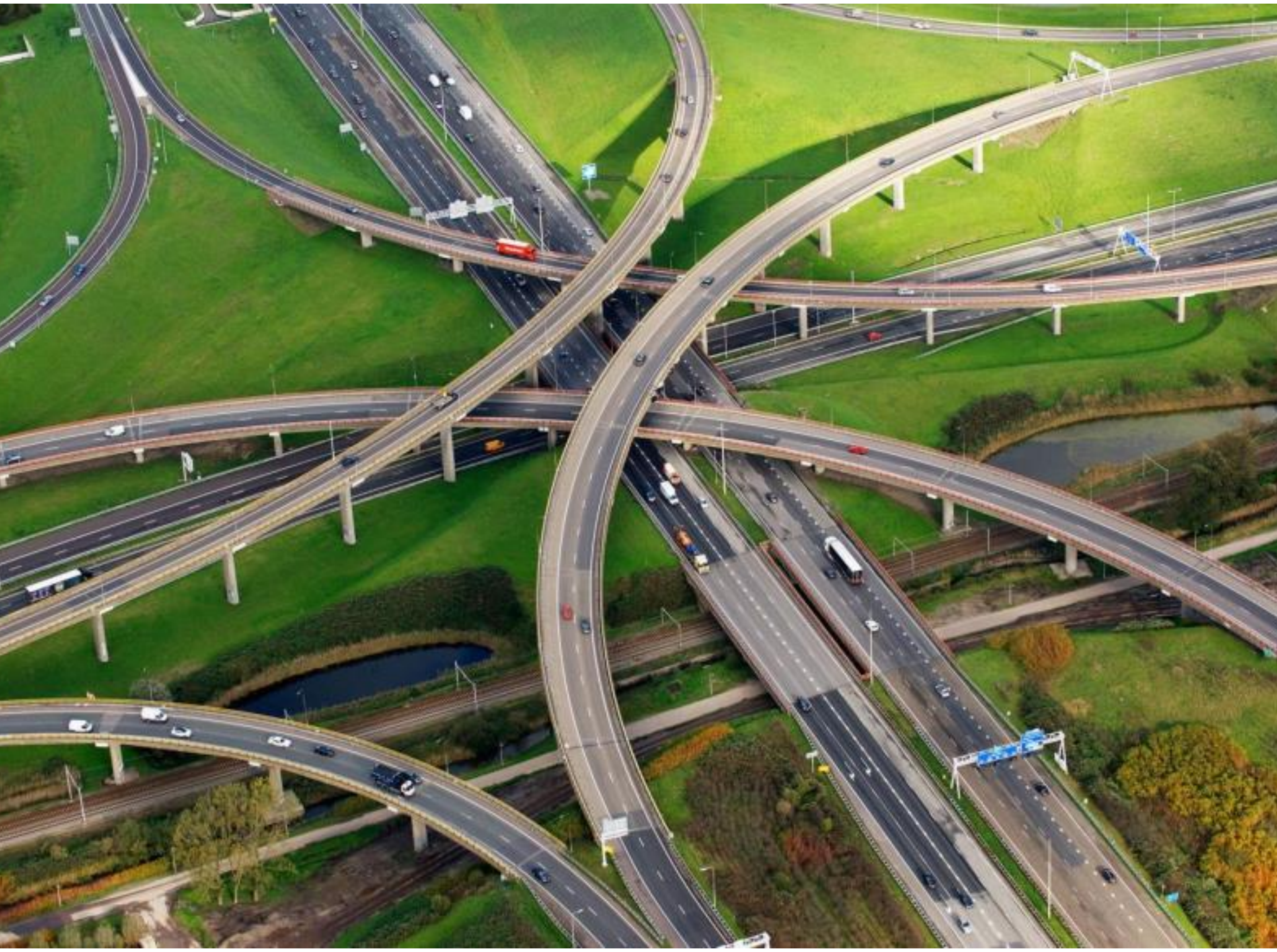
Developing a Sustainability Assessment Tool for Assessing Dutch Highway Designs



MSc Thesis Report

Dieko van Belzen

11-5-2022

TU Delft

anteagroup

[This page is intentionally left blank]

Developing a Sustainability Assessment Tool for Assessing Dutch Highway Designs

By

Dieko van Belzen

in partial fulfilment of the requirements for the degree of
Master of Science
in Construction, Management and Engineering (CME)

at the
Delft University of Technology (TU Delft)

Cover Image

Place:	A4 Haaglanden-N14, The Netherlands
Source:	*https://anteagroup.nl/nieuws-media/nieuws/ontwerp-tracebesluit-a4-haaglanden-n14-gepubliceerd*

Author

Name:	Dieko van Belzen
E-mail:	D.vanBelzen@student.tudelft.nl
Student number:	4500334

Study Program

Name:	Delft University of Technology
Faculty:	Faculty of Civil Engineering and Geosciences
Study:	Master Construction, Management and Engineering (CME)

Graduation Company

Name:	Antea Group
Address:	Rivium Westlaan 72 Capelle a/d IJssel 2909 LD
Telephone number:	+31 (0)10 235 17 45

Thesis Committee

Chair:	Prof.dr. P.W. Chan	Architecture Faculty TU Delft
1st supervisor:	Dr.ir. M. Molaei	Architecture Faculty TU Delft
2nd supervisor:	Dr. D.F.J. Schraven	CEG Faculty TU Delft
1st company supervisor:	Ir. A. van Damme	Antea Group
2nd company supervisor:	Ir. T. van der Meijs	Antea Group

TU Delft Delft University of Technology

anteagroup

Preface

Before you lies a report about the development of a sustainability assessment tool for assessing Dutch highway designs, which is the graduation project of my MSc Construction, Management and Engineering (CME) of the Faculty of Civil Engineering and Geosciences at Delft University of Technology.

In the past decades, sustainability has become increasingly important for the construction industry, in particular highway infrastructure, as it can generate both positive and negative impacts on the social and physical environment. As a result of the impact on the environment and the growing awareness of environmental protection, the effects on society and economic development, there is a pressing need and sense of urgency for the sector to become more sustainable. The need for delivering sustainable highway infrastructure has motivated me to explore the concept of sustainability and ways in which highway infrastructure can make a positive change to the preservation of the environment, well-being of humans, economic prosperity for future generations and the transition of the sector towards sustainable development.

Over the past eleven months, I had the fantastic opportunity to research the integration and assessment of sustainability in the context of Dutch highway infrastructure. After joining Antea Group I embarked on a journey to explore the concept of sustainability within the highway infrastructure. A large part of this research was conducted during the COVID-19 pandemic, in which socializing was severely limited and the graduation process felt lonely at times. Therefore, I want to acknowledge the moral support of my committee members and my family who kept me motivated during the challenging times of the pandemic. In addition, I want to thank all the committee members for their wonderful collaboration.

Paul, the knowledge, information and examples you shared with me on academic papers and research helped me structure and organize my research. You helped me understand why and how research is conducted by asking me in-depth questions about my own research, which greatly aided me in formulating my research problem and objective. I am thankful for that. Maedeh, you have been a great help to me throughout the graduation process. I could always reach out to you if I needed to talk, discuss or reflect on my thoughts, ideas or progress, which helped me stay on track. Thank you for your suggestions, guidance and assistance throughout this process, it helped me in achieving my research objective. Daan, your feedback and comments made me reflect on my work from an academic point of view. In addition, you gave me great tips and advice during the meetings on which methods to use in my research. All of this was extremely helpful, thank you.

Angelique, you introduced me to the research topic, assisted me in contacting experts, helped me build a network within Antea Group and gave valuable tips and ideas for conducting the research. I am deeply grateful for your personal help during the graduation process. This gave me the confidence I needed to succeed. Tom, throughout the process and especially when Angelique was on sabbatical, you assisted me in the best ways possible. Thank you for your guidance, feedback and tips.

Finally, I want to acknowledge my friends and family for their support, Antea Group for providing me the opportunity to conduct this research and the experts within Antea Group for their time, energy, valuable input, opinions and feedback during the interviews and questionnaire survey.

This thesis gave me the opportunity to challenge myself, gain life-long knowledge and experiences, build a network within Antea Group, create awareness for sustainability, enrich the literature on sustainability and make it explicit for practice. I am herby proud to present my final results of the graduation thesis.

Dieko van Belzen
Delft, May 2022

[This page is intentionally left blank]

Executive Summary

There has been growing interest in the concept of sustainable development and its influence on highway design. Highways are one of the most important infrastructures for bringing change to society, due to their large investments and impact on the environment and existing communities. Highways can have positive effects of increased accessibility, liveability, or enhancing regional growth and economic competitiveness. Along with these benefits, highways can also have negative impacts, such as unfavourable landscape changes, increased noise levels, air pollution, or damage to ecological functions. Given that highway development can generate both positive and negative effects in surrounding areas means that designers and decision-makers must consider a variety of complex issues when investing in highway development. As a result of the high negative impact on the environment and the growing awareness of environmental protection, the effects on society and economic development, there is a pressing need and sense of urgency for the sector to become more sustainable. For a highway to be truly sustainable it needs to take the social, environmental and economic dimensions of sustainability (People, Planet, Prosperity) into account. Over the past decades, some sustainability assessment approaches have been developed in an attempt to integrate sustainability in the assessment of infrastructure projects. Despite these attempts, these sustainability assessment approaches do not address all the dimensions of sustainability thoroughly and are biased to either an environmental or an economic assessment, the social dimension is taken less into consideration. However, how designers and decision-makers can integrate these dimensions into the assessments of highway design options is less known. This lack of integration of the three dimensions of sustainability makes it impossible to evaluate and assess the sustainability consequences of highway design choices and options and thus represents a significant limitation. For this research, the following problem statement is proposed for investigation:

There is a need to support designers and decision-makers in making well-informed highway design choices and giving advice on design options to achieve progress toward sustainable development.

This research is carried out for the engineering consultancy firm Antea Group. To address the observed problem, the main objective of this research is to not only provide designers and decision-makers with a sustainability assessment tool that integrates the social, environmental and economic dimensions of sustainability (People, Planet, Prosperity), but also with an understanding of how this can be used during the planning- and design phase to decrease highways negative impact, to add value and make their highway designs more sustainable and to move towards sustainable development.

Based on the problem statement and objective of this research, the main research question is formulated as:

"How can the three dimensions of sustainability be integrated into one comprehensive sustainability assessment tool for making integral design choices and assessing design options during the planning- and design phase in the Dutch highway context?"

To answer the main research question, four sub research questions are formulated. The answers to these questions provide the information needed to answer the main research question and to achieve the objective of this research.

The first sub research question elaborates on a literature review on sustainability and sustainability assessment approaches. The TBL (3Ps) theory coined by John Elkington, a well-known concept in sustainable development was selected as a sound theory regarding the three interdependent dimensions of sustainability. Subsequently, the literature review and analysis of the existing sustainability assessment (SA) approaches took place. The findings showed that despite the numerous

SA approaches available, none of them address sustainability as a whole. While there are positive characteristics associated with each approach, some practical issues remain unsolved. The literature review showed that there is no simple solution for the assessment of projects, specifically when tackling the sustainability of highway projects. In other words, all SA approaches have their strengths and weaknesses, but none of the tools and methods analysed are suitable for a comprehensive assessment of the sustainability of highway design options that are currently available. However, the multi-criteria analysis (MCA) approach seemed to be the most suitable for developing a new SA tool that integrates criteria from the three dimensions of sustainability. Since, the MCA approach is (1) a flexible method to assess sustainability; (2) allows decision-makers to account for a wide range of criteria; (3) can assign weighting coefficients to the criteria, evaluate design options and finally provide a ranking of the design options; (4) can comprehensively consider sustainability on the three dimensions of sustainability (TBL); (5) can incorporate results from a wide array of techniques, tools and methods; and (6) is straightforward for designers and decision-makers to use. In line with the results of the analysis of existing SA approaches, it was concluded that combining results from existing SA approaches and SA criteria in one comprehensive MCA SA framework could be beneficial for effectively integrating and balancing all dimensions of sustainability (TBL) in the assessment of design choices and options.

The second sub research question elaborates on a literature review on SA criteria in the context of the construction and infrastructure sector. The review of existing assessment frameworks and rating systems shows that a large number of studies propose frameworks with SA criteria but fail to integrate them into a unified and more comprehensive framework. In addition, only a few studies have looked at highways, but not at identifying relevant SA criteria specific for the planning- and design phase (ex-ante evaluation) and specific for the Dutch highway context, which is exactly the gap this research aims to fill. A total of 64 SA criteria (22 environmental, 30 social and 12 economic respectively) from the construction and infrastructure sector were identified through surveying recent literature, which formed the preliminary list of criteria.

The third sub research question elaborates on conducting a filtering process on the SA criteria and subsequently a questionnaire survey to establish which are relevant to the Dutch highway context. The following steps were applied during the filtering process: (1) criteria with similar context (overlapping) were merged, while sector-specific criteria were excluded and (2) criteria presented in rating systems were included in de proposed SA framework. The filtering process resulted in a reduction to 34 SA criteria. After this process, a questionnaire survey was sent to experts within Antea Group to check the relevance of the SA criteria during the planning- and design phase of the Dutch highway context. The proposed SA framework with 34 SA criteria was validated by 12 experts from Antea Group and while two criteria were excluded from the list, an additional four criteria (namely: energy consumption (construction & demolition), energy consumption (fuel), environmental cost indicator, material production) were added based on expert opinions and experience. The survey resulted in the development of the conceptual SA framework. This SA framework consists of 36 SA criteria, which are categorised in their corresponding social, environmental and economic (3Ps) dimensions of sustainability and related 9 themes (depicted below).

