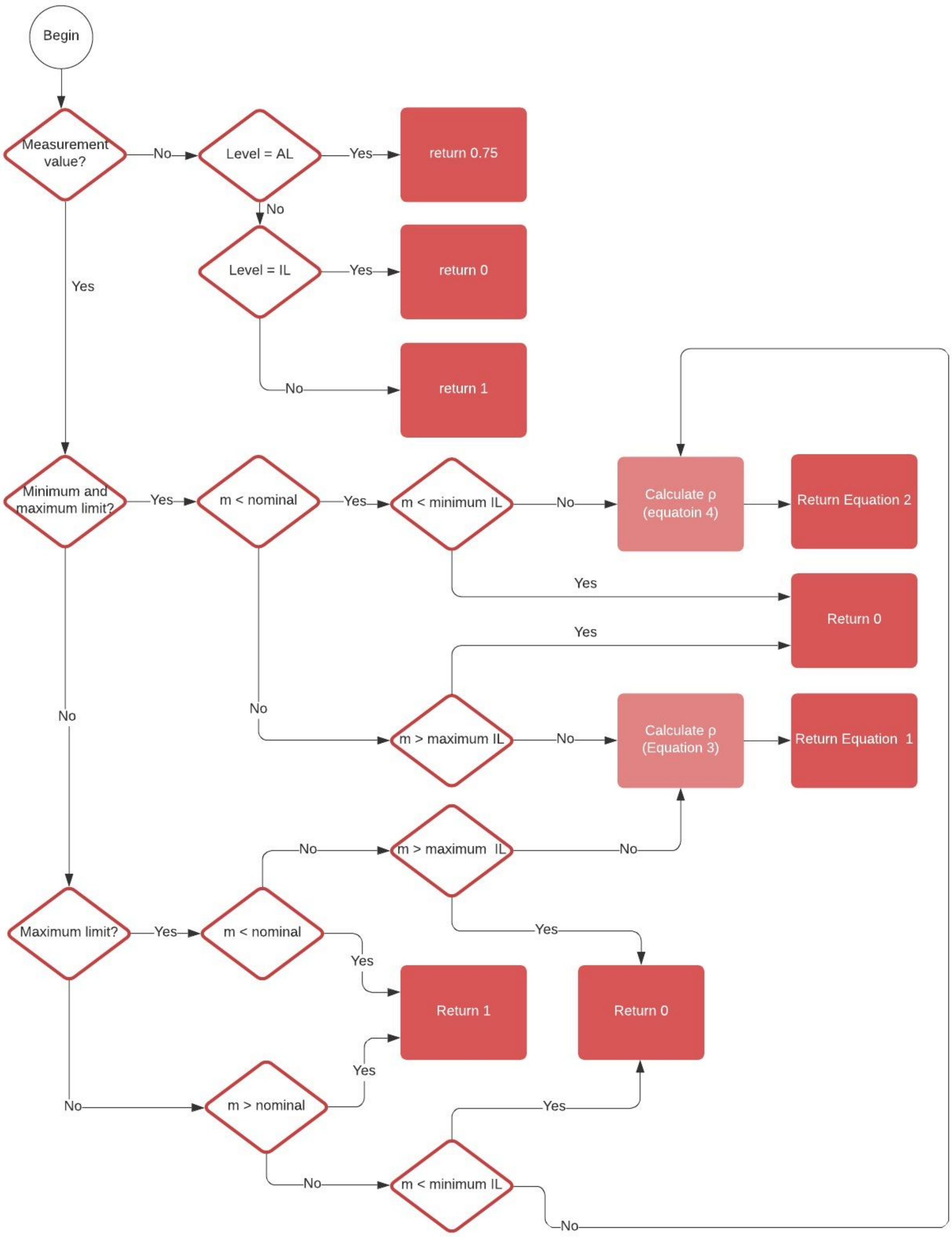
E.2. Future recommended division of geometric parameters

Railway switch segment	**Geometric parameters**
Tongue section (Straight and diverging entry) Dutch: *"Tongbeweging (Recht doorgaand en afbuigend)"*	- Mal 1 meting 1 - Mal 1 meting 2 - Mal 1 meting 3 - Mal 2 meting 1 - Mal 2 meting 2 - Vrije wielpassage
Point section (Straight and diverging entry) Dutch: *"Punstukgedeelte (Recht doorgaand en afbuigend)"*	- Inloopmaat - Strijkmaat - Groefbreedte
Whole railway switch (Straight and diverging Entry) Dutch: *"Gehele wissel (Recht doorgaand en afbuigend)"*	- Scheluwte - Spoorwijdte - Verkanting - Kopslijtage horizontaal - Kopslijtage verticaal - Kopslijtage hoek

Appendix F: Normalisation algorithm

The normalisation algorithm is used to transform the measurement of a geometric parameter into a quality score between zero and one.

- m: the measurement value of a geometric parameter
- level: the label of an exceeded threshold value



Appendix G: AHP model Excel sheet

Description of the calculations:

- The pairwise comparison matrices are filled in by a railway switch expert while fulfilling the constraint of Equation 5
- The normalized matrices are calculated using Equation 6
- The weights are calculated using Equation 7
- The values in column ‘Aw’ are calculated by using Equation 8
- The values in column ‘Aw/w are calculated by dividing the value of column ‘Aw’ by their corresponding weights (This is an intermediate step of Equation 9)
- Using Equation 9 and 10 the consistency index is calculated
- The consistency ratio is calculated using Equation 11

Pairwise comparison matrices

Wisselgedeelte	Aansluitgedeelte voorkant	Tongbeweging	Middengedeelte	Puntstukgedeelte	Aansluitgedeelte achterkant	Gehele wissel
Aansluitgedeelte voorkant	1	0.1667	0.5	0.2	1	0.5
Tongbeweging	6	1	5	1	5	2
Middengedeelte	2	0.2	1	0.5	2	1
Puntstukgedeelte	5	1	2	1	5	2
Aansluitgedeelte achterkant	1	0.2	0.5	0.2	1	0.5
Gehele wissel (Scheluwte)	2	0.5	1	0.5	2	1

Afbuigend t.o.v. rechtdoorgaand	Rechtdoorgaand	Afbuigend
Tongbeweging		
Rechtdoorgaand	1	0.1667
Afbuigend	6	1
Middengedeelte		
Rechtdoorgaand	1	0.3333
Afbuigend	3	1
Puntstukgedeelte		
Rechtdoorgaand	1	0.2
Afbuigend	5	1
Gehele wissel (Scheluwte)		
Rechtdoorgaand	1	0.3333
Afbuigend	3	1

Aansluitgedeelte voorkant	Spoorwijdte	Verkanting	Kopslijtage verticaal	Kopslijtage horizontaal	Kopslijtage hoek
Spoorwijdte	1	3	3	3	2
Verkanting	0.3333	1	1	1	0.5
Kopslijtage verticaal	0.3333	1	1	1	0.5
Kopslijtage horizontaal	0.3333	1	1	1	0.5
Kopslijtage hoek	0.5	2	2	2	1

Normalized matrices

Wisselgedeelte	Aansluitgedeelte voorkant	Tongbeweging	Middengedeelte	Puntstukgedeelte	Aansluitgedeelte achterkant	Gehele wissel
Aansluitgedeelte voorkant	0.0588	0.0543	0.05	0.0588	0.0625	0.0714
Tongbeweging	0.3529	0.3261	0.5	0.2941	0.3125	0.2857
Middengedeelte	0.1176	0.0652	0.1	0.1471	0.125	0.1429
Puntstukgedeelte	0.2941	0.3261	0.2	0.2941	0.3125	0.2857
Aansluitgedeelte achterkant	0.0588	0.0652	0.05	0.0588	0.0625	0.0714
Gehele wissel	0.1176	0.163	0.1	0.1471	0.125	0.1429

Afbuigend t.o.v. rechtdoorgaand	Rechtdoorgaand	Afbuigend
Tongbeweging		
Rechtdoorgaand	0.1429	0.1429
Afbuigend	0.8571	0.8571
Middengedeelte		
Rechtdoorgaand	0.25	0.25
Afbuigend	0.75	0.75
Punstukgedeelte		
Rechtdoorgaand	0.1667	0.1667
Afbuigend	0.8333	0.8333
Gehele wissel (Scheluwte)		
Rechtdoorgaand	0.25	0.25
Afbuigend	0.75	0.75

Aansluitgedeelte voorkant	Spoorwijdte	Verkanting	Kopslijtage verticaal	Kopslijtage horizontaal	Kopslijtage hoek
Spoorwijdte	0.4	0.375	0.375	0.375	0.4444
Verkanting	0.1333	0.125	0.125	0.125	0.1111
Kopslijtage verticaal	0.1333	0.125	0.125	0.125	0.1111
Kopslijtage horizontaal	0.1333	0.125	0.125	0.125	0.1111
Kopslijtage hoek	0.2	0.25	0.25	0.25	0.2222

Consistency check

Weights	Aw	Aw/w	Consistency index	Consistency ratio
0.059	0.0581	0.9802	-1	-0.81
0.345	0.3326	0.9634		
0.116	0.1097	0.9431		
0.285	0.2942	1.0308		
0.061	0.0619	1.0126		
0.133	0.1435	1.0818		

Weights	AwT	AwT/wT	Consistency index	Consistency ratio
0.143	0.1429	1	-1	0
0.857	0.8571	1		
0.25	0.25	1	-1	0
0.75	0.75	1		
0.167	0.1667	1	-1	0
0.833	0.8333	1		
0.25	0.25	1	-1	0
0.75	0.75	1		

Weights	AwT	AwT/wT	Consistency index	Consistency ratio
0.394	0.4011	1.0184	-1	-0.89
0.124	0.125	1.0092		
0.124	0.125	1.0092		
0.124	0.125	1.0092		
0.234	0.2238	0.9546		

Middengedeelte afbuigend	Spoorwijdte	Verkanting	Kopslijtage verticaal	Kopslijtage horizontaal	Kopslijtage hoek
Spoorwijdte	1	2	3	2	0.5
Verkanting	0.5	1	2	1	0.5
Kopslijtage verticaal	0.3333	0.5	1	0.5	0.333
Kopslijtage horizontaal	0.5	1	2	1	0.333
Kopslijtage hoek	2	2	3.003	3.003	1

Middengedeelte afbuigend	Spoorwijdte	Verkanting	Kopslijtage verticaal	Kopslijtage horizontaal	Kopslijtage hoek	Weights	AWT	AWT/WT	Consistency index	Consistency ratio
Spoorwijdte	0.2308	0.3077	0.2727	0.2666	0.1875	**0.253**	0.2357	0.9313	-1	**-0.89**
Verkanting	0.1154	0.1538	0.1818	0.1333	0.1875	**0.154**	0.1559	1.0098		
Kopslijtage verticaal	0.0769	0.0769	0.0909	0.0666	0.1249	**0.087**	0.0941	1.0787		
Kopslijtage horizontaal	0.1154	0.1538	0.1818	0.1333	0.1249	**0.142**	0.1331	0.9385		
Kopslijtage hoek	0.4615	0.3077	0.2729	0.4002	0.3751	**0.363**	0.3812	1.0487		

Puntstukgedeelte rechtdoorgaand	Spoorwijdte	Verkanting	Inloopmaat	Strijkmaat	Groefbreedte
Spoorwijdte	1	2	0.25	0.333	0.25
Verkanting	0.5	1	0.1667	0.1667	0.1667
Inloopmaat	4	5.9988	1	2	1
Strijkmaat	3.003	5.9988	0.5	1	1
Groefbreedte	4	5.9988	1	1	1