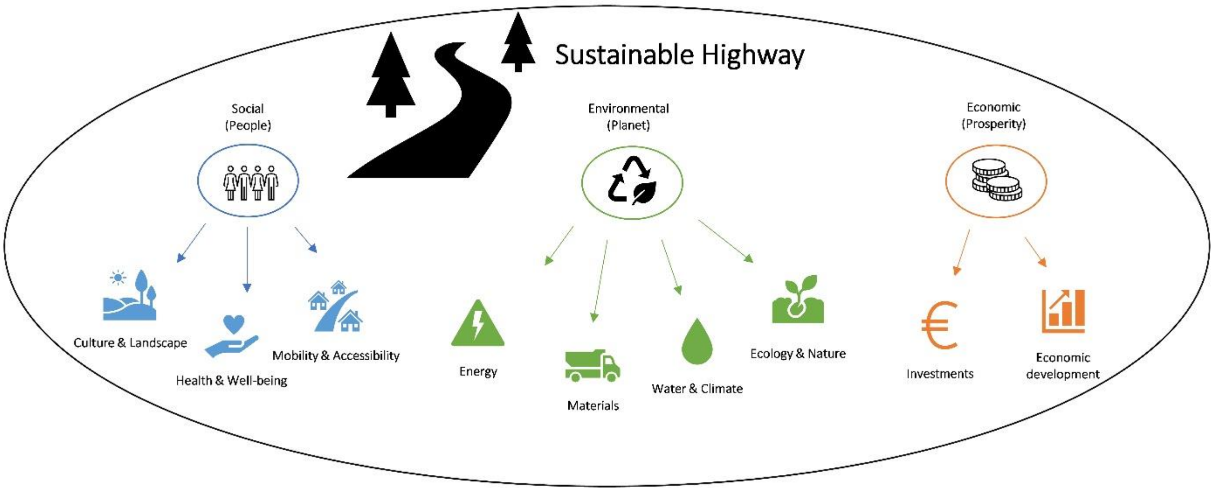


Figure - Sustainable Highway

The fourth sub research question elaborates on providing the assessment procedure for the conceptual SA framework, to form the proposed SA tool. The SA tool is basically a design option analysis in which the design choices and options are assessed on their contribution to sustainability. For this analysis, a trade-off matrix (TOM) is utilized. The TOM consists of the themes and SA criteria presented in the conceptual SA framework. In this SA tool, the best-worst method (BWM) (MCA approach) is used to determine the weighting factors of the themes. For each project, the weighting must be determined in consultation between the project team (consisting of experts from Antea Group), RWS and stakeholders (e.g. local residents, landowners). The weights are not fixed in the SA tool. Each design option can be assessed on the SA criteria so that a score is provided. In the SA tool, design options are compared to each other to be able to give well-informed advice to RWS and make a carefully considered choice.

After developing the proposed SA tool, the SA tool is tested by applying it to a reference case (a highway project in the Netherlands). Based on the results from the reference case, the functioning, applicability, efficiency and possible implications of the proposed SA tool were evaluated by an expert involved in the project. From the evaluation of the SA tool with the expert, some recommendations followed that need further research.

Based on the knowledge and results acquired through answering the sub research questions, the main research question can now be answered. In the developed SA tool, the social, environmental and economic dimensions of sustainability (People, Planet, Prosperity) are integrated into one comprehensive framework specific for the Dutch highway context. The SA tool can assess, compare, evaluate and rank design options based on the relevant SA criteria. The SA criteria assess to what extent a design choice and option contributes to the creation of sustainable added value and the realization of sustainability objectives of Rijkswaterstaat (RWS) aimed at realizing a sustainable living environment and rank them accordingly. In this SA tool, design options can be explicitly weighed upon all dimensions of sustainability, related themes and corresponding SA criteria which can support the decision-making.

The conceptual SA framework can be used as an overview and frame of reference when making integral design choices. To help substantiate design choices and tackle sustainability from the very first phases to the implementation of a project. The SA framework offers a practical way to secure that sustainability is an integral part of the design choices, considerations and effect determination during the regular design process. This helps designers make a choice that leads to more sustainability. As a result, Antea Group can realize that RWS (can) make integral decisions regarding sustainability so that sustainable solutions can be included in the design options.

The added value of the conceptual SA framework is that it provides a systematic overview of all possible aspects of sustainability that can be taken into account during the planning- and design phase (MIRT-Exploration and MIRT-Plan Elaboration phase) of a highway project. In addition, it can help designers and decision-makers understand how the environmental, economic and social dimensions of sustainability (People, Planet, Prosperity) can be used to decrease the negative impacts of highway projects and embrace the principles of sustainability with respect to environmental protection, economic profitability and human well-being, to make their highway designs more sustainable and to contribute towards sustainable development (SD). With this, the objective of the research is achieved.

The main scientific contribution of this research is that the comprehensive SA framework based on the concept of sustainability (TBL) helps tackle the research gap in the literature with regard to sustainability integration into highway projects and the effectiveness of existing SA approaches. Ultimately, the conceptual SA framework and proposed SA tool integrate the principles of sustainability and enables new practical and theoretical solutions to help enhance the integration of sustainability within the highway infrastructure sector.

Keywords

Triple bottom line, highway design options, sustainability assessment criteria, sustainability assessment tool, sustainability assessment framework, best-worst method

Contents

List of Figures

List of Tables

List of Abbreviations

AHP	Analysis Hierarchy Process
CBA	Cost-benefit analysis
EIA	Environmental impact assessment
LCA	Life cycle analysis
LCC	Life cycle costs
MCA	Multi-criteria analysis
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision-making
MIRT	Multi-Year Programme for Infrastructure, Spatial Planning and Transport
PPP, 3Ps	People, Planet, Prosperity/Profit
IPM	Integrated Project Management
IenW	Ministry of Infrastructure and Water Management
SC	Sustainable construction
SD	Sustainable development
SDGs	Sustainable Development Goals
SLCA	Social life cycle assessment
SQ	Sub question
TBL	Triple bottom line
UN	United Nations
UNCED	UN Conference on Environment and Development
WSSD	World Summit on Sustainable Development

CHAPTER 1
INTRODUCTION

1 Introduction

This chapter gives an overview of the research conducted and is broken down into eight sections. The first section introduces the key topics and background of the research (see 1.1): (1.1.1) introducing sustainability, (1.1.3) sustainability in highway infrastructure and (1.1.4) sustainability assessment in infrastructure. The second section describes the scope of the research. Besides, the role and company profile of Antea Group is highlighted (see 1.2). The third section presents the problem statement, which is based on the gap and key topics of the research (see 1.3). The fourth section elaborates on the research objectives (see 1.4). Next, the research questions are presented which are formulated based on the gap, problem and objectives (see 1.5). The sixth section describes the research strategy and used methods (see 1.6). The seventh section presents the research structure (see 1.7). The eight section shows the outline of this report (see 1.8).

1.1 Key Topics of the Research

In this section, three key topics in the context of this research are introduced: (1.1.1) sustainability, (1.1.3) transition towards sustainable highway infrastructure and (1.1.4) sustainability assessment in infrastructure, in which the knowledge gap of this research is explained.

1.1.1 Introducing Sustainability

The primary concept of sustainability, called 'sustainable development' (SD) emerged in 1972 during the first United Nations (UN) Conference on the Human Environment held in Stockholm, which was specifically aimed at the issues of the environment (United Nations, 2022). Since the emergence and worldwide recognition of the concept of sustainability, many researchers, institutions and academics have been trying to capture the definition of the holistic approach SD. Presented below is the definition of 'sustainable development' (SD) used as a reference in the current research. The ISO 26000:2010 standard and Brundtland Commission's definition of SD are stated in the UN report *Our common future*:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN World Commission on Environment, 1987).

SD is later incorporated into the three sub-principles of People, Planet and Profit (i.e. Triple-P, PPP, 3Ps) to imply that SD is concerned with social conditions, economic vitality and protecting the environment (Taselaar, 2009). Meanwhile, the concept of SD in its broadest sense has taken many forms and is used in a variety of sectors, such as infrastructure and buildings. SD has broad support, but the concrete implementation is often still a point of much discussion.

Several authors define sustainability as finding the right balance between current and future needs for enviromental, social and economic dimensions, with a long-term concern, also referred to as the triple bottom line (TBL) concept of sustainability (Elkington, 1997; Gudmundsson et al., 2016; X. Liu et al., 2019; Mouter et al., 2021; Sala et al., 2015). The three dimensions/pillars: environmental, social and economic define sustainability.

A historical review by Goh et al. (2020) shows that in the 1980s, the concept of SD started to come into prominence and as a result increased in popularity and practical use. In 1994, Charles Kibert proposed the term 'sustainable construction' (SC) defining this as *"the creation and responsible management of a healthy built environment based on resource efficient and ecological principles"* (Kibert, 1994), to support broader SD. Later in 2020, Goh et al. (2020) argued that SC must ensure a balanced and optimal delivery of environmental, social and economic sustainability, without one pillar dominating the others. In the aforementioned studies, the concept of SC is considered a multidimensional issue.

1.1.2 Transition Towards Sustainability

Various sustainability transition movements can be found all over the world (Liu et al., 2019). Several of these movements are driven by global agreements and agendas, such as the Sustainable Development Goals (SDGs) presented in *The 2030 Agenda for Sustainable Development* and the *Paris Accord* (Jackson et al., 2018). These movements arose to encourage and assist countries, national governments, public agencies, organizations, businesses and individuals in realizing their sustainable ambitions, long-term goals and strategic objectives by taking a holistic approach. For instance, *The 2030 Agenda for Sustainable Development* which *"represents a shared commitment by UN member states to address development challenges in the national context, provides another means of conceptualising sustainability objectives related to infrastructure"* (Adshead et al., 2019).

In turn, organizations embed their ambitions, goals and objectives towards sustainability in their mission statement and working principles. The Dutch national government in that respect strives for long-term prosperity and environmental protection for future generations while working in a sustainable way (Green Deals, 2021). At the same time, Rijkswaterstaat (RWS), a major public client in the construction industry in the Netherlands, strives to work on a clean, green, pleasant and sustainable living environment, also for future generations. To realize a sustainable living environment, RWS has several sustainability objectives for the following eight components (Rijkswaterstaat, 2020):

- *Climate and energy:* By 2030, RWS wants to be energy-neutral. That requires generating as much energy as is consumed. In addition, they also aim to be completely climate-neutral by 2030, this implies no net CO2 emissions and other greenhouse gases (GHG), not even by their contractors and chain partners. This objective applies to the entire Ministry of Infrastructure and Water Management (IenW). Finally, in 2050, the Netherlands will be as water-robust and climate-proof as possible (Rijkswaterstaat, 2020);

- *Circular economy:* RWS wants to use 50% less raw materials by 2030 and work circularly. Circular working implies reusing high-quality raw materials and producing as little waste as possible. Minimizing the impact of materials is at the core of circular working. As a result, materials and components produced sustainably contribute to a circular economy (CE) (Rijkswaterstaat, 2021g). As the concept 'sustainability', 'circular economy' has quite different interpretations, to which a great diversity of content is attributed. CE has been recognized in the literature as pursuing similar, if not the same, goals as sustainability (Liu et al., 2019). In this research, CE means an economy without waste, in which healthy materials and raw materials are reused in a high-quality manner, without harmful CO2 emissions and in which natural resources are not exhausted (Rijkswaterstaat, 2019a). CE is still developing and evolving. In 2016, at the national government level, the cabinet outlined, how the Dutch economy can be transformed into a sustainable, fully CE by 2050 (Rijkswaterstaat, 2021g);

- *Sustainable area development:* Sustainable area development means that before the (re)design of an area, RWS first talks with partners such as municipalities, companies and residents, to optimally coordinate developments. In addition, RWS combines user functions and provides space for sustainable initiatives and solutions. When RWS works on a project, they already work closely with the environment. However, they are still working on how to approach the project from an area development perspective as well. Another achievement in 2017 is that sustainability has been made concrete for all construction projects. RWS has drawn up the *Handreiking Verduurzaming MIRT-projecten* for this purpose. The guideline contains concrete tips on how sustainability can be given a place in each phase of a project (Rijkswaterstaat, 2021c);

- *Sustainable mobility:* Sustainable mobility is about solving mobility issues in an environmentally friendly and future-proof way. For example, how traffic jams and congestions are reduced and cities can be kept accessible. The aim is to reduce CO2 emissions while improving accessibility at the same time. This is linked to a better, healthier living environment. More electric transportation, for example, means cleaner air (Rijkswaterstaat, 2021f);

- *Sustainable water management:* When working on water systems, RWS pays attention to the chemical and ecological quality of water. Good water quality is not only important for our drinking water, but also for the quality of life in our waters. The water quality of this water has a major impact on plants, animals, nature and biodiversity. RWS achieves this goal together with all parties involved in water- and nature management (Rijkswaterstaat, 2021b);

- *Sustainable procurement civil engineering:* RWS can contribute to a large extent to environmental improvements in the civil engineering sector. In addition to the price of products, services, or works, sustainable procurement requires that you also pay attention to the effects of procurement on the environment and social aspects. Sustainable procurement is also known as responsible and sustainable procurement (RSP). By making sustainability a standard part of the procurement process for civil engineering works and by collaborating with market parties, important contributions can be made to CO2 reduction. The signing of the *Green Deal Duurzaam GWW* has been an important achievement in this regard. Since 2020, sustainability has been given a place in all contracts with market parties (Rijkswaterstaat, 2021a);

- *Natural capital and biodiversity:* Together with area partners, RWS strives to preserve natural capital and biodiversity, strengthen and where possible use natural capital sustainably. RWS tries to combine functions and include natural capital early in the design of projects. RWS is increasingly seeking out other parties to make the value of natural capital visible and measurable together. Besides, RWS aims to use its land to protect biodiversity (Rijkswaterstaat, 2021e). Natural capital is the stock of natural resources (soil, water, air) that can provide people with useful goods and services. For instance, raw materials such as wood and bioplastics that can be used as construction materials. This also includes services such as food, water storage, cooling, CO2-sequestration and the generation of sustainable energy. Biodiversity, in the form of flora and fauna, makes an important contribution to natural capital. Awareness is growing that natural capital and biodiversity are vital. It is important to include natural capital as early possible in projects and decision-making (Rijkswaterstaat, 2021e);

- *Healthy living environment:* Organize the living environment in such a way that it contributes to people's health by, for example, encourages exercising. This is another important goal that RWS is working towards. In addition to the classic health aspects, such as clean air and noise reduction, RWS is now also looking for ways to contribute preventively to the health of residents and users of an area (Rijkswaterstaat, 2021d).

To summarize, sustainability is interwoven and anchored in the goals, objectives, or ambitions of projects in various ways. Often an approach from RWS is requested that focuses on sustainable objectives like: energy-neutral, climate-proof, circular and sustainable area development. For this research, given the above explanations, 'sustainable infrastructure' is about creating the best infrastructure for the client and environment on an economic, ecological and socio-cultural level within technical and process possibilities. This can be achieved with an active contribution towards sustainability goals, by utilizing opportunities in projects and area development.

1.1.3 Transition Towards Sustainable Highway Infrastructure

There is a need for delivering sustainable infrastructure as sustainability becomes more important for the construction industry (van Eldik et al., 2020). In the construction industry, highways are one of the most important infrastructures for bringing change to society, due to their large investments and impact on the environment and existing communities (Abdel-Raheem & Ramsbottom, 2016). In addition, highway projects are complex, because of specific elements such as investments and materials and highways involve and affect many stakeholders (Rogers & Enright, 2016).