Puntgedeelte rechtdoorga	Spoorwijdte	Verkanting	Inloopmaat	Strijkmaat	Groefbreedte	Weights	AWT	AWT/WT	Consistency index	Consistency ratio
Spoorwijdte	0.08	0.0953	0.0857	0.074	0.0732	**0.082**	0.0792	0.97	-1	**-0.71**
Verkanting	0.04	0.0476	0.0572	0.037	0.0488	**0.046**	0.048	1.0405		
Inloopmaat	0.3199	0.2857	0.3429	0.4445	0.2927	**0.337**	0.3483	1.0331		
Strijkmaat	0.2402	0.2857	0.1714	0.2222	0.2927	**0.242**	0.2301	0.9491		
Groefbreedte	0.3199	0.2857	0.3429	0.2222	0.2927	**0.293**	0.2944	1.0059		

Puntstukgedeelte afbuigend	Spoorwijdte	Verkanting	Inloopmaat	Strijkmaat	Groefbreedte
Spoorwijdte	1	3	0.2	0.2	0.2
Verkanting	0.3333	1	0.1667	0.1667	0.1667
Inloopmaat	5	5.9988	1	2	1
Strijkmaat	5	5.9988	0.5	1	1
Groefbreedte	5	5.9988	1	1	1

Puntgedeelte afbuigend	Spoorwijdte	Verkanting	Inloopmaat	Strijkmaat	Groefbreedte	Weights	AWT	AWT/WT	Consistency index	Consistency ratio
Spoorwijdte	0.0612	0.1364	0.0698	0.0458	0.0594	**0.075**	0.0628	0.8429	-1	**-0.71**
Verkanting	0.0204	0.0455	0.0582	0.0382	0.0495	**0.042**	0.0472	1.1142		
Inloopmaat	0.3061	0.2727	0.3488	0.458	0.297	**0.337**	0.3553	1.0557		
Strijkmaat	0.3061	0.2727	0.1744	0.229	0.297	**0.256**	0.238	0.9302		
Groefbreedte	0.3061	0.2727	0.3488	0.229	0.297	**0.291**	0.2967	1.0205		

Aansluitgedeelte achterkant	Spoorwijdte	Verkanting	Kopslijtage verticaal	Kopslijtage horizontaal	Kopslijtage hoek
Spoorwijdte	1	3	3	3	2
Verkanting	0.3333	1	1	1	0.5
Kopslijtage verticaal	0.3333	1	1	1	0.5
Kopslijtage horizontaal	0.3333	1	1	1	0.5
Kopslijtage hoek	0.5	2	2	2	1

Aansluitgedeelte achterka	Spoorwijdte	Verkanting	Kopslijtage verticaal	Kopslijtage horizontaal	Kopslijtage hoek	Weights	AWT	AWT/WT	Consistency index	Consistency ratio
Spoorwijdte	0.4	0.375	0.375	0.375	0.4444	**0.394**	0.4011	1.0184	-1	**-0.89**
Verkanting	0.1333	0.125	0.125	0.125	0.1111	**0.124**	0.125	1.0092		
Kopslijtage verticaal	0.1333	0.125	0.125	0.125	0.1111	**0.124**	0.125	1.0092		
Kopslijtage horizontaal	0.1333	0.125	0.125	0.125	0.1111	**0.124**	0.125	1.0092		
Kopslijtage hoek	0.2	0.25	0.25	0.25	0.2222	**0.234**	0.2238	0.9546		

Middengedeelte rechtdoorgaand	wijdte	nting	erticaal	ori zonta	hoek
Spoorwijdte	1	3	3	3	2
Verkanting	0.3333	1	1	1	0.5
Kopslijtage verticaal	0.3333	1	1	1	0.5
Kopslijtage horizontaal	0.3333	1	1	1	0.5
Kopslijtage hoek	0.5	2	2	2	1

Middengedeelte rechtdoor	wijdte	nting	erticaal	ori zonta	hoek	eights	AWT	AWT/WT	ndex	ratio
Spoorwijdte	0.4	0.375	0.375	0.375	0.4444	**0.394**	0.4011	1.0184	-1	**-0.89**
Verkanting	0.1333	0.125	0.125	0.125	0.1111	**0.124**	0.125	1.0092		
Kopslijtage verticaal	0.1333	0.125	0.125	0.125	0.1111	**0.124**	0.125	1.0092		
Kopslijtage horizontaal	0.1333	0.125	0.125	0.125	0.1111	**0.124**	0.125	1.0092		
Kopslijtage hoek	0.2	0.25	0.25	0.25	0.2222	**0.234**	0.2238	0.9546		

Appendix H: AHP results

H.1. Weight factors for railway switch segments

Wisselgedeelte	Weighting
Aansluitgedeelte voorkant	0.059321
Tongbeweging	0.345227
Middengedeelte	0.116297
Puntstukgedeelte	0.285423
Aansluitgedeelte achterkant	0.061132
Gehele wissel (Scheluwte)	0.132601

H.2. Weight factors for railway switch entry

Wisselgedeelte	Uitwijking	Weighting
Aansluitgedeelte voorkant	Rechtdoorgaand	0.5
Aansluitgedeelte voorkant	Afbuigend	0.5
Tongbeweging	Rechtdoorgaand	0.142857
Tongbeweging	Afbuigend	0.857143
Middengedeelte	Rechtdoorgaand	0.25
Middengedeelte	Afbuigend	0.75
Puntstukgedeelte	Rechtdoorgaand	0.166667
Puntstukgedeelte	Afbuigend	0.833333
Aansluitgedeelte achterkant	Rechtdoorgaand	0.5
Aansluitgedeelte achterkant	Afbuigend	0.5
Gehele wissel	Rechtdoorgaand	0.25
Gehele wissel	Afbuigend	0.75

H.3. Weight factors for geometric parameters

Wisselgedeelte	**Uitwijking**	**Parameter**	**Weighting**
Aansluitgedeelte voorkant	Rechtdoorgaand	Spoorwijdte	0.3938889
		Verkanting	0.1238889
		Kopslijtage verticaal	0.1238889
		Kopslijtage horizontaal	0.1238889
		Kopslijtage hoek	0.2344444
	Afbuigend	Spoorwijdte	0.3938889
		Verkanting	0.1238889
		Kopslijtage verticaal	0.1238889
		Kopslijtage horizontaal	0.1238889
		Kopslijtage hoek	0.2344444
Tongbeweging	Rechtdoorgaand	Spoorwijdte	0.1278716
		Verkanting	0.0430951