The main purpose of a highway is to fulfill the transportation needs of society. To clarify, highways are infrastructures that allow people to travel long distances and transport goods from one location to another (Zakaria et al., 2013). They can have positive effects of increased accessibility or liveability (Hamersma et al., 2017) or enhancing regional growth and economic competitiveness (Suprayoga et al., 2020). Along with these benefits, highway development may have negative impacts, such as unfavorable landscape changes, increased noise and air pollution, barrier effects from blocked views, or damage to ecological functions such as flora and fauna (Hamersma et al., 2017). Given that highway development can generate both positive and negative effects in surrounding areas, means that designers and decision-makers must consider a variety of complex issues when investing in highway development (Hamersma et al., 2017). As a result of the high negative impact on the environment and the growing awareness of environmental protection, the effects on society and economic development, there is a pressing need and sense of urgency for the sector to become more sustainable in their projects (van Eldik et al., 2020).

Highway projects often involve considerable land use, need long-term investments, cause negative impacts on the environment and use a huge amount of resources, materials and energy (Amiril et al., 2014). This causes habitat fragmentation, change to society and intergenerational consequences (Suprayoga et al., 2020). Especially in these large spatial projects, a relatively large amount of sustainable benefit can be achieved.

Given the above argument, the involvement of highway development towards SD efforts is critical (Amiril et al., 2014). Better integration of the SD dimensions is needed, if highway projects want to make a positive change to the preservation of the environment, well-being of humans, economic prosperity for future generations and the transition of the sector towards SD.

1.1.4 Sustainability Assessment in Infrastructure (Knowledge Gap)

Since the Brundtland Commission coined the sustainable development (SD) concept in 1987, there has been a growing interest from national governments, organizations and researchers in developing a tool called 'sustainability assessment' (SA) (Suprayoga et al., 2020), to help decision-making in infrastructure projects towards sustainability. According to Verheem (2002), the primary goal of SA is to ensure that plans and activities positively contribute to SD. The SA methodology ensures that decisions are made comprehensively, taking into account all dimensions/pillars of SD (environmental, social and economic), as well as indirect effects (Hacking & Guthrie, 2008; Sala et al., 2015). SA is applied in transportation projects to evaluate whether a project *"contributes to favor economic development and fulfill the* *transportation needs of the society in a manner consistent with ecological and human values"* (P. C. Bueno et al., 2015). According to Gibson et al. (2005), decision-makers not only need *"criteria based on the core requirements of sustainability and the particularities of the context"*, but also appropriately designed processes, guidance on the weighing of design options and suitable tools.

Bueno et al. (2015) found that over the past decades some approaches have been developed in an attempt to integrate sustainability in the assessment of infrastructure projects, such as sustainability rating systems, appraisal methods and tools for decision-making, impact assessment techniques, different evaluation frameworks and models. Overall, these SA approaches are extremely useful for providing structured information about the impacts of different infrastructure designs and choices. However, the effectiveness of these tools and methods and the integration of the dimensions of sustainability can still be improved. Bueno et al. (2015) concluded that these SA approaches do not address all the dimensions of sustainability (economic, social and environmental) thoroughly and focus on either an environmental or an economic assessment and are biased toward either one. SA approaches usually focus more on the environmental and economic dimension rather than the social one, which implies that the dimensions are not evenly considered during the assessment. In the same vein, Abdel-Raheem & Ramsbottom (2016) noticed that in construction projects, the environmental dimension has been given more priority and is usually considered before the economic and social dimensions, recognizing the significance of the environmental dimension (Torres-Machi et al., 2014). Additionally, Sierra et al. (2018) found that the evaluation of the social dimension in infrastructure projects is taken less into consideration and that the assessment of these social aspects is still an emerging topic. This lack of integration of dimensions makes it impossible to evaluate and assess the sustainability implications of design choices and options. Thus this represents a significant limitation (Berardi, 2012).

However, for a highway project to be truly sustainable, all three dimensions of sustainability are required (Ahmadi et al., 2017; Bueno et al., 2015; Mahmoudi et al., 2019). Until now, several researchers have proposed SA frameworks and developed SA tools that include all three dimensions, although with a greater focus on environmental sustainability. In addition, there is literature available regarding sustainability in the construction industry and infrastructure sector, but a very limited number of studies focused on the sustainability of highway projects (Abdel-Raheem & Ramsbottom, 2016), in particular in the Dutch highway context (Molaei et al., 2021; Tamak, 2017).

Next to improving the effectiveness of the SA approaches and integrating the dimensions of sustainability in highway projects, a widely accepted list of SA criteria against which design choices and options can be assessed, evaluated and compared in the Netherlands is lacking, since none are comprehensive and inclusive and are usually context-specific (Bueno et al., 2013). Integration of separate frameworks with SA criteria into a comprehensive SA framework helping designers and decision-makers incorporate sustainability into their highway designs is currently unavailable. The existing SA criteria are still fragmented and have not been integrated into a comprehensive SA framework.

From the above-mentioned studies, it can be concluded that in the assessment of highway design choices and options the three dimensions of sustainability are not treated equally and have not been integrated into one comprehensive SA framework. However, to reach true sustainability in a highway project, all the three dimensions must benefit simultaneously (Liu et al., 2019). Although the existing SA approaches provide useful support in the decision-making, they are widely seen as an area for improvement.

1.2 Research Scope

Sustainability, triple bottom line and sustainability assessment in the construction industry are extensive topics in research. For this reason, the following choices for the boundaries are made to define the scope in which this research will be conducted. The following boundaries and focus are set:

- Within the construction industry and transport infrastructure sector, the focus will be on highway infrastructure projects. Since in the construction industry, highway projects can have significant impacts on sustainability (see 1.1.3) and a relatively large amount of sustainable gain can be achieved in these large spatial projects. In addition, Antea Group has a great deal of knowledge in this area and has been supporting public and private parties for many decades in the development and management of highway infrastructure (see chapter 4);
- The focus of this research will be on assessing and evaluating to what extent a design choice or option (alternative or variant) contributes to the creation of sustainable added value and the realization of sustainability objectives of RWS. To not develop a generic approach, the sustainability assessment is adjusted to particular circumstances and context, in this case, the planning- and design phase of highway development in the Netherlands;
- In the Netherland, roads are designed according to the *Kader wegontwerproces 2.0*, developed by RWS. This framework indicates which products must be made at what time to properly implement the road design process in a general sense and specifically in the *MIRT-process*. In the *MIRT-process*, Antea Group has the task of designing the highway and giving advice to public clients, for instance, RWS. Antea Group is involved in the MIRT-Exploration and MIRT-Plan Elaboration phase (i.e. planning- and design phase of the road design process). Furthermore, since Antea Group advices clients in the MIRT-Exploration and MIRT-Plan Elaboration phase, this research is conducted from the engineering point of view, in this case specifically from the perspective of Antea Group (see Figure 4.4, further explained in chapter 4).

1.2.1 Company Profile of Antea Group

This research is conducted with support from Antea Group, which will provide empirical information and knowledge to be used and consulted in this research. Antea Group is an international engineering and environmental consulting firm with over 60 years of experience in infrastructure, urban development, water and the environment. As an engineering consultancy firm, they use their high-quality knowledge by applying a pragmatic approach to create solutions that are feasible and implementable, with an eye for sustainability. Antea Group's consultants and engineers know what it takes to design, engineer and realize civil engineering structures. Whether it concerns roads, tunnels, bridges, viaducts, locks, or pumping stations: thanks to their versatile knowledge, they offer clients solutions that are cost-effective, feasible and maintainable. For this reason, governments and contractors have been calling on their expertise for more than 40 years (Antea Group, 2020). Antea Group offers broad support in products, projects and services for clients like Rijkswaterstaat, provinces, municipalities, contractors and privates parties. For this research it is important to know that Antea Group assists and advises clients in making well-informed choices and considerations within projects, based on information, experience and expert knowledge.

When looking at sustainability, Antea Group has sustainable ambitions, they work on sustainability using design principles, one of its design principles is: *"focusing on sustainable solutions at the front-end of projects"* (Antea Group, 2021a). To help make this ambition a reality, they are looking for ways to make sustainability explicit and be able to include it from the start of projects, so that integral solutions can be created. In addition, they want to develop new sustainable applications, products, services, innovations and processes to offer sustainable solutions to clients. With their knowledge and expertise, they want to support their clients in finding a balance between People, Planet, Prosperity/Profit (PPP) in their projects.

Antea Groups strives to provide well-informed advice about Dutch highway designs regarding their sustainability. They want to be able to substantiate why a certain design choice or option is more sustainable compared to others during the planning- and design phase. However, this is still limited within Antea Group. They would like to give their firm advice about what is needed to achieve sustainability goals. They see that governments easily set goals (for example, energy-neutral and circular in 2050), with insufficient focus on measures to achieve these goals. If Antea Group has more internal knowledge, they can give more specific advice, for instance *"these measures are necessary to indeed become sustainable"*. To summarize, they want to expand their knowledge so that they can give better advice about what is needed in the field of sustainability. For further information on Antea Group, please refer to chapter 4.

1.3 Problem Statement

In literature numerous studies are aimed at assessing the dimensions of sustainability, however, only a few address these two points: (1) identification of relevant SA criteria for highway development in the Netherlands and (2) propose a comprehensive list of SA criteria (environmental, economic and social dimension) that are integrated into one SA framework for assessing highway design choices and options in the early phases of the project. Over the past decades, some sustainability assessment approaches have been developed in an attempt to integrate sustainability in the assessment of infrastructure projects. Despite these attempts, these sustainability assessment approaches do not address all the dimensions of sustainability thoroughly and are biased to either an environmental or an economic assessment and the social dimension is taken less into consideration. However, how designers and decision-makers can integrate these dimensions into the assessments of highway design options is less known. This lack of integration of the three dimensions of sustainability makes it impossible to evaluate and assess the sustainability consequences of highway design choices and options. Therefore, represents a significant limitation. For this research, the following problem statement is proposed for investigation:

There is a need to support designers and decision-makers in making well-informed highway design choices and giving advice on design options to achieve progress toward sustainable development.

1.4 Research Objective

To address the observed problem, the main objective of this research is to not only provide designers and decision-makers with a sustainability assessment tool that integrates the social, environmental and economic dimensions of sustainability (People, Planet, Prosperity), but also with an understanding of how this can be used during the planning- and design phase to decrease highways negative impact, to make their highway designs more sustainable and to move towards sustainable development.

The aim of the research is achieved by (1) stating the importance of sustainability in highway projects, (2) reviewing existing SA frameworks and tools from literature and practice, (3) identify SA criteria relevant to assess, evaluate and compare design choices and options in the planning- and design phase within the Dutch highway context and (4) propose a SA tool that can be used by designers and decision-makers to compare different design options.

The purpose of the SA tool is to:

- Give sustainability an important place in making integral design choices and evaluating options;
- Provide an overview and frame of reference when making integral design choices, when ambitions are focussed on sustainability; and
- Tackle the issue of assessing, comparing and ranking design options regarding their contribution to sustainability;

1.5 Research Questions

In order to achieve the main research objective and fill the knowledge gap, the following main research question is formulated:

"How can the three dimensions of sustainability be integrated into one comprehensive sustainability assessment tool for making integral design choices and assessing design options during the planning- and design phase in the Dutch highway context?"

To be able to answer this main research question, four sub research questions are derived. These questions guide conducting the research. Related sub research questions leading to answering the main research question:

SQ1: What are the existing sustainability assessment approaches used in the construction industry and infrastructure sector that attempt to integrate the three dimensions of sustainability?

SQ2: What are the sustainability assessment criteria from the literature that cover all the three dimensions of sustainability to form a preliminary list?

SQ3: Which sustainability assessment criteria are relevant for the Dutch highway context to form the comprehensive sustainability assessment framework?

SQ4: How can the sustainability assessment tool be applied in practice?

1.6 Research Methodology

To answer the main research question and four sub research questions, it is key to use the right research strategy and methodology for data collection, analysis and interpretation. This section explains the steps followed and the methodologies used in this research. For further details and explanations on the research methodology, please refer to chapter 3.

Step 1: Literature review – Selection of a sound theoretical concept to be used in the research

The first step will be conducting the literature review. In this review, background information about sustainability emergence, sustainable development, triple bottom line, sustainable construction and sustainability assessment will be presented, which forms the basis of the research. Main principles and definitions of sustainability related to the research will be explained to form a sound theory to be used throughout the research.

Step 2: Literature review – Review existing sustainability assessment approaches

The second step is to review and analyze existing SA approaches to find out if they can provide a suitable framework for integrating sustainability dimensions into one comprehensive SA framework.

Step 3: Literature review – Form the preliminary list of sustainability assessment criteria

The third step is to identify potential SA criteria by reviewing previous literature (existing SA tools, methods and frameworks from several industries (e.g. construction industry and infrastructure sector), transport rating systems and RWS documents to form the preliminary list of SA criteria.

Step 4: Filtering process – Development of the sustainability assessment framework

The fourth step is to conduct a filtering process on the SA criteria to form the proposed SA framework.

Step 5: Questionnaire survey – Development of the sustainability assessment framework

The fifth step is to conduct a questionnaire survey to establish which SA criteria are relevant to the Dutch highway context to form the conceptual SA framework.

Step 6: Assessment procedure – Development of the sustainability assessment tool

The sixth step is to providing the assessment procedure for the conceptual SA framework, to form the proposed SA tool.

Step 7: Testing the proposed sustainability assessment tool – Development of the sustainability assessment tool

The seventh step of the research is applying the proposed SA tool to a reference case to test the applicability.

Step 8: Evaluate the proposed assessment framework by expert interview – Development of the sustainability assessment tool

In the eight step of the research the proposed SA tool will be evaluated by expert interview.

Step 9: Conclusion, discussion and recommendations

Last but not least, the findings, implications and results of the research will be presented. Answers to the research questions will be followed by a discussion, conclusion and recommendations for future research.

1.7 Research Structure

The research structure below, is a schematic and visualised representation of the steps that need to be taken in order to achieve the research objective, with the method, strategy and approach mentioned.