		Kopslijtage verticaal	0.0473162
		Kopslijtage horizontaal	0.0489306
		Kopslijtage hoek	0.0815488
		Mal 1 meting 1	0.1071107
		Mal 1 meting 2	0.0818402
		Mal 1 meting 3	0.0962227
		Mal 2 meting 1	0.1286253
		Mal 2 meting 2	0.1022126
		Vrije wiel passage	0.1352262
	Afbuigend	Spoorwijdte	0.0464848
		Verkanting	0.0472098
		Kopslijtage verticaal	0.0268387
		Kopslijtage horizontaal	0.0279646
		Kopslijtage hoek	0.0752935
		Mal 1 meting 1	0.0891531
		Mal 1 meting 2	0.0759901
		Mal 1 meting 3	0.1377509
		Mal 2 meting 1	0.2236665
		Mal 2 meting 2	0.205336
		Vrije wiel passage	0.0443119
Middengedeelte	Rechtdoorgaand	Spoorwijdte	0.3938889
		Verkanting	0.1238889
		Kopslijtage verticaal	0.1238889
		Kopslijtage horizontaal	0.1238889
		Kopslijtage hoek	0.2344444
	Afbuigend	Spoorwijdte	0.2530442
		Verkanting	0.1543652
		Kopslijtage verticaal	0.0872553
		Kopslijtage horizontaal	0.1418371
		Kopslijtage hoek	0.3634981
Puntgedeelte	Rechtdoorgaand	Spoorwijdte	0.0837382
		Verkanting	0.041772
		Kopslijtage verticaal	0.0496418
		Kopslijtage horizontaal	0.0358162
		Kopslijtage hoek	0.0481362
		Inloopmaat	0.2723965
		Strijkmaat	0.2207749
		Groefbreedte	0.2477242
	Afbuigend	Spoorwijdte	0.0754198
		Verkanting	0.0402447
		Kopslijtage verticaal	0.0497185
		Kopslijtage horizontaal	0.0373541
		Kopslijtage hoek	0.0497185
		Inloopmaat	0.2702353
		Strijkmaat	0.227039
		Groefbreedte	0.2502701

Aansluitgedeelte	Rechtdoorgaand	Spoorwijdte	0.3938889
		Verkanting	0.1238889
		Kopslijtage verticaal	0.1238889
		Kopslijtage horizontaal	0.1238889
		Kopslijtage hoek	0.2344444
	Afbuigend	Spoorwijdte	0.3938889
		Verkanting	0.1238889
		Kopslijtage verticaal	0.1238889
		Kopslijtage horizontaal	0.1238889
		Kopslijtage hoek	0.2344444
Gehele wissel	Rechtdoorgaand	Verkantingsverschil	1
	Afbuigend	Verkantingsverschil	1

Appendix I: Code for calculating quality scores

I.1. Data preparation

In [158]:

```
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib
import numpy as np
import ipywidgets as wdg
from ipywidgets import interact, interactive, fixed, interact_manual
import math
import pandasql as ps

from ipywidgets import interact, interactive, fixed, interact_manual
import ipywidgets as wg
%matplotlib inline
```

Data Preperation

In [264]:

```
filepath = 'C:\\Users\\Daniël\\Documents\\ProRail\\'

# Wisselmetingen, OHD-waardes, wisselgangen, wisselkentekens en wisselspoortakken
wm = pd.read_csv(filepath+'export_20200318test.csv', low_memory=False, sep=';', decimal=',')
ohd = pd.read_csv(filepath+'OHD00022-1 V007 incl Hanzeln zonder verkantingafwijking_v14-0.csv', low_memory=False, sep=';'\
                    , decimal='.')
wg = pd.read_csv(filepath+'wisselgang_v14-0.csv', low_memory=False, sep=';')
wk = pd.read_csv(filepath+'wisselgangkenmerken_v14-0.csv', low_memory=False, sep=';')
ws = pd.read_csv(filepath+'wisselgangspoortak_v14-0.csv', low_memory=False, sep=';')


# Remove time from DateTime
wm['DateTime']=pd.to_datetime(wm['DateTime']).dt.date
# Only take the data of regular railway switches
wm = wm.loc[(wm['Gang']=='Links')|(wm['Gang']=='Rechts')]
```

In [179]:

```
# SQL script to merge metingen, wisselgangen, wisseltekeningen, spoortakken en ohd tables
sqlcode ='''
SELECT wm.Equipmentnummer, wm.DateTime, wm.Gang, wg.UITWBAAN, wm.Parameter, wm.DPName, wk.SOORT,
    ohd.Gebiedsnaam, wm.MaxValue, wm.Level, ohd.'BW+', ohd.'BW-',
    ohd.'VW+', ohd.'VW-', ohd.'Nominaal'
FROM wm AS wm
LEFT JOIN wg
    ON wm.Equipmentnummer = wg.EQNR AND wm.Gang=wg.GANG
LEFT JOIN wk
    ON wg.TEKNR = wk.TEKNR AND wg.GANG = wk.GANG AND wg.UITWBAAN = wk.UITWTEK
LEFT JOIN ws
    ON wm.Equipmentnummer = ws.EQNR AND wm.Gang = ws.GANG
LEFT JOIN ohd
    ON wg.TEKNR = ohd.Tekeningnr AND wm.Gang = ohd.Gang AND wg.UITWBAAN = ohd.Ontwuitw AND wm.Parameter = ohd.Parameter AND
    wm.Van >= ohd.Positie_van AND wm.Van < ohd.Positie_tot AND
    ws.LOKALE_SNELHEID >= ohd.VMIN AND ws.LOKALE_SNELHEID <= ohd.Vmax
ORDER BY wm.Equipmentnummer, wm.DateTime, wm.Gang, wm.Parameter, wm.DPName
'''
df = ps.sqldf(sqlcode,locals())
```

In [180]:

```
# Clean the merged data
df[['BW+', 'VW+']] = df[['BW+', 'VW+']].replace('Nee', np.nan)
df[['BW+', 'VW+']] = df[['BW+', 'VW+']].astype(float)

# Adding nominal values to OHD values to get absolute values
df.loc[df['BW+'].notnull()& df['Nominaal'].notnull(), 'BW+'] = df['BW+']+ df['Nominaal']
df.loc[df['BW-'].notnull()& df['Nominaal'].notnull(), 'BW-'] = df['BW-']+ df['Nominaal']
df.loc[df['VW+'].notnull()& df['Nominaal'].notnull(), 'VW+'] = df['VW+']+ df['Nominaal']
df.loc[df['VW-'].notnull()& df['Nominaal'].notnull(), 'VW-'] = df['VW-']+ df['Nominaal']


# Add OHD values for Verkanting
df.loc[df['Parameter']=='Verkanting', ['Gebiedsnaam', 'BW+', 'BW-', 'VW+', 'VW-']] = ['Gehele Wissel', 10, -10, 30, -30]
df.loc[((df['Parameter']=='Kopslijtage_Hoek_R')|(df['Parameter']=='Kopslijtage_Hoek_L')) & ((df['DPName']=='Ar')|\
    (df['DPName']=='Al')|(df['DPName']=='A')), ['Gebiedsnaam', 'BW+', 'BW-', 'VW+', 'VW-', 'Nominaal']] = \
    ['Aansluitgedeelte achterkant', 30, np.nan, 32, np.nan, 0]

# Add missing nominal values
df.loc[df['Parameter'].str.contains('Inloopmaat'), 'Nominaal'] = 1375
df.loc[df['Parameter'].str.contains('Groefbreedte'), 'Nominaal'] = 41
df.loc[df['Parameter']=='Verkanting', 'Nominaal'] = 0
df.loc[df['Parameter']=='Vrije_wielpassage', 'Nominaal'] = 1378


# Remove rows where Spoorwijdte has no OHD values
df = df.fillna(value=np.nan)
df = df[df['Gebiedsnaam'].notna()]
df = df.loc[df['SOORT']=='GW']
df = df.drop(columns=['SOORT', 'Gebiedsnaam'])

# merge Toets_mal2_2_BW_1 and Toets_Mal2_2_VW_1 together in a single row
df.loc[((df['Parameter']=='Toets_mal2_2_BW_1')|(df['Parameter']=='Toets_mal2_2_VW_1'))&\
       ((df['Level']=='Geen overschrijding')|(df['Level']=='Geen overschrijding')|(df['Level']=='Niet geinspecteerd')|\
        (df['Level']=='SW')),['Level']]=1
df.loc[((df['Parameter']=='Toets_mal2_2_BW_1')|(df['Parameter']=='Toets_mal2_2_VW_1'))&(df['Level']=='BW'),['Level']]=2
df.loc[((df['Parameter']=='Toets_mal2_2_BW_1')|(df['Parameter']=='Toets_mal2_2_VW_1'))&(df['Level']=='VW'),['Level']]=3
df.loc[(df['Parameter']=='Toets_mal2_2_BW_1')|(df['Parameter']=='Toets_mal2_2_VW_1'), 'Parameter']='Toets_mal2_2_VW_1'
df = df.groupby(['Equipmentnummer', 'DateTime', 'Gang', 'Parameter', 'DPName']).max()
df = df.reset_index()
df.loc[(df['Parameter']=='Toets_mal2_2_VW_1')&(df['Level']==1), ['Level']] = 'Geen Overschrijdingen'
df.loc[(df['Parameter']=='Toets_mal2_2_VW_1')&(df['Level']==2), ['Level']] = 'BW'
df.loc[(df['Parameter']=='Toets_mal2_2_VW_1')&(df['Level']==3), ['Level']] = 'VW'
```

I.2. Normalisation function

Normalisation

In [184]:

```
yRho = 0.75

# Maximazation value function
def maxValueFunction(min, max, rhoX, rhoY, x):
    rho = math.log(rhoY)/math.log((rhoX - min)/(max-min))
    if x < min:
        return 1
    elif x > max:
        return 0
    else:
        return ((max-x)/(max-min))**rho

# Minimization value function
def minValueFunction(min, max, rhoX, rhoY, x):
    rho = math.log(rhoY)/math.log((max-rhoX)/(max-min))
    if x < min:
        return 0
    if x > max:
        return 1
    else:
        return ((x-min)/(max-min))**rho

# General function for normalizing the geometric measurements
def calculateQualityIndicator(level, value, nominal, BWplus, BWminus, VWplus, VWminus):
#     if there is no measurement value (e.g. mal meting 1 and mal meting 2) use the level to determine the quality indicator
    if (np.isnan(BWplus) & np.isnan(BWminus) & np.isnan(VWplus) & np.isnan(VWminus)):
        if level == 'BW': return yRho
        elif level == 'VW': return 0
        else: return 1
#       Maximum and minimum threshold values
    elif (~np.isnan(BWplus) & ~np.isnan(BWminus) & ~np.isnan(VWplus) & ~np.isnan(VWminus)):
        if value > nominal:
            return maxValueFunction(nominal, VWplus, BWplus, yRho, value)
        else:
            return minValueFunction(VWminus, nominal, BWminus, yRho, value)
#     Maximum threshold values
    elif ~np.isnan(BWplus) & ~np.isnan(VWplus):
        return maxValueFunction(nominal, VWplus, BWplus, yRho, value)
#     Minimum threshold values
    elif ~np.isnan(BWminus) & ~np.isnan(VWminus):
        return minValueFunction(VWminus, nominal, BWminus, yRho, value)
    else:
        return null
```

In [185]:

```
# Apply normalisation function to all measurements
vfunc = np.vectorize(calculateQualityIndicator)
df['Quality Indicator'] = df.apply(lambda row: vfunc(row['Level'], row['MaxValue'], row['Nominaal'],\
                                                    row['BW+'], row['BW-'], row['VW+'], row['VW-']), axis = 1)
```

```
C:\Anaconda\lib\site-packages\numpy\lib\function_base.py:2167: RuntimeWarning: invalid value encountered in ? (vectorized)
  outputs = ufunc(*inputs)
```