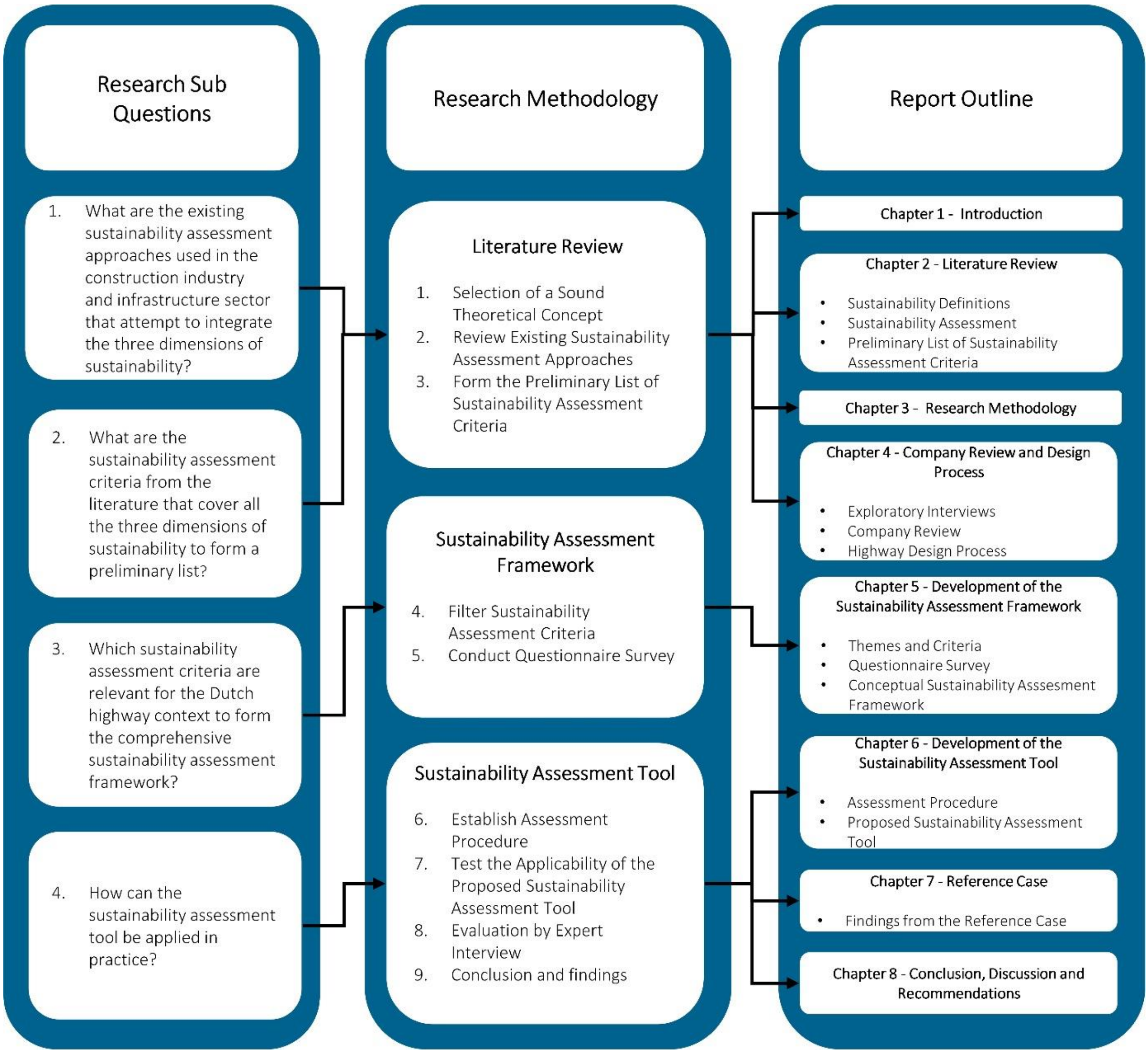


Figure 1.1 - Research structure (own Illustration)

1.8 Report Outline

The report is structured as follows:

Chapter 1: Introduction: introduces the topic and background of the research, presents the problem statement, the knowledge gap, relevance and research questions composed based on the research objective.

Chapter 2: Literature Review: presents a review of the current knowledge in literature about sustainability concepts, existing sustainability assessment (SA) methods, tools and frameworks and the preliminary list of SA criteria used to assess design options on the three dimensions of sustainability (TBL) found in literature.

Chapter 4: Company Review: explains the role of the engineering consultancy firm Antea Group and the highway design process that they follow.

Chapter 5: Development of the Sustainability Assessment Framework: shows how the conceptual SA framework is developed by performing a filtering process on the preliminary list of SA criteria and subsequently conducting a questionnaire survey to validate the conceptual SA framework.

Chapter 6: Development of the Sustainability Assessment Tool: shows how the proposed SA tool is developed by providing an assessment procedure for the conceptual SA framework, to form the proposed SA tool.

Chapter 7: Reference Case: the proposed SA tool will be tested by applying it to a reference case to evaluate the applicability, barriers and implications of the proposed SA tool when implementing it into current practice and real-world project of Antea Group. In addition, it will be evaluated by an expert who is involved in the case and in the field of infrastructure and sustainability.

Chapter 8: Conclusion, Discussion and Recommendations: answer will be given to the main question of the research and a set of conclusions, key findings, final reflections and recommendations for future research on this topic will be presented.

References: presents the references cited in the research.

Appendices: contains important additional or extensive information on the text and contents of the research and includes information on the interviews with experts, framework, tool and reference case.

The following chapter will focus on the literature review conducted in the context of this research.

CHAPTER 2
LITERATURE REVIEW

2 Literature Review

This chapter is broken down into three sections. The first section (see 2.1), which is divided into five subsections, introduces sustainability for the selection of a sound theoretical concept to be used in the research. The second section (see 2.2) shows the review of existing SA approaches used to assess sustainability in infrastructure and which can provide SA criteria for the assessment of highway projects. The review presents in which phase the SA approaches can be applied and if they can provide SA criteria or be integrated in the new SA tool. The third section (see 2.3) presents SA criteria found in the literature of the construction industry and infrastructure sector that form the preliminary list of SA criteria.

2.1 Main Definitions and Principles of Sustainability

Before reviewing the existing SA approaches and identifies SA criteria for the assessment of design choices and options, it is helpful for the reader to understand what is meant with the term sustainability and what the concept entails. This section gives a clear definition of the concept of sustainability to be used in the research.

2.1.1 Sustainable Development

This research uses the definition of 'sustainable development' (SD) as the primary concept of sustainability presented in subsection 1.1.1. In a nutshell, SD is about attempts to create short-term improvements while avoiding long-term negative consequences (Mansell et al., 2019). This subsection provides a brief overview of the concept's introduction. According to a historical review by Goh et al. (2020), the concept of sustainable development (SD) grew in popularity and use in the 1980s, after it was published in the Brundtland report in 1972. Later, in 1992 and 2002 the UN held two other important conferences. Namely, the first UN Conference on Environment and Development (UNCED) held in Rio de Janeiro at the 1992 Earth Summit (Fernández-Sánchez & Rodríguez-López, 2010), which resulted in *The Rio Declaration* and *Agenda 21* and the World Summit on Sustainable Development (WSSD) convened in Johannesburg in 2002, which resulted in the additional Millennium goals. In this period the concept began to go beyond the environmental aspect and started to include economic and social aspects (C. Bueno et al., 2013). In between these conferences the term 'sustainable construction' (SC) was introduced by Charles Kibert in 1994, further explained in (2.1.3). All of these conferences and events have let towards the formulation of the concept SD. The basic requirements for SD can be seen as environmental preservation, social development and economic development. To adhere to this, a sustainable project needs to be socially involved, socially responsible, economically attractive, environmentally friendly and future-proof.

Nowadays, the concept of sustainability has contributed to strengthening the need of bringing balance between the human needs and preservation of natural resources. Present day there are many definitions of sustainability found in literature, two of them are globally accepted. One of them is about finding the right balance between environmental, social and economic aspects, also referred to as the triple bottom line (TBL) concept of sustainability by John Elkington, which encourages to treat environmental and social issues in the same way as economic aspects in project and business practices (Kivilä et al., 2017). The other one is about the intergenerational balance between current and future needs, which takes special attention for reducing the use of natural resources (Mouter et al., 2021). The TBL concept was introduced by Elkington to indicate that an organisation's results should be measured along the interrelated dimensions of sustainability (environmental, economic and social) (Elkington, 1997), further explained in subsection 2.1.2. Several academics argue that SD can only be achieved when the three dimensions of sustainability are brought into balance with each other (Liu et al., 2019; Sabini et al., 2019; Silvius & Schipper, 2014) or when there is a trade-off between these three dimensions (Mansell et al., 2019).

2.1.2 Triple Bottom Line & People, Planet, Prosperity

Initially, the triple bottom line (TBL) framework was used as an accounting framework that tried to include environmental and social dimensions into the traditional finance-centric measurement of business performance (Elkington, 1994). Later, the concept of TBL (i.e. 3BL) evolved to support the delivery of SD and measure sustainability performance (Goh et al., 2020). TBL is now the extension of the traditional economic profitability framework considering social and environmental aspects (Marcelino-Sádaba et al., 2015) and translates sustainability into three measurable dimensions; economic, social and environmental sustainability (Elkington, 1997).

Within literature there is a common agreement that sustainability can be divided into three individual, but equally important and interrelated dimensions of sustainability: economic (profit), social (people) and environmental (planet) (Elkington, 1997). The TBL dimensions are also frequently called the Triple-P, PPP or 3Ps (People, Planet and Profit). 3Ps is a widely used term in SD. Within the TBL, the dimensions People and Planet have been the same over the last decades, but the Profit dimension has been adjusted to Prosperity, at the Johannesburg World Summit on Sustainable Development (2002). The UN stated that the social profits weigh just as much as the financial profits, so Prosperity is broadening the concept of Profit to extend this dimension beyond economic development. People, Planet and Prosperity can be described as follows:

Planet: treats the (living)environment, it aims to restore, protect and maintain the harmony between the natural/biological and the built environment for the entire lifecycle of a project (Sjostrom & Bakens, 1999). More specifically, it is about ensuring that infrastructure solutions do not disrupt or dissociate the natural cycle and that it is integrated into the (natural)environment as well as possible.

People: treats society and people's wishes and examines community development, social and cultural systems, user comfort, public engagement, health and safety, equality and diversity within a project (Goh, 2018). When looking at infrastructure, the origin and initiation of projects often or partly come from the People dimension. After all, infrastructure is realized because there are (social and/or economic) needs, for instance better traffic flow.

Prosperity: encompasses the financial costs and benefits over the life cycle of a project and also refers to maximising the financial gains and flow of income from projects for the benefit of project stakeholders (Abidin, 2010). Budgets are decisive in the realization of infrastructure projects. The extent to which sustainability can be included in this, is therefore partly depended on the costs that this requires. However, sustainable does not necessarily mean more expensive. On the contrary, through efficient and cost-saving measures in the life cycle, sustainability can actually save costs.

According to Liu et al. (2019), there is an interdependence among the TBL dimensions of sustainability. In addition, the authors mentioned that in order to reach true sustainability, all the three dimensions should benefit simultaneously, this is true when all dimensions overlap in the center of the Venn diagram, as shown in Figure 2.1. The resultant of all dimensions must be as positive as possible. What is positive, is project and ambition specific. In a sustainable design there is a balance that matches the sustainable goals, objectives and ambitions of the client. The three dimension set the principles of SD. If one of the dimensions is disregarded, it would threaten the sustainability (Ciegis et al., 2009). To clarify, sustainability does not only demand attention for the environment. People and Prosperity are equally important. It is about the ideal balance and harmony between People, Planet and Prosperity. The domains of the Venn diagram and harmony between the dimensions of sustainability are described according to the interpretation of (Tamak, 2017):

Equitable: this domain is indicated as the harmony between the social (People) and economic (Prosperity) dimensions of sustainability, meaning that for the involved stakeholders, the economic value generated must be fair and long-term oriented;

Bearable: this domain is indicated as the harmony between the social (People) and environmental (Planet) dimensions of sustainability, meaning that environmental preservation is considered by all the involved stakeholders in order to evaluate society's and the environment's bearing capacity; and

Viable: this domain is indicated as the harmony between the economic (Prosperity) and environmental (Planet) dimensions of sustainability, meaning that environmental preservation must be carried out while taking into account the economic factors that make it viable.

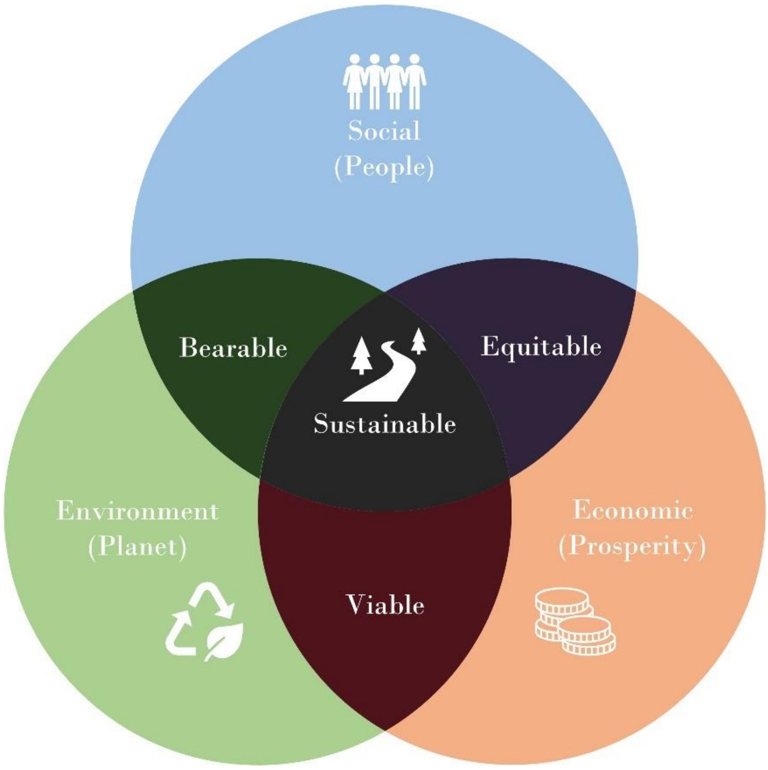


Figure 2.1 - The TBL (3Ps) dimensions of sustainability (based on Elkington, 1997; Liu et al., 2019)

Given the above explanations, designing sustainable is in fact nothing more than making conscious choices for People, Planet and Prosperity. The degree to which you choose to counteract negative effects or to bring about positive effects and contribute to realizing sustainability is the degree of sustainability in your design. This means that sustainability is about making smart combinations within a project. Sustainability is an integrated approach, looking at how projects in their area contribute to the People, Planet and Prosperity mindset.

Given the explanation above regarding sustainability, the author selected the concept of triple bottom line (TBL) i.e. People, Planet, Prosperity as a sustainability theory to be adopted in the research to define a sustainable highway and explore sustainability in highway designs and move towards sustainable development. The definition of a sustainable highway is explained in 2.1.5.

2.1.3 Sustainable Construction

In 1994, Charles Kibert proposed the term 'sustainable construction' (SC) during the first international conference on SC held in Tampa, USA, defining this as:

"the creation and responsible management of a healthy built environment based on resource efficient and ecological principles" (Kibert, 1994).

During the conference, Kibert presented a comparison of the traditional design criteria of quality, cost and performance with the sustainability design criteria of creating a healthy environment, minimization of environmental degradation and resource depletion, applying this to the construction process phases of planning, design, operation, renovation and demolition to incorporate the basic matters of sustainable development (SD). As a result, new project targets and criteria were added to the traditional project criteria of time, quality and cost. The transition to sustainability can be viewed as a paradigm shift (see Figure 2.2). In order to achieve SC, Kibert (1994) stated that it is important to maintain harmony between the three dimensions of SD (economic, social and environmental). The concept of SC entails applying sustainability in the construction phases over the entire project life cycle. Bueno et al. (2015) on the other hand defined SC *"as a building process that incorporates the basic principles of sustainable development",* which implies that SC is a subset of SD. So, the practices of SC should also address the three pillars of sustainability. Later in 2020, Goh et al. argued that *"sustainable construction must ensure the delivery of environmental, social and economic sustainability in a balanced and optimal manner, without one pillar dominating any others".* According to the aforementioned authors, the concept of SC is a multidimensional issue.

To conclude, SC can be seen as a construction undertaken by applying SD principles throughout the entire project life cycle.

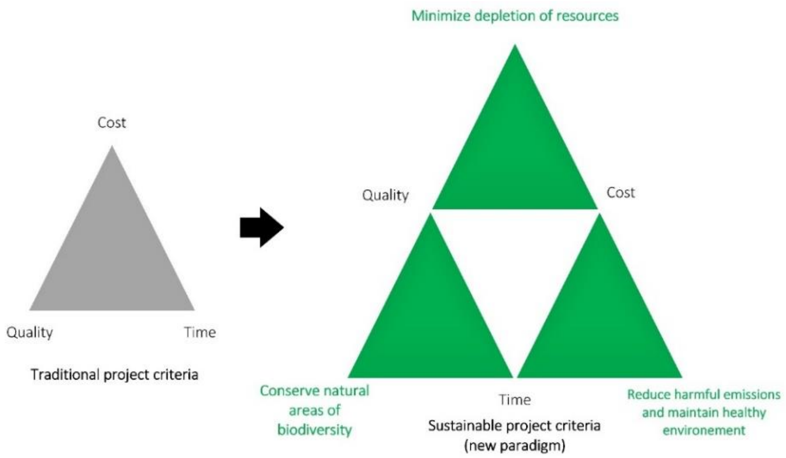


Figure 2.2 - Challenges of sustainable construction (SC) (adapted from Kibert, 1994)

2.1.4 Sustainable Design Principles

In recent years, Rijkswaterstaat has developed sustainable design principles in collaboration with Witteveen+Bos (engineering consultancy firm) that can be used during the MIRT-Elaboration and MIRT-Plan Elaboration phase (see Table 2.1). The main principles focus on prevention, value preservation (existing objects/systems) and value creation (new construction), which are translated into a total of 8 design principles. They offer guidance for designers to apply sustainable design principles at object level during the *MIRT-process*, for both existing objects and new projects. This research adopts the design principles which can be used in making sustainable design choices related to road design, civil engineering structures and road lay-out to limit the environmental impact.

Table 2.1 - Sustainable design principles (Rijkswaterstaat, 2019a)

Main principles	Design principles	MIRT-process
Prevention	1. Prevent: don't do what is not necessary	MIRT-Initiative
Value retention	2. Extend the service life of existing objects	MIRT-Exploration & MIRT-Plan Elaboration
	3. Make sustainable use of existing objects, materials, raw materials and natural processes	
Value creation	4. Design for multiple life cycles	
	5. Design future-proof	
	6. Design for optimal management and maintenance	
	7. Design for sustainable material use	
	8. Design for minimal raw material and energy consumption in construction and use phase	

During the MIRT-process the emphasis is placed on different design principles (Rijkswaterstaat, 2019a):

- *MIRT-Initiative:* in this phase the emphasis is on prevention, because that is how the greatest benefits can be achieved. For example, think of ways to make better use of existing infrastructure, resulting in improvement of the traffic flow without extra asphalt; and

- *MIRT-Exploration & MIRT-Plan Elaboration:* in these phases, it is determined how the project can contribute to value preservation and value creation. For example, for value preservation you can think of ways to utilize the value of (existing) infrastructure in the next life cycle, in terms of value creation, one can think of ways to create as much long-term value as possible with using as little material as possible.

In addition to these examples, there are far more possibilities that can be considered or applied. These will be examined and presented as practical examples in the SA framework.

2.1.5 Sustainable Highway

In this subsection the TBL (3Ps) theory is applied to define a sustainable highway. The TBL (3Ps) theory coined by John Elkington, is a well-known concept in sustainable development (SD) and a sound theory regarding the three interdependent dimensions of sustainability. The author proposes the following definition of a sustainable highway based on the TBL (3Ps) theory:

"A highway is truly sustainable if all dimensions of sustainability (economic, environmental and social) are taken into account, while embracing the principles of sustainability in terms of environmental protection, economic profitability and human well-being."

The TBL theory will form the basis of the new SA framework which integrates the three dimensions to allow designers and decision-makers to evaluate how design choices and options affect and/or contribute to the creation of sustainable added value, shifting the focus away from the iron triangle of cost, time and quality and toward broader impacts such as sustainability in the design process and decision-making (Silvius & Schipper, 2014).

Now that the sustainability theory is selected and a definition of a sustainable highway presented, the next section will explore which existing sustainability assessment approaches are used in the construction industry and infrastructure sector that try to integrate the three dimensions of sustainability. To establish which approach seems to be the most suitable for developing the SA tool that can integrate the three dimensions of sustainability.

2.2 Sustainability Assessment

In general, sustainability assessment (SA) approaches are appraisal and evaluation techniques that can be used to compare different design choices and options (Gasparatos & Scolobig, 2012) and also make decision-making easier (Bond et al., 2012). According to Bond et al. (2012) SA is emerging everywhere as a key decision-making tool. The following section will explain when and how SA can be performed.

2.2.1 Sustainability Assessment in Different Phases

Bueno et al. (2015) argued that sustainability can be a part of the 'ex-ante appraisal and decision-making' or part of an 'ex-post sustainability evaluation'. The terms 'appraisal' and 'evaluation' are regularly used as synonyms in the literature. To clarify, Table 2.2 explains the differences between the terms and shows how sustainability may be used as an ex-ante or ex-post evaluation in assessment. In general, *"'appraisal' represents project ex-ant evaluation and 'evaluation' represents project ex-post evaluation"* (Dimitriou et al., 2016).

Table 2.2 - Sustainability as an ex-ante or ex-post evaluation

	Ex-ante sustainability (appraisal) evaluation	Ex-post sustainability evaluation	Source
Project life cycle phase	Planning and design (front-end)	Realisation, operation & maintenance (implementation)	(Bueno et al., 2015; Rogers & Duffy, 2012; Ugwu et al., 2006)
Sustainability is part of	The appraisal and the decision-making of alternatives on the basis of all the data and information gathered (i.e. analysis of documents) pre-implementation	The monitoring process, after implementation of the selected design alternative for evaluation of the effective outcomes and thus obtain relevant data and useful feedback on the whole process	(Bueno et al., 2015; Rogers & Duffy, 2012; Ugwu et al., 2006)
Sustainability activities are	Forward-looking and thus rely extensively on forecasts, estimates and predictions	Backward-looking and are concerned with assessing in a retrospective sense and on the basis of direct observations, the performance of a project, after it has been implemented	(Bueno et al., 2015; Rogers & Duffy, 2012)
Sustainability aims at	Supporting the selection of the best alternative that maximizes beneficial outcomes on all dimension of sustainability	Quantifying sustainable practices associated with the construction and maintenance processes. Sustainability can be used to certify and monitor infrastructure projects	(Boardman et al., 2017; Bueno et al., 2015; Gühnemann et al., 2012; Rogers & Duffy, 2012; Ugwu et al., 2006)

Means by which sustainability can be used	A process where sustainability is used to provide guidance on appraisal and decision-making: (1) After identifying the impacts of the alternatives on the TBL dimensions, compare, evaluate and rank the alternatives, for instance with the use of a multi-criteria approach; (2) Obtain the ranking order of the design alternatives and select the alternative with the highest sustainability performance.	Sustainability as monitoring tool can be used in different processes to: (1) Evaluate the project against original objectives it was designed for and expected benefits at the time; (2) Assess, compare and award the constructed alternative, depending on its performance against relevant criteria earlier defined; (3) Improve current practices in construction (i.e. learn from the past) and do more than the minimum requirements; (4) Suggest best practices and procedures in future projects, due to the retrospective character it implies.	(Boardman et al., 2017; Bueno et al., 2015; Gühnemann et al., 2012; Rogers & Duffy, 2012; Ugwu et al., 2006)

Meex et al. (2018) observed that most SA tools are developed for end-product ex-post sustainability evaluation. This means that the assessment is only possible when the design phase or even the construction phase is finished. However, decisions that have the highest impact on the sustainability of the design are often made in the front-end phase (C. Bueno et al., 2018; C. Bueno & Fabricio, 2018). According to (Reid et al., 2013), it is critical to consider sustainability early in the planning and design (i.e. front-end) phases of a project's life cycle, because opportunities to incorporate sustainability in the project change and eventually diminish as the project progresses through its life cycle. For instance, significant operational cost savings can be realized in the future if sustainability is considered early in the planning and design phases (Tsai & Chang, 2012). In addition, Bueno et al. (2015) argued that SA should start with the appraisal and decision-making, the reason is that designers and decision-makers can significantly influence the future sustainability performance of the project early in the planning- and design phases. Consequently, they must understand the impact of their designs and decisions upon sustainability. In principle, this understanding can be achieved by systematically analysing the long-term benefits and negative effects offered by a highway design option (Tsai & Chang, 2012). Mouter et al. (2021) concluded that the planning, design and construction phases of a transport infrastructure project are critical for considering sustainability, because decisions made at these phases will affect the project's entire life cycle. However, in reality, in the implementation phase the design options are often so clearly defined that sustainability eventually turns out to be overlooked, i.e. has not received the required attention.

While a number of years ago, due to a lack of experience and knowledge, difficult discussions had to be made, much more is now known about how potential sustainable added value can be achieved. The greatest difficulty in giving a project-specific sustainable interpretation during the design is still in fitting sustainable solutions within the ambition of the client.

To summarize, integrating TBL dimensions in the assessment of highway projects at the planning- and design phase is more effective then after construction. Inti & Tandon (2021) observed that certain highway phases require a greater focus on sustainability than others. Therefore, it can be extremely valuable to focus on the early design phases of a highway project, because design choices at the beginning of the life cycle are very important for realizing sustainability in later phases. Hence, this research focuses on the ex-ante appraisal of sustainability during the planning- and design phase of highway projects. The planning is show as the second step and the ex-ante evaluation (appraisal) is the third step in the project life cycle (see Figure 2.3). This is the phase in which design choices and different design options are assessed against assessment criteria (Dimitriou et al., 2016). After this phase the implementation of the project follows, where the selected preferred design option is realised.

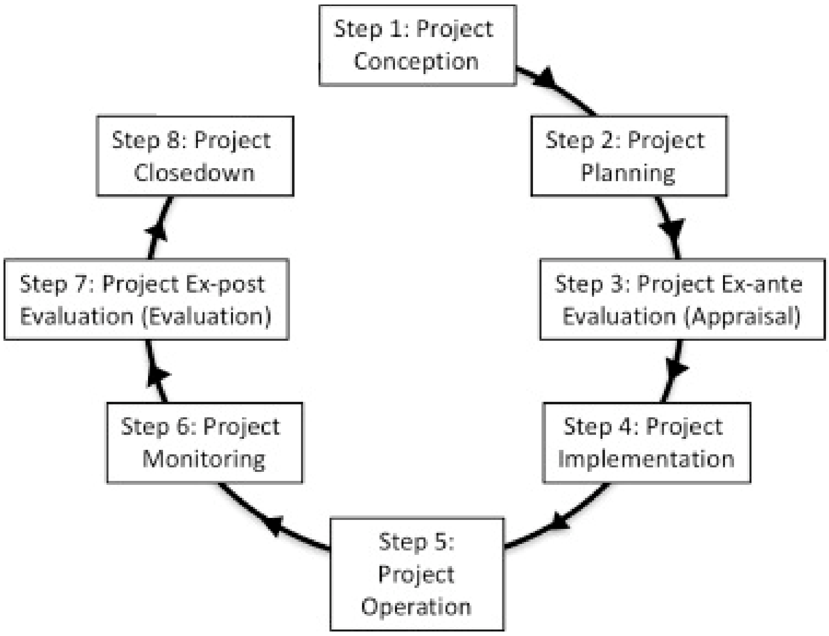


Figure 2.3 - The project life cycle (Dimitriou et al., 2016)

2.2.2 Overview of Available Approaches for Sustainability Assessment

In literature, many academics characterize sustainability assessment (SA) approaches differently. This research adopts the classification of Bueno et al. (2015), to investigate how SA is applied in practice to guide designers and decision-making in different project phases. Bueno et al. (2015) classifies the methods and tools in the SA of transportation projects into three distinct approaches: (1) (2.2.2.1) project appraisal methods for decision-making, being (2.2.2.2) cost-benefit analysis (CBA) and (2.2.2.3) multi-criteria analysis (MCA); (2) (2.2.3) methods for impact assessment, being (2.2.3.1) environmental impact assessment (EIA), (2.2.3.1) life cycle assessment (LCA), (2.2.3.3) social life cycle assessment (SLCA), (2.2.3.4) life cycle costs (LCC) and (3) (2.2.4) international rating systems. The SA approaches are discussed in the following sections. In this literature review, the author gives a general description of the main SA approaches, especially when assessing sustainability.

2.2.2.1 Appraisal Methods and Tools for Decision-Making

In this section, the appraisal methods and tools for decision-making are briefly examined. First, the cost-benefit analysis (CBA) is studied and afterwards the multi-criteria analysis (MCA) method. They both are used as ex-ante evaluation appraisal methods to assess, compare, evaluate and select design options once it has been decided to implement a highway project (Suprayoga et al., 2020). These methods and tools are now the most commonly used in the decision-making processes of transport project appraisal and they are evolving towards the introduction of sustainability aspects and criteria (P. C. Bueno et al., 2015).

2.2.2.2 Cost-Benefit Analysis

Cost-benefit analysis (CBA) supports sustainability by providing a tangible and rational assessment of the benefits and costs of project design options (Damart & Roy, 2009), so mainly from the economic point of view. According to Beria et al. (2012), CBA can be used as a comprehensive and useful methodology in decision-making processes. CBA is based on the ability to monetize both positive (benefits) and negative (costs) effects (Bueno et al., 2015), which makes it a useful support tool because it is a rigorous, transparent and formal appraisal tool.