I.3. AHP data preparation

Weighting

In [398]:

```
# Load data from the AHP Excel document
AHP_excel = 'Kopie van AHP model versie 3 ingevuld GB zonder kopslijtage puntstuk.xlsx'
AHP_wg = pd.read_excel(filepath+AHP_excel, sheet_name='Wisselgedeelte weighting')
AHP_uitwijk = pd.read_excel(filepath+AHP_excel, sheet_name='Uitwijking weighting')
AHP_parameter = pd.read_excel(filepath+AHP_excel, sheet_name='Parameter weighting')
pargroup = pd.read_excel(filepath+AHP_excel, sheet_name='Unique parameters')
wisselgedeeltes = pd.read_excel(filepath+AHP_excel, sheet_name='Punt per wisselgedeelte')

AHP = pd.merge(AHP_uitwijk, AHP_wg, how='right')
AHP = pd.merge(AHP_parameter, AHP, how='right')
AHP['Total weighting'] = AHP['Parameter weighting'] * AHP['Uitwijk weighting'] * AHP['Wisselgedeelte weighting']
```

In [399]:

```
# Changing Uitwijkbaan from ja or nee to afbuigend and rechtdoorgaand
def checkUitwijkbaan(gang, uitwijkbaan):
    if (gang==uitwijkbaan):
        return 'Afbuigend'
    else:
        return 'Rechtdoorgaand'
vfuncCheckUitwijkbaan = np.vectorize(checkUitwijkbaan)

# Merge tables with parameter groups and railway sections
x = pd.merge(df, pargroup, how='left', left_on='Parameter', right_on='Parameter')
x = pd.merge(x, wisselgedeeltes, how='left', left_on='DPName', right_on='DPName')
x['Uitwijking'] = x.apply(lambda row: vfuncCheckUitwijkbaan(row['Gang'], row['UITWBAAN']), axis=1)

# merge with AHP weights
merge_AHP = pd.merge(x, AHP, how='left', left_on=['Parameter groep', 'Wisselgedeelte', 'Uitwijking'], \
                     right_on=['Parameter', 'Wisselgedeelte', 'Uitwijking']).drop(columns='Parameter_y')
```

I.4. Aggregation

Aggregation for overall quality score

In [400]:
```
temp = merge_AHP
temp['Product'] = temp['Total weighting'] * temp['Quality Indicator']
temp = merge_AHP[['Equipmentnummer', 'DateTime', 'Parameter groep', 'Wisselgedeelte', 'Uitwijking',\
                  'Product', 'Total weighting']].groupby(['Equipmentnummer', 'DateTime', 'Parameter groep', \
                                                          'Wisselgedeelte', 'Uitwijking']).mean()

quality_scores = temp.groupby(['Equipmentnummer', 'DateTime']).sum()
quality_scores = quality_scores.loc[quality_scores['Total weighting']>=0.9999999]
# quality_scores = quality_scores.drop(columns='Total weighting')

with pd.option_context('display.max_rows', None, 'display.max_columns', None):
    display(quality_scores.sort_values('Product'))

```

Equipmentnummer	DateTime	Product	Total weighting
10265426	2018-02-15	0.709523	1.0
10266563	2020-02-20	0.713784	1.0
10201095	2019-03-15	0.717876	1.0
10266563	2019-02-14	0.737422	1.0
10525128	2018-02-15	0.738801	1.0
10266563	2019-01-08	0.742227	1.0
10201095	2018-08-31	0.742795	1.0
10264861	2019-02-08	0.743907	1.0
	2020-02-21	0.746589	1.0
10201095	2018-08-06	0.748371	1.0
10265426	2018-02-08	0.761588	1.0

Aggregation per sub-indicator

In [408]:
```
quality_table = merge_AHP
quality_table['Parameter index'] = quality_table['Parameter weighting'] * quality_table['Quality Indicator']
quality_table['Uitwijking index'] = quality_table['Parameter index'] * quality_table['Uitwijk weighting']
quality_table['Wisselgedeelte index'] = quality_table['Uitwijking index'] * quality_table['Wisselgedeelte weighting']
quality_table['Total weighting'] = quality_table['Parameter weighting'] * quality_table['Uitwijk weighting'] * quality_table

quality_table = quality_table[['Equipmentnummer', 'DateTime', 'Wisselgedeelte', 'Uitwijking', 'Parameter groep', 'Quality In
          'Parameter weighting', 'Uitwijk weighting', 'Wisselgedeelte weighting', 'Parameter index', 'Uitwijking index', 'Wi
    .groupby(['Equipmentnummer', 'DateTime', 'Wisselgedeelte', 'Uitwijking', 'Parameter groep']).mean()

quality_table = quality_table.reset_index()
```