Conversely, there has been considerable research aimed at identifying substantive problems when appraising the sustainability of transport projects with a CBA. By examining the prospect of CBA application in promoting or demoting sustainable development (SD), (P. C. Bueno et al., 2015) found *"abundant arguments disfavouring the application of CBA, represented by limitations such as: (i) trying to evaluate what are often not 'evaluable,' that is, non-economic values and (ii) limited considerations regarding distributional equity (including inter-temporal equity)"* (Omura, 2004, p. 44). Given these drawbacks, it can be concluded that CBA suffers from the objectivity/subjectivity dilemma. In other words, the technique can be classified as 'pseudo-objective' since it still has difficulties in quantifying non-market goods. According to (Bueno et al., 2015) CBA has still serious problems in evaluating incommensurable goods.

In the Netherlands, social cost-benefit analysis (SCBA) is used as an information tool that supports the policy process and political decision-making. The SCBA helps, in substantiating a preferential decision (*voorkeursbeslissing*) in the Multi-Year Program Infrastructure and Spatial Planning (*Meerjarenprogramma Infrastructuur, Ruimte en Transport (MIRT)*) by relating the costs incurred to realize a project to the welfare benefits for Dutch society. In a SCBA, the effects are expressed in monetary terms as much as possible. This makes the effects mutually comparable and makes it possible to estimate the total effect on prosperity. The Ministry of Infrastructure and Water Management (*Ministerie van Infrastructuur en Waterstaat (IenW)*) has been using SCBAs in decision-making for the MIRT, during the MIRT-Exploration (*MIRT-Verkenning*) of a MIRT-project (e.g. road- and highway projects - both national- and large regional projects). A SCBA assesses all relevant aspects that have an effect on welfare in society, these aspects are taken into account in the decision-making process. The SCBA can also provide insight into where effects end up. Often the most important impact determinations for the SCBA are the available data on cost estimates, the traffic or other analyzes performed and the data from the environmental impact assessment (EIA) (*milieueffectenrapportage (MER)*).

Overall, it can be concluded that the CBA is unable to include the TBL in a precise and narrow manner because the intangible items' monetization process is questionable. There is more uncertainty in measurement, forecasting and evaluation when the approach tries to price 'priceless things'. Furthermore, typical CBA does not consider the entire life cycle of a project, for example, end of life aspects are rarely included. The output and results of this method can however be integrated in the SA tool in the economic dimension.

2.2.2.3 Multi-Criteria Analysis

Over the past decades, the use of multi-criteria analysis (MCA) has been increasing in literature (C. Bueno et al., 2013). MCA is applied when several criteria (including criteria that are difficult to monetize and quantify) are considered simultaneously (Beria et al., 2012). Compared to CBA, the MCA can cover project impacts comprehensively (i.e., the environmental, social and economic impacts) and allow stakeholder participation by including their subjective judgments (Pope & Morrison-Saunders, 2013).

Generally a MCA concerns the making of choices using multiple and often conflicting, criteria, in efforts to arrive at pre-considered desired outcomes. MCA in particular, looks to deciding on preferences by choosing among design options (Ward et al., 2016). The MCA process, is as follows (Soltani et al., 2015):

- Define the problem and the assessment structure;
- Determine the weights/importance of the criteria that integrate the assessment structure;
- Evaluate the different design options with respect to each criterion;
- Evaluate the design options against the weight of each criterion.
- Select the preferred design option.

The MCA approach can provide a good framework for dealing with sustainability, but the assessment process can become very subjective. Because qualitative assessment and the imputation of value-laden weightings to assumptions can lead to subjective biasing (Beria et al., 2012). According to (P. C. Bueno et al., 2015) it has to do with the transparency of decisions and their impact on the MCA's final results.

The MCA approach, which can be multi-disciplinary, could be a very suitable approach given the need to comprehensively capture the economic, environmental and social dimension. Because it can integrate criteria into one framework, incorporate results and input from other tools and methods, give weights to the criteria and finally compare and evaluate design options using a ranking method. To conclude, the MCA approach can be used to develop a SA tool that addresses sustainability thoroughly.

2.2.3 Methods for Assessing Environmental-, Cost- and Social Impacts

Methods considered in the analysis to assess the economic, environmental and social impacts of transport project design options include: the environmental impact assessment (EIA), life cycle assessment (LCA), social life cycle assessment (SLCA) and life cycle costs (LCC). These methods tend to focus on either economic, environmental or social topics only, they are usually integrated or combined with other tools for a complete.

2.2.3.1 Environmental Impact Assessment

The purpose of an environmental impact assessment (EIA) (*milieueffectenrapportage (MER)*) is to include environmental effect in decision-making for activities and plans that may have negative environmental consequences, such as the construction of a new highway. Certain negative environmental effects can be avoided or limited by mapping out the possible environmental impacts prior to making a decision on an activity. The EIA has been legally formed in the Netherlands by the Environmental Management Act and the Environmental Impact Assessment Decree 1994 (*Wet milieubeheer en het Besluit milieueffectrapportage 1994*) (Rijkswaterstaat, 2019b). An EIA is drawn up during the MIRT-Exploration, in which solution directions (*oplossingsrichtingen*) and promising alternatives (*kansrijke alternatieven*) are examined. In the MIRT-Plan Elaboration, this is sometimes supplemented with extra information. These two parts then jointly form the project-EIA (Rijkswaterstaat, 2019b).

To conclude, in the EIA, design options are analyzed so that the option where the environmental impact is the lowest can be selected (Broniewicz & Ogrodnik, 2020). In this method, selection is based on most favourable design option from the environmental point of view. EIA is only undertaken for certain projects and at a more developed stage of feasibility study. Sustainability objective and criteria from other dimensions are not incorporated in the assessment. Bueno et al. (2013) argued that there is a need for integrating the EIA with other assessment tools and that the EIA is seen by many as a first step towards a sustainability assessment tool. For this reason, factors (such as soil, air, water, climate) described and assessed in the EIA can be useful to form assessment criteria in the new SA tool for the environmental dimension.

2.2.3.2 Life Cycle Assessment

Life cycle assessment (LCA) is part of the life cycle considerations (Mattinzioli et al., 2020). LCA is one of the most used methods for evaluating and calculating the environmental impact of a product, service, project or entire contract over certain life phases or entire life cycle (Marcelino-Sádaba et al., 2015) by quantifying the potential environmental impact of (raw) material use, energy consumption, waste generation and produced emissions (Meex et al., 2018). However, an LCA provides more information in one project than in others and its application remains tailor-made and depends on the project. Calculating and testing an LCA takes quite a lot of time and requires considerable effort. An LCA is therefore only proportional in large projects, like highway projects (PIANOo, 2022). An LCA for construction works and -products consists of four life phases:

Table 2.3 - Life phases of a product, service or work (PIANOo, 2020)

Life phases of a product, service or work	Detailed
A. Production	A1. Resource extraction
	A2. Transport to producer
	A3. Production process
A. Construction	A4. Use product
	A5. Maintenance
B. Use	B1. Use of product
	B2. Maintenance
	B3. Repair
	B4. Replacement, wear of parts
	B5. Renovation
	B6. Energy consumption of product
	B7. Water consumption of product
C. Demolition	C1. Demolition
	C2. Transport to waste processing
	C3. Waste treatment process
	C4. Deposit
D. Reuse	D1. Recovery of materials

An LCA can be calculated for a full life cycle (A-D) or partial life cycle (e.g. A and B). An LCA with a limited scope looks at parts of a life cycle, for example the environmental impact during the production and construction phase (A1-A5). To compare the environmental impact, a full life cycle assessment is the most comprehensive. A full LCA calculates to what extent all used materials can be reused after the life cycle. From a theoretical point of view, this is always preferable. However, in a practical sense, it is not always feasible or desirable to request an entire LCA (PIANOo, 2020).

For instance, if the demolition or reuse phase is still very uncertain, then a limited LCA with a focus on a sustainable production phase (A1-A3) or efficient transport movement is sometimes sufficient to compare the environmental impact between different design options.

In the Netherlands, clients like Rijkswaterstaat and ProRail are increasingly interested in procuring sustainable solutions. They can do this by taking into account the environmental impact in addition to the price. With this, the client challenges the market to become more sustainable. At the same time, this contributes to objectives with regard to CO2-reduction and the circular economy (CE) (PIANOo, 2020).

In order to assess and compare the environmental impacts of a service, delivery or work, an objective measure is used. Environmental impacts can be expressed using the Environmental Cost Indicator (ECI) (hereafter: *milieukostenindicator (MKI)*), which is an outcome of a life cycle assessment (LCA) expressed in euros [€]. The MKI expresses this environmental impact in a single value. The MKI-value can be considered in various phases, namely construction, use, maintenance and end of life. This financial value represents the expected social costs (*maatschappelijke kosten*) if the environmental impacts that occur have to be reversed using known solutions. We call this the 'shadow costs' (*schaduwkosten*). Including shadow costs in the procuring process is not only useful, but also necessary to meet the climate targets. It can also help to monitor progress towards these goals (PIANOo, 2020).

MKI is increasingly used as a measuring tool for construction works and -products. As indicated earlier, Rijkswaterstaat and ProRail use the MKI as standard for tenders. By co-adding for the lowest possible environmental costs (*milieukosten*), market parties are encouraged to reduce the environmental impact of their solution. A well-known sustainability tool in the Netherlands is *Duurzaam bouwen calculator* 'DuboCalc' developed by Rijkswaterstaat to calculate and compare the sustainability and environmental costs of tenders (PIANOo, 2022), which uses MKI-data to arrive at a score (PIANOo, 2020). This calculated MKI-value is a good indicator for external environmental costs (PIANOo, 2016). DuboCalc calculates all the effects of material and energy consumption from cradle to grave, or from extraction to the demolition and reuse phase. All relevant environmental effects during the entire life course are included in the calculation. The method is based on the LCA methodology in accordance with the ISO14040 standard and on *Bepalingsmethode Milieuprestatie Gebouwen en Bouwwerken*.

Another useful tool recently developed is the materials passport (*materialenpaspoort*). A materials passport contains a lot of measurable data, such as the financial value and the circularity index (*circulariteitsindex*). In a materials passport, the residual value of a certain material must be measurable, so that the discussion can shift from 'not throwing materials away' to 'careful harvesting of materials'. This also changes the design process (PIANOo, 2022). However, the materials passport is still in its early stages of development for the civil engineering sector.

To conclude, because LCAs primary purpose is limited to the assessment of the environmental impacts of a given activity, work or product, this method cannot measure all three dimensions of sustainability. Although LCA results should be integrated into other assessment tools, it is an insufficient tool for assessing all three dimensions of sustainability on its own. As a result, integrating LCA results in other assessment tools can be seen as a particular step towards the development of a comprehensive sustainability assessment tool.

To summarize, LCAs cannot measure all three dimensions of sustainability because their primary purpose is to assess the environmental impacts of a given activity, work, or product. However, LCA results should be integrated into other assessment tools. As a result, integrating LCA results into the new SA tool can be useful to form assessment criteria for the environmental dimension.

2.2.3.3 Social Life Cycle Assessment

The evaluation of social impacts has been implemented by using several different approaches. In this light, one study conducted by Jørgensen et al. (2008) found that the perception of social impacts is very variable across the SLCA method. Furthermore, these authors recognized *"SLCA is in an early stage of development where consensus building still has a long way".*

In conclusion, the inclusion of social aspects into LCA, called the SLCA, is still under development and has not been well integrated into the decision-making process. There is currently no standardized method for evaluating the social and distributional effects of highway projects, for example. Even though social impacts are considered as part of an impact assessment, economic and environmental factors still receive more attention.

2.2.3.4 Life Cycle Costs

Life cycle costs (LCC) is based only on the economic dimension sustainability. LCC is a method for mapping the financial costs and benefits of a system or project. LCC requires a different view of the cost structure, in which the investment-, engineering-, maintenance- and disposal (demolition) costs associated with the entire life cycle of a certain project are made comparable (PIANOo, 2016). LCC is the sum of all types of costs incurred over the entire life cycle of a project discounted to the present. The objective of LCC is to select the most cost-effective (least cost) approach among various design options to achieve the lowest long-term cost of ownership (i.e. total costs of ownership (TCO)) (Mangili et al., 2019). In this way it becomes clear which design option provides the most value and, as a result, how public funds (investments) are best spent (PIANOo, 2016).

Simply put, it is advisable to use LCC if there are cost types in the project that can differ greatly over the entire life cycle. For example, for highways, groundwork, thickness of the asphalt layer, noise barriers and civil structures (e.g. bridges and tunnels) are very decisive for the LCC of the highway. It is therefore sensible to consider the construction- and maintenance costs of these of various objects and cost types to compare and score them accordingly in different design options (PIANOo, 2016).

LCC can be used not only to reduce direct LCC, but also to reduce environmental costs, provided these costs can be estimated and monitored (PIANOo, 2016). In the Netherlands, the *Standaardsystematiek Kostenramingen 2010 (SSK-2010)* is used as an unambiguous system for making cost estimates.

To conclude, the primary purpose of LCC is limited to the assessment of the economic impacts of a given project. Hence, for the same reasons as for the LCA method there is a need for integrating LCC results into the new SA tool for the economic dimension.

2.2.4 Rating Systems

Rating systems are self-evaluation tools developed for the construction industry (P. C. Bueno et al., 2015). In 2012, there were already more than 600 rating tools and 170 evaluation criteria in the building industry, the most popular are LEED and BREEAM (Berardi, 2012). However, compared to the building industry, the development of infrastructure rating systems has been relatively slow (Liu et al., 2018).

In the early 2000s, it became clear that there was a lack of tools like LEED and BREEAM for infrastructure projects. This initiated the development of the CEEQUAL rating system. Currently, CEEQUAL is an integral part of the UK's construction industry and its strategy towards SD (Griffiths et al., 2018). At the moment, CEEQUAL is by far the most used rating system for infrastructure sustainability (Amiril et al., 2014). The infrastructure rating systems are based on the more established building rating schemes. Other countries developed similar rating systems that are often tailored to specific agencies to fit the local context and needs (Liu et al., 2018). Rating systems that evaluate the sustainability of transport infrastructure include: Greenroads, GreenLITES, INVEST and I-LAST (C. Bueno et al., 2013).

The philosophy of rating systems is based on various categories, each of which explains one sustainability attribute and subcategories that cover various topics (C. Bueno et al., 2013). The aforementioned authors found that all the SA and award schemes work in the same way. They are intended to assess, compare and award a planned or existing project, depending on its performance against relevant sustainability criteria.

To summarize, the aim of rating systems is to provide an objective and comprehensive method for evaluating a broad range of sustainability attributes in a consistent way. The main characteristics of the rating systems are shown in Table 2.4.

Table 2.4 - Rating systems (based on Bueno et al., 2015; Clevenger et al., 2013; Griffiths et al., 2018; Mouter et al., 2021; van Eldik et al., 2020)

Focus area	Rating system	Main categories and topics
Roads	GreenLITES (Green Leadership in Transportation and Environmental Sustainability)	Sustainable sites, water quality, material resources, atmosphere, innovation
	GreenRoads	Project requirements; access and equity; material and resources; pavement technologies; construction activities; environment and water; custom credits
	I-LAST (Illinois Livable and Sustainable Transportation)	Planning, design, environmental water quality, transportation, lighting, materials and innovation
	BE²ST-In-Highways™ (Building Environmentally and Economically Sustainable Transportation-Infrastructure-Highways)	Greenhouse Gas Emission (GGE), energy use, waste reduction (in-situ/ex-situ), water consumption, hazardous waste, traffic noise, social requirements and social cost of carbon saving
Civil infrastructure (e.g. airport-, road-, plant-, pipeline- and rail construction)	ENVISION	Leadership; quality of life; resource allocation; natural world; climate change and risk, Life cycle cost (LCC)
	CEEQUAL (Civil Engineering Environmental Quality Assessment and Award Scheme)	Project strategy; PM; people and communities; physical resources; land use and landscape; the historic environment; ecology and biodiversity; the water environment; transport
	LEED (Leadership in Energy and Environmental Design)	Sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design, regional priority
	IS rating system	Management and governance; people and places; using resources; materials and waste; ecology; innovation
Buildings	Building Research Establishment Environment Assessment Method (BREEAM)	-

In general, as we can see in Table 2.4, the rating tools have comparable categories even though there were differences in weighting systems and indicator values. Even so, the rating systems contain some common issues that can be grouped into the following sections: environment, water, energy, material and technological and strategic innovation to improve the environmental performance. Despite the assessment tools have fixed weights and benchmarks reflecting their own criteria, at the end they are based on similar methodological approaches (C. Bueno et al., 2013).

Doan et al. (2017) found that there are large differences in scopes of the rating systems. While some systems only cover the environmental dimension of sustainability, others include social and economic aspects as well. However, no rating system thoroughly assesses all three dimension. In addition, Lee et al. (2011) criticized its use by indicating that *"they lack transparency and objectiveness in the criteria selection and weighting process and are not based on a standardized methods of performance measurement"*. In spite of this, there will have to be some subjectivity due to the wide nature of projects, there location and externalities (C. Bueno et al., 2013).

To conclude, rating systems can be implemented at the planning stage and then continue through design and construction phases. However, in EU countries they are not used to assist with designing or in the decision-making process. Therefore, rating systems are not applied to conduct a comparison among different design options. Presently, CBA and MCA are the most common methods used in EU countries to make decisions (P. C. Bueno et al., 2015). All in all, the rating systems can still provide valuable information and criteria to be integrated in the new SA tool for the different dimensions.

2.2.5 Dutch Standards and Guidelines

Most countries have their own and therefore different road design guidelines (C. Bueno et al., 2013). In the Netherlands, the design of road and highway infrastructure is obliged to comply with some requirements and standards to suit local requirements. The following guidelines apply to the Netherlands: the *MIRT-process* and *Kader wegontwerp 2.0*. These guidelines are considered as recommendations for any road infrastructure project under the authority the Ministry of Infrastructure and Water Management.

2.2.6 Conclusion on Existing SA Approaches

As outlined above, despite the numerous SA approaches available, none of them address sustainability as a whole. While there are positive characteristics associated with each tool, some practical issues remain unsolved (Bueno et al., 2013). As the literature has shown there is no simple solution for the assessment of projects, specifically when tackling sustainability of highway projects. In other words, all SA approaches have their strengths and weaknesses, but none of the tools and methods analysed are suitable for a comprehensive assessment of the sustainability of highway design options as they are currently.

However, it is concluded that among the existing tools and methods, the MCA approach seems to be the most suitable, for developing an new SA tool that integrates criteria for the three dimensions of sustainability. Since, the MCA approach is (1) the most flexible method to assess the socio-economic and environmental viability; (2) allows decision-makers to account for complex problems through for a wide range of multiple criteria (Pope & Morrison-Saunders, 2013); (3) can assign weighting coefficients to the criteria, evaluates design options and finally provide a ranking of the design options (Beria et al., 2012); (4) several criteria can be taken into account simultaneously in a scheme to comprehensively consider sustainability on the three dimensions of sustainability (TBL); (6) can incorporate results from a wide array of techniques, tools and methods (complementary attributes) (Bueno et al., 2015); (7) simple to use and apply by designer and decision-makers (Pellicer et al., 2016).

In line with the results of the analysis of existing SA approaches, it is concluded that combining results from existing tools, methods and SA criteria in a one comprehensive MCA assessment framework could be beneficial for effectively integrating and balancing all dimensions of sustainability (TBL) in the assessment of design choices and options. In addition, MCA frameworks can be tailor-designed for particular context (Ward et al., 2016), in this case Dutch highway context. In the next section, existing assessment frameworks will be consulted and assessment criteria for sustainability will be identified through available literature.

2.3 Preliminary List of Sustainability Assessment Criteria

In this section a thorough analysis of the existing assessment frameworks, rating systems and RWS documents will be performed to identify assessment criteria for sustainability in the construction industry and infrastructure sector. This will form the preliminary list of criteria to be integrated in the SA framework for assessing, evaluating and comparing the impacts and effects of different highway design choices and options on the dimensions of sustainability. The TBL theory (3Ps) will be used for the SA framework to identify criteria and themes which enable assessment of highway design options regarding sustainability. First, existing assessment frameworks focused on the construction industry and infrastructure sector will be discussed. These are either specific (e.g. roads, railways, highways) or generally applicable to any type of infrastructure or construction project. Furthermore, these frameworks differ in terms the dimension (TBL) they focus on and the assessment type (quantitative or qualitative). The existing assessment frameworks identified and studied during the literature review will serve as a basis for the development of a new, integrated SA tool (see 2.3.1). Next, the criteria from these frameworks were identified for the three dimensions of sustainability in the construction industry and infrastructure sector to form the preliminary list of SA criteria (see 2.3.3).

2.3.1 Existing Assessment Frameworks

Over the past years, many assessment frameworks have been developed in an attempt to extend the TBL theory, which evaluates environmental, social and economic dimensions, to measure the sustainability of construction projects. Through literature reviews and empirical research, researchers have identified essential metrics, indicators and criteria for assessing sustainability (B. Liu et al., 2021). In particular, ecological challenges, economic performances, environmental influences and social impacts are all issues to consider. While several assessment frameworks with assessment criteria exist, many of the frameworks focus on a particular dimension of sustainability, for instance, on the environmental dimension or are sector specific (e.g. roads, railways, buildings etc.). While sustainability can be divided into three individual dimensions, they are still equally important and interrelated dimensions of sustainability. Thus, an assessment framework covering all dimensions simultaneously should be adopted. The studies summarized in Table 2.5 provide the most assessment criteria for sustainability.

Table 2.5 - Relevant contributions and assessment frameworks covering assessment criteria for sustainability

No.	Source of assessment framework	Type	Sector	Economic	Environmental	Social
1	Inti & Tandon (2021)	Quantitative	Highway infrastructure	x	x	x
2	Mahmoudi et al. (2019)	Qualitative	Urban transportation	x	x	x
3	Amiril (2014)	Qualitative	Railway infrastructure	x	x	x
4	Broniewicz & Ogrodnik (2020)	Qualitative	Transportation infrastructure		x	x
5	Bueno & Vassallo (2015)	Quantitative	Transport infrastructure	x	x	x
6	Mansourianfar & Haghshenas (2017)	Quantitative	Urban transportation		x	x
7	Sierra et al. (2018)	Qualitative	Infrastructure			x
8	Suprayoga et al. (2020)	Qualitative	Road infrastructure	x	x	x
9	Fernández-Sánchez & Rodríguez-López (2010)	Qualitative	Construction industry	x	x	x
10	Ibrahim & Shaker (2019)	Qualitative	Highway infrastructure	x	x	x
11	Koo et al. (2009)	Qualitative	Underground infrastructure	x	x	x
12	Liu et al. (2021)	Qualitative	Infrastructure	x	x	x
13	Lin et al. (2021)	Qualitative	Infrastructure		x	
14	Pakzad et al. (2016)	Qualitative	Infrastructure		x	x
15	Rooshdi et al. (2014)	Qualitative	Highway infrastructure		x	
16	Shen et al. (2011)	Qualitative	Infrastructure		x	x
17	Ugwu & Haupt (2007)	Qualitative	Infrastructure	x	x	x
18	Yu et al. (2018)	Qualitative	Construction industry		x	x
19	Sahely et al. (2005)	Quantitative	Construction industry	x	x	x

2.3.1.1 Existing Assessment Frameworks for the Construction Industry Analysed

There exist numerous studies on measuring the sustainability with the use of assessment frameworks. First, we discuss the frameworks from the construction industry, then from the infrastructure sector and at last the rating systems. In general, the frameworks of Fernández-Sánchez & Rodríguez-López, 2010; Sahely et al., 2005; Yu et al., 2018 were found to be most prominent in the literature and relevant for this research.

The paper of Fernández-Sánchez & Rodríguez-López (2010) analysed problems in sustainability. Based on ISO 21929-1 and risk management standards, the authors developed a methodology for identifying, classifying and prioritizing sustainability indicators. They developed a set of indicators for construction projects that focused on the three dimensions of sustainable development (regarding environment, social integration and social economy). The proposed methodology is a first step toward standardizing the identification and selection of sustainability indicators in construction projects.

Yu et al. (2018) presents an effort conducted in Taiwan to propose a Construction Project Sustainability Assessing System (CPSAS) that takes into account the three dimensions of sustainability based on the theoretical backgrounds from the literature and former successful sustainable projects. They developed a sustainability evaluation framework for construction projects that considered the project life cycle based on the concept of Labuschagne et al. (2005).

The study of Sahely et al. (2005) developed a framework for assessing the sustainability of urban infrastructure systems throughout their life cycle. The framework focuses on key interactions and feedback mechanisms between infrastructure and surrounding environmental, economic and social systems. One way of understanding and quantifying these interacting effects is through the use of sustainability criteria and indicators. The authors propose a generic set of sustainability criteria and sub-criteria, as well as system-specific indicators. The research also included a list of sustainability criteria and sub-criteria for various infrastructure systems.

2.3.1.2 Existing Assessment Frameworks for the Infrastructure Sector Analysed

Next we analyse the assessment frameworks specific for the infrastructure sector. Amiril et al., 2014; Broniewicz & Ogrodnik, 2020; Bueno Cadena & Vassallo Magro, 2015; Inti & Tandon, 2021; Koo et al., 2009; Lin et al., 2021; B. Liu et al., 2021; Mahmoudi et al., 2019; Mansourianfar & Haghshenas, 2018; Pakzad & Osmond, 2016; Rooshdi et al., 2018; Shen et al., 2011; Sierra et al., 2018; Suprayoga et al., 2020; Ugwu & Haupt, 2007; Ibrahim & Shaker, 2019 were found to be most prominent in the literature and relevant for this research.

Amiril et al. (2014) have reviewed, synthesized and developed an integrated framework of relationships between sustainability factors and sustainability performance for Malaysia railway infrastructure projects. The results from the literature show that, sustainability factors and performance can be categorized under environment, economic, social, engineering/resource utilization and project management. The authors identified 27 sustainability factors specific to transportation infrastructure projects.

Broniewicz & Ogrodnik (2020) examined the possibility of using multi-criteria methods in order to select the route alternative most favourable for the environment. They also gave an overview of transport infrastructure's negative impacts on the environment to be assessed when comparing different route alternatives.

Bueno & Vassallo (2015) presented sustainability criteria for transport project appraisal. In addition, they suggested eliciting criteria weights based on both expert preferences and the importance that the sustainability criteria have in the geographical and social context where the project is developed. This novel methodology is applied to a real case study to quantify sustainable practices associated with the design and construction of a new roadway in Spain. The authors take into account the opinion of evaluators through the AHP method and the contextual conditions.

In their study, Inti & Tandon (2021) integrated LCCA (economic), E-LCA (environmental) and S-LCA (social) to assess each road design systematically and comprehensively and 12 measurable indicators were thereby recommended for assessing specific road designs to select the sustainable design. They noted that these measurable indicators are not all-inclusive and it is likely that new ones will emerge that will further change the sustainable landscape. In addition, the application of the proposed approach was demonstrated by selecting a sustainable road design for El Paso, Texas.

Koo et al. (2009) focuses on the development process of a sustainability assessment model (SAM) suited for application during an underground infrastructure project. Sustainability assessment indicators to be used for underground infrastructure projects were identified and the development of a modelling framework is described. Forty-seven sustainability indicators representing sustainability issues constitute the framework of the SAM.

Lin et al. (2021) constructed an evaluation framework, including four dimensions and related ten criteria, using a new hybrid-modified multiple attribute decision-making (MADM) model for developing and improving the green infrastructure (GI) for promoting environmental sustainability.

Liu et al. (2021) reviewed infrastructure assessment studies and international rating systems, this study identified 50 metrics measuring infrastructure sustainability (IS). The proposed IS metric system consists of 4 measurement dimensions integrating the triple bottom line (TBL) (economic, social and environmental sustainability) and managerial sustainability. It is claimed that, on the one hand, the IS metric system is formal enough to accommodate 4 dimensions, 15 criteria and 50 metrics required for lifecycle IS evaluation.

Mahmoudi et al. (2019) identified evaluation criteria for sustainability in all aspects including economic, social and environmental dimensions of urban transportation network (UTN) and evaluating importance of these criteria. While most researches have only focused on economic aspect of transportation systems, this paper considers economic, social as well as environmental dimensions. Then a framework based on Best-Worst method (BWM) to make decisions in the different MCDM problems, has been proposed to evaluate and prioritize sustainability dimensions and evaluation criteria. To show the usefulness of the proposed model, it is applied to a real-world case study of transportation in Isfahan, Iran. The paper presents a list of most used sustainability criteria related urban transportation networks based on previous papers.

In the study of Mansourianfar & Haghshenas (2018) the objective was to assess the sustainability of infrastructure projects on urban transportation systems and evaluate their compliance with principles of sustainable development (SD). They proposed a framework that can assist policy-makers and traffic engineers to evaluate the sustainability of urban transportation infrastructure projects. The paper presents a list of sustainable transportation indicators.

Pakzad & Osmond (2016) presented a conceptual framework to facilitate the development of an inclusive model for the sustainability assessment of green infrastructure (GI). The framework focuses on key interactions between human health, ecosystem services and ecosystem health. This integrated framework was then applied to develop a composite indicator-based assessment model to measure and monitor performance of green infrastructure (GI) projects and support future studies. The outcome of the study is the development of a set of performance indicators aimed at enhancing project outcome and funding opportunities.