I.5. Interface

In [1]:

```
def selectEq(eq):
    wdg.interact(selectDate, eq=fixed(eq), \
                 date=quality_table.loc[quality_table['Equipmentnummer']==eq]['DateTime'].unique())

def selectDate(eq, date):
    print('Overall quality indicator: ' + str(getRailQuality(eq, date)))
    display(getSegmentQuality(eq, date))
    wdg.interact(selectUitwijking, eq=fixed(eq), date=fixed(date), seg=quality_table['Wisselgedeelte'].unique())

def selectUitwijking(eq, date, seg):
    display(getUitwijkQuality(eq, date, seg))
    wdg.interact(selectParameter, eq=fixed(eq), date=fixed(date), seg=fixed(seg), uitw=quality_table['Uitwijking'].unique())

def selectParameter(eq, date, seg, uitw):
    display(getParameterQuality(eq, date, seg, uitw))
    wdg.interact(getPointQuality, eq=fixed(eq), date=fixed(date), seg=fixed(seg), uitw=fixed(uitw),\
                 par=quality_table.loc[(quality_table['Wisselgedeelte']==seg)&(quality_table['Uitwijking']==uitw)]\
                 ['Parameter groep'].unique())

def getRailQuality(eq, date):
    return quality_table.loc[(quality_table['Equipmentnummer']==eq)&(quality_table['DateTime']==date)]\
                ['Wisselgedeelte index'].sum()

def getSegmentQuality(eq, date):
    return quality_table.loc[(quality_table['Equipmentnummer']==eq)&(quality_table['DateTime']==date)]\
                    [['Uitwijking index','Wisselgedeelte', 'Wisselgedeelte weighting']]\
                    .groupby('Wisselgedeelte').agg({'Uitwijking index':'sum', 'Wisselgedeelte weighting':'mean'})

def getUitwijkQuality(eq, date, seg):
    return quality_table.loc[(quality_table['Equipmentnummer']==eq)&(quality_table['DateTime']==date)&\
                             (quality_table['Wisselgedeelte']==seg)][['Parameter index', 'Uitwijking', 'Uitwijk weighting']]
                            .groupby('Uitwijking').agg({'Parameter index':'sum', 'Uitwijk weighting':'mean'})

def getParameterQuality(eq, date, seg, uitw):
    return quality_table.loc[(quality_table['Equipmentnummer']==eq)&(quality_table['DateTime']==date)&\
                             (quality_table['Wisselgedeelte']==seg)&(quality_table['Uitwijking']==uitw)]\
                            [['Parameter groep', 'Quality Indicator', 'Parameter weighting']]

def getPointQuality(eq, date, seg, uitw, par):
    return merge_AHP.loc[(merge_AHP['Parameter groep'] ==par)&(merge_AHP['Equipmentnummer']==eq)&\
                         (merge_AHP['DateTime']==date)&(merge_AHP['Wisselgedeelte']==seg)&(merge_AHP['Uitwijking']==uitw)]\
                        [['Parameter_x', 'DPName', 'Quality Indicator']]

def quality_interface():
    wdg.interact(selectEq, eq=quality_table['Equipmentnummer'].unique())

quality_interface()
```

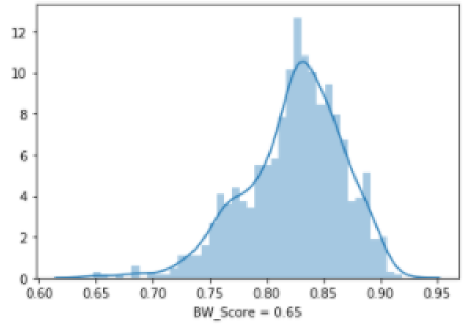
Appendix J: Sensitivity analysis

J.1. Example of the data

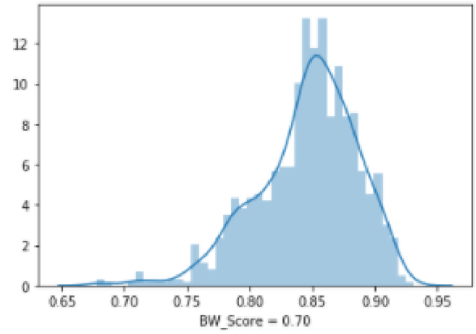
Equipmentnummer	DateTime	BW_score = 0.65	BW_score = 0.70	BW_score = 0.75	BW_score = 0.80	BW_score = 0.85	Rank, BW_score = 0.65	Rank, BW_score = 0.70	Rank, BW_score = 0.75	Rank, BW_score = 0.80	Rank, BW_score = 0.85
10265441	28/02/2019	0.918973171	0.931169977	0.943111572	0.954831688	0.966358492	940	940	940	940	940
10525140	08/01/2019	0.911509394	0.924444808	0.937183452	0.949773259	0.962267518	939	939	939	939	939
11332452	13/07/2018	0.90602	0.920084251	0.933889468	0.947468125	0.960847302	938	938	938	938	938
11066522	08/11/2017	0.90449716	0.918695814	0.932666205	0.946438585	0.960038258	937	937	937	937	937
11066522	26/01/2018	0.904090236	0.918204879	0.932138819	0.945922207	0.959580232	936	936	936	936	936
11585197	31/08/2018	0.902352797	0.916747349	0.930945719	0.944981647	0.958883184	935	935	935	935	935
10264955	01/03/2020	0.90232684	0.916557404	0.930657724	0.944654466	0.958569794	934	934	934	933	933
10265468	28/02/2019	0.901423994	0.916104394	0.930537353	0.944756381	0.958789709	933	933	933	934	934
10525140	28/02/2019	0.901141988	0.915697339	0.930004032	0.944117425	0.9580961	932	932	932	932	932
11332452	08/01/2019	0.900775618	0.915305602	0.929670686	0.94390265	0.958028894	931	931	931	931	931
10525140	01/03/2020	0.900431597	0.915036968	0.92947036	0.9437631	0.957941519	930	930	930	930	930
10265609	21/02/2020	0.89977922	0.914316682	0.928748725	0.943097979	0.957383191	929	929	929	929	929
11585234	31/08/2018	0.898842911	0.913699726	0.928379862	0.942912522	0.957321972	927	927	928	928	928
11587208	30/08/2019	0.899080065	0.913728069	0.928256409	0.942694863	0.957068507	928	928	927	926	926
10525149	08/03/2017	0.898227887	0.913263218	0.928090054	0.942738684	0.957234317	924	925	926	927	927
11585197	31/08/2019	0.89873812	0.913463337	0.928046404	0.942525538	0.956933506	926	926	925	925	925
10265441	08/02/2018	0.898597612	0.913214254	0.927723386	0.942167473	0.956584304	925	924	924	924	924
11066522	13/07/2018	0.8965265	0.911836462	0.926923366	0.941819827	0.956553496	922	922	923	923	923
10265608	21/02/2020	0.897369319	0.912190075	0.926918102	0.941581351	0.956203049	923	923	922	922	922
10265625	14/02/2019	0.895716639	0.910969541	0.926060287	0.941019448	0.955872684	919	921	921	921	920
10265609	08/02/2019	0.89584756	0.910967421	0.925976903	0.940897302	0.955746214	920	920	920	919	919
10265664	08/02/2018	0.894670938	0.910334896	0.925740753	0.940925163	0.955918921	918	918	919	920	921
11595525	20/02/2020	0.896241328	0.910837152	0.925360262	0.939891719	0.954518272	921	919	918	915	914
11587208	15/03/2019	0.894109592	0.909612003	0.924942737	0.940134375	0.955214269	915	916	917	918	918
11333233	08/01/2019	0.89451804	0.909745197	0.924868726	0.939923042	0.954938096	917	917	916	917	916
11066520	26/01/2018	0.893366629	0.909060711	0.924561973	0.9398981	0.955092077	913	914	915	916	917
10265608	08/02/2019	0.893477867	0.908904758	0.924221553	0.939456451	0.954633086	914	913	914	914	915
11046234	31/08/2019	0.894315292	0.909253135	0.924209092	0.939207747	0.954269764	916	915	913	913	912
10265444	08/03/2017	0.891531213	0.907540301	0.923339011	0.938954987	0.95441119	912	912	912	912	913
11585213	31/08/2019	0.890729015	0.9069625	0.922940149	0.938695763	0.954257514	908	911	911	911	911
10265655	24/08/2017	0.890897485	0.906837063	0.922622312	0.938278935	0.953828324	910	909	910	909	909
11046234	07/08/2017	0.890628327	0.906710301	0.922595886	0.938316081	0.953896602	906	908	909	910	910
11585190	31/08/2019	0.891304	0.906889808	0.922421068	0.937922479	0.953414743	911	910	908	907	905
11316392	07/07/2017	0.88939408	0.905850812	0.922040761	0.937997732	0.953749971	904	905	907	908	908

J.2. Distribution for different AL scores

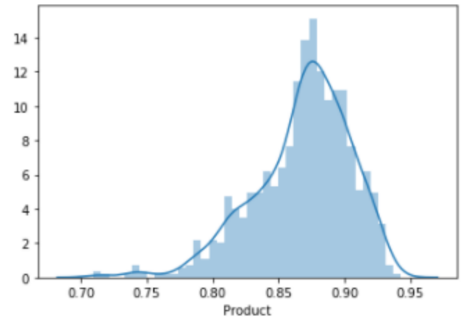
```
count    940.000000
mean       0.824279
std        0.042826
min        0.647170
25%        0.798963
50%        0.829173
75%        0.853817
max        0.918973
Name: BW_Score = 0.65, dtype: float64
```



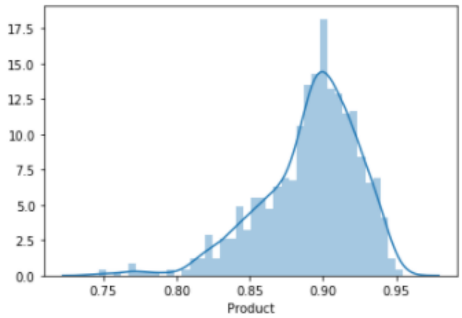

```
count    940.000000
mean       0.845981
std        0.040010
min        0.677340
25%        0.822685
50%        0.851206
75%        0.873395
max        0.931170
Name: BW_Score = 0.70, dtype: float64
```



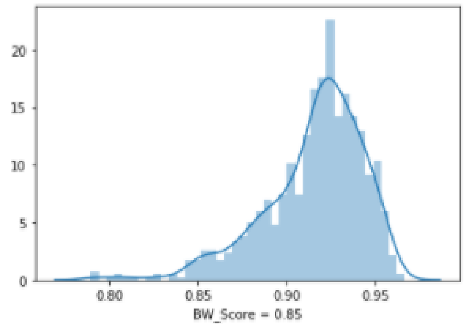

```
[940 rows x 2 columns]
count    940.000000
mean       0.868312
std        0.036687
min        0.709523
25%        0.847814
50%        0.873831
75%        0.893881
max        0.943112
Name: Product, dtype: float64
```




```
[940 rows x 2 columns]
count    940.000000
mean       0.891405
std        0.032781
min        0.746466
25%        0.873768
50%        0.896963
75%        0.914288
max        0.954832
Name: Product, dtype: float64
```




```
count    940.000000
mean       0.915439
std        0.028190
min        0.789614
25%        0.901444
50%        0.920518
75%        0.934968
max        0.966358
Name: BW_Score = 0.85, dtype: float64
```



Appendix K: IAL and IL as maximum scores

The normalisation is implemented for two different cases using the data of the distance between flange and rail track ('Inloopmaat').

Firstly, the quality scores are calculated using the IL as minimum score and the AL set equal to 0.75. This results in a distribution of quality scores with a mean of 0.931 and a standard deviation of 0.109. Secondly, the quality scores are calculated using the IAL as minimum and the IL set equal to 0.75. In this case the mean is 0.967 and the standard deviation is 0.052. Both distributions are plotted in a histogram where blue represents the quality scores with IL as maximum and orange represents the quality scores with IAL as maximum.

In both cases most quality scores are close to the perfect score and therefore the distributions are skewed heavily to the right. This could be explained by the fact that the distance between the flange and the rail track are generally in good condition. However, there is considerable difference between the spread of both distributions. The standard deviation of the first distribution is almost two times as big. In addition, the minimum value of the first distribution is 0, while the minimum of the second distribution is 0.167.

So, the spread is larger for the IL as maximum score than for the IAL as maximum score. Therefore, the IL is chosen as minimum score, because the quality scores are less concentrated around the perfect score resulting in more distinguishable quality scores.

```
count    8282.000000
mean        0.880377
std         0.192880
min         0.000000
25%         0.806081
50%         1.000000
75%         1.000000
max         1.000000
Name: Quality Indicator max IL, dtype: float64

count    8282.000000
mean        0.941788
std         0.096306
min         0.166844
25%         0.907244
50%         1.000000
75%         1.000000
max         1.000000
Name: Quality Indicator max IAL, dtype: float64
```