The paper of Rooshdi et al. (2019) aims to explain the determination of weightage for criteria of design and construction activities of highway infrastructure in order to categorize which criteria most contribute to the green practices based on the priority. They presented a list of criteria of sustainable design and construction.

Shen et al. (2011) found that, although existing studies have suggested various methods for practicing sustainable development principles in the process of implementing infrastructure projects, effective assessment indicators are unavailable, which presents a barrier to the effective assessment of infrastructure project sustainability. The study introduces key assessment indicators (KAIs) for assessing the sustainability performance of an infrastructure project. A procedure for using the KAIs is demonstrated by a case study. These research findings provide an alternative solution to appraise the sustainability of infrastructure projects. The study presents a list of assessment indicators for infrastructure project sustainability.

Sierra et al. (2018) conducted a review on multi-criteria assessment of the social sustainability of infrastructures. They reviewed the current state of multi-criteria infrastructure assessment studies that include social aspects. The authors presented a list of 23 social criteria used in the assessment methods.

At the road scale, Suprayoga et al. (2020) recently evaluated the degree of application of sustainability assessment to road infrastructure projects in terms of the environmental, economic and social dimensions. Based on 31 analysed papers, they found that the ´project appraisal´ method covers the most extensive criteria and is recommended as the most suitable approach for decision-making. They presented a list of integrated indicators to assess the sustainability of road infrastructure projects.

Ugwu & Haupt (2007) proposed an indicator system with key performance indicators (KPIs) and assessment methods for assessing infrastructure sustainability focusing on the project operation stage in the South African construction industry.

Ibrahim & Shaker (2019) developed a sustainability index for Egyptian highways construction projects that reflects the amount of sustainable choices highways engineers, mangers and highways agencies need to implemented during both the construction and maintenance processes. This paper presents a scoring sheet for determining a sustainability index for highway construction projects for design and construction.

2.3.1.3 Rating Systems for Transportation Infrastructure Analysed

In a previous section 2.2.4 the author already discussed the backgrounds and weaknesses of rating systems, created by third-party certification institutions. In this section analysis is done on the transport rating systems in particular. As mentioned earlier, most assessments are defined for a certain country or state. In response, some institutions developed new innovative approaches for project assessment, these are called ‘rating systems’ that measures sustainability. Sustainability efforts are often measured in six categories by rating systems: environment, energy, materials, water quality and use, transport and waste (Clevenger et al., 2013; Mansourianfar & Haghshenas, 2018). The most important rating systems for transportation infrastructure include GreenLITES, BE2ST-In-Highways™, Envision, I-LAST and GreenRoads (P. C. Bueno et al., 2015; Clevenger et al., 2013), see Table 2.6.

Table 2.6 - Most important rating systems for transportation infrastructure

Rating system	Origin	Rating method	Criteria categories, themes and topics	Sources
GreenLITES	USA	Sum of credit criteria	Sustainable sites; Water quality; Materials & resources Energy & atmosphere; Innovation/ Unlisted	(Bueno et al., 2015; Clevenger et al., 2013; Mattinzioli et al., 2020)
GreenRoads	USA	Cumulative total of credits awarded	Project requirements; Environment & water; Construction activities; Materials & design; Utilities & controls; Access & liveability; Creativity & effort; Life Cycle Assessment (LCA)	(Bueno et al., 2015; Clevenger et al., 2013; Mattinzioli et al., 2020)
I-LAST	USA	Sum of credit criteria	Planning, Design, Environmental water quality, Transportation, Lighting, Materials and Innovation	(Clevenger et al., 2013)
BE²ST-In-Highways™	USA	Quantitative assessment	Greenhouse Gas Emission (GGE), energy use, waste reduction (in-situ/ex-situ), water consumption, hazardous waste, traffic noise, social requirements, Life Cycle Cost (LCC) and social cost of carbon saving	(Bueno et al., 2015; Clevenger et al., 2013; Mattinzioli et al., 2020)
ENVISION	USA	Sum of credit criteria	Leadership; Quality of life; Resource allocation; Natural world; Climate change and risk and resilience, Life Cycle Cost (LCC)	(Bueno et al., 2015; Clevenger et al., 2013; Mattinzioli et al., 2020)

The rating system approach is not perfect and some weaknesses are acknowledged about it when dealing with the concept of sustainability. First, most SA approaches, like rating systems are often tailored to specific agencies to fit the local context (varying geographical) and needs (Liu et al., 2018). In addition, the differences within the weighting scheme make the use outside of the origin of the country problematic. Therefore, a "one size fits all" solution would not be applicable (Mattinzioli et al., 2020). Second, they have large differences in scopes (Doan et al., 2017). Third, they lack transparency in the definition of criteria and selection of weightings, which are not based on standardized methods of performance measurement (Lee et al., 2011). For example, the percentage weighing of the environmental sub-criteria differ greatly: Envision has the highest percentage of related sub-criteria (36%). While in the other systems: I-LAST, Greenroads and GreenLITES the following percentages of sub-criteria are included 22%, 10% and 6% respectively (except for BE²ST-In-Highways™, the percentage is determined by the project team). Fourth, despite that these approaches can be implemented at the planning, design and construction phases, European Union (EU) does not apply them to support the decision-making process. Finally, the most important weakness of rating systems is that most systems only cover the environmental dimension of sustainability and often neglect the economic and social dimensions, therefore, represents a huge limit for the rating systems (Berardi, 2012). To conclude, no rating system thoroughly assesses all three dimensions of sustainability (TBL). However, these systems still provide valuable information on how to assess transportation infrastructure. For this reason, the rating systems CEEQUAL, GreenLITES, BE2ST-In-Highways™, Envision and GreenRoads will be consulted to identify assessment criteria for sustainability. Consequently, this research will try to comprehensively integrate different criteria of transport rating systems from various countries into one framework.

2.3.1.4 Rijkswaterstaat Documents

It is worth noting that a MCA can be employed to integrate CBA and EIA results, as well as other types, within its framework, to support full integration and become more comprehensive and inclusive (Dimitriou et al., 2016). The documents of Rijkwaterstaat (RWS): *MIRT en m.e.r., verkenning en planuitwerking* and *Werkwijzer MKBA bij MIRT-verkenningen* provide information about the EIA and CBA used in the Dutch highway context. Each of these assessment methodologies examines design options under a different lens (environmental or economic).

First, the document *MIRT en m.e.r., verkenning en planuitwerking* is analysed in order to derive environmental criteria, used in the EIA to assess design choices and options from the environmental viewpoint. Then the document *Werkwijzer MKBA bij MIRT-verkenningen* is analysed to derive economic criteria, used in the CBA to assess design options from the economic viewpoint. The framework for the SA tool will integrate the criteria of these various approaches, which seem appropriate for evaluating the sustainability of highway design options. In this way, a number of SA criteria are considered in parallel focussing on the environmental and economic dimensions.

2.3.2 Conclusion on the Existing Assessment Frameworks

The review of existing assessment frameworks and rating systems presented above shows that, a large number of studies propose frameworks with SA criteria but fail to integrate them into a unified and more comprehensive framework. In addition, only a few studies have looked at highways, but not at identify relevant SA criteria specific for the planning and design phase of the Dutch highway context, which is exactly the gap this research aim to fill. This means that there is currently no MCA framework that ensures that sustainability is integrally included when making design choices and comparing design options in order to create sustainable added value in the Dutch highway development. The following section will identify the SA criteria and combine them into a single, more comprehensive framework that thoroughly addresses all dimensions of sustainability (TBL).

2.3.3 Identification of Sustainability Assessment Criteria

The aim of this subsection is to identify and develop a preliminary list of SA criteria based on recent literature considering sustainability in the construction industry and infrastructure sector. This is done by surveying the literature.

According to Lin et al. (2021) sustainability embodies a multidimensional concept (TBL), which must consider and integrate economic (Prosperity), social (People) and environmental (Planet) criteria. This line of reasoning is followed during the research. In general, assessment criteria (e.g. measures of performance) are criteria by which design choices and options are assessed during assessment and evaluation (Ward et al., 2016). In this research, SA criteria need to be identified, which are defined as the basic fundamentals or principles used to judge, compare and evaluate the sustainability (Bueno Cadena & Vassallo Magro, 2015). They can be grouped into different dimensions of sustainability (TBL), namely economic, social and environmental. It is important to note that SA criteria that in one way or another may influence sustainability over the life cycle of the highway should be integrated in de SA tool.

With the use of the 'qualitative content analysis' method, all criteria found in the literature were grouped based on the dimension they relate to, to develop an integrated set. After surveying and reviewing 19 studies, 5 transport rating systems and RWS documents for analysis, 64 SA criteria from the construction industry and infrastructure sector, These criteria will form the list of SA criteria found in literature identified for the three dimensions of sustainability (TBL), which are presented in the tables below, see Table 2.7, Table 2.8, Table 2.9 (full list of SA criteria with references are available in the appendix B.1):

Table 2.7 - Environmental (Planet) assessment criteria according to the literature

No.	Environment (Planet) Criteria	Total no. of sources
Env. 1	Energy consumption	17
Env. 2	Energy efficiency	9
Env. 3	Generation of renewable energy	5
Env. 4	Material balance with circular economy (CE)	9
Env. 5	Sustainable procured materials	6
Env. 6	Reusability	4
Env. 7	Non-renewable materials consumption	5
Env. 8	Life-Cycle Assessment (LCA)	2
Env. 9	Recycled materials	9
Env. 10	Design for disassembly	1
Env. 11	Surface and groundwater quality	17
Env. 12	Buffers for ecological land	6
Env. 13	Climate adaptation (flooding)	10
Env. 14	Stormwater runoff & drainage	6
Env. 15	Climate adaptation	8
Env. 16	Soil quality	12
Env. 17	Soil consumption	8
Env. 18	Biodiversity	14
Env. 19	Waste	10
Env. 20	Ecosystem functions	17
Env. 21	Protected natural areas	7
Env. 22	Streams, wetlands, waterbodies and their riparian areas	5

Table 2.8 - Social (People) assessment criteria according to the literature

No.	Social (People) Criteria	Total no. of sources
Soc. 1	Reliability	5
Soc. 2	Adaptability	5
Soc. 3	Robustness	7
Soc. 4	Agricultural land	7
Soc. 5	Development land	6
Soc. 6	Archeological & historic sites	7
Soc. 7	Landscape structures	12
Soc. 8	Brownfields	6
Soc. 9	Wayfinding	6
Soc. 10	Residential, recreational and working areas	6
Soc. 11	Aesthetics & degradation	2
Soc. 12	Spatial and visual quality	12
Soc. 13	Vulnerability from vandalism & sabotage	1
Soc. 14	Traffic safety	9
Soc. 15	Local character	7
Soc. 16	Emissions and air quality	20
Soc. 17	Noise pollution and vibration	17
Soc. 18	Light pollution	10
Soc. 19	Cultural heritage	12
Soc. 20	Stakeholder involvement & participation	8
Soc. 21	Connectivity between functions and communities	8
Soc. 22	Public support	4
Soc. 23	Traffic flow	7
Soc. 24	Economic efficiency	6
Soc. 25	Pedestrian & bicycling facilities	3
Soc. 26	Flexibility	3
Soc. 27	External safety	6

Soc.28	Nuisance during construction	4
Soc. 29	Construction safety	3
Soc. 30	Utility services	3

Table 2.9 - Economic (Prosperity) assessment criteria according to the literature

No.	Economic (Prosperity) Criteria	Total no. of sources
Econ. 1	Cost-effective design	1
Econ. 2	Innovation	6
Econ. 3	Infrastructure network	4
Econ. 4	Accessibility to employment	3
Econ. 5	Management and maintenance costs (LCC)	8
Econ. 6	Financial risks	4
Econ. 7	Construction costs	8
Econ. 8	Road operating costs	4
Econ. 9	Social cost-benefit analysis (SCBA)	3
Econ. 10	Residual value of structure	1
Econ. 11	Local economy	11
Econ. 12	Regional development	8

SA approaches such as: life cycle assessment (LCA), life cycle costs (LCC), social cost-benefit analysis (SCBA) and environmental impact assessment (EIA) have been presented in some studies as criterion. LCA, LCC, SCBA and EIA are as we have mentioned in 2.2.3 recognized methods which help to achieve sustainability over the entire life cycle. The outcomes of these approaches can be integrated as a criterion in the SA tool. The author already established in 2.2.6 that incorporating results from other tools and methods could be beneficial for effectively integrating and balancing all dimensions of sustainability (TBL). For a more comprehensive SA of highway design choices and options. For these reasons, this research does include them in the SA framework. The next subsection 2.3.4 summarizes the conclusions of this chapter.

2.3.4 Conclusion on the Preliminary List of Sustainability Assessment Criteria

The outcome of this chapter is the preliminary list of 64 SA criteria that were identified in the existing SA frameworks, rating systems and RWS documents reviewed. The list presented in appendix B.1, integrates SA criteria from the social, environmental and economic dimensions of sustainability (People, Planet, Prosperity).

The list is critical input for the development of the SA framework, because it provides the point of departure to investigate the SA criteria relevant for the Dutch highway context. In chapter 5, a filtering process will be performed on the list to eventually compile a final list (proposed SA framework) for validation during a questionnaire survey, the validation will result in the conceptual SA framework. The next chapter presents the methods used in this research (see chapter 3).

CHAPTER 3
RESEARCH METHODOLOGY

3 Research Methodology

This chapter presents the research methodology and approach that will be followed to meet the objectives of this research. This chapter is broken down into four sections. The first section introduces the different parts within the research (see 3.1). The second section explains the first part of the research (see 3.2). The third section explains the second part of the research(see 3.3). Finally, the last section explains the third part of the research (see 3.4). After that the company is introduced and background information on the highway design process is provided based on exploratory interviews held with experts within Antea Group (see chapter 4).

3.1 Introduction

This research is divided into three parts and follows a mixed approach of qualitative and quantitative research. The first part addresses the theoretical background on sustainability, sustainable development (SD) and the triple bottom line (TBL) to select a sound theoretical concept to be used in the research. This part also includes a review of existing sustainability assessment (SA) approaches as well as the identification of SA criteria in literature. The second part describes the methodological steps taken to develop the new SA framework and collect empirical evidence to adjust and validate the conceptual SA framework. The third part describes the methodological steps taken to develop the SA tool and test it on a reference case. Then, the proposed SA tool is evaluated by expert interview. Finally, the results from all these parts help to answer the main research question.

The research framework below, is a schematic and visualised representation of the steps presented in section 1.6 that need to be taken in order to achieve the research objective, with the strategy and approach mentioned. This research framework serves as a point of reference for the reader to understand the sequence of this research. The following sections provide in-depth explanations of the different parts mentioned earlier.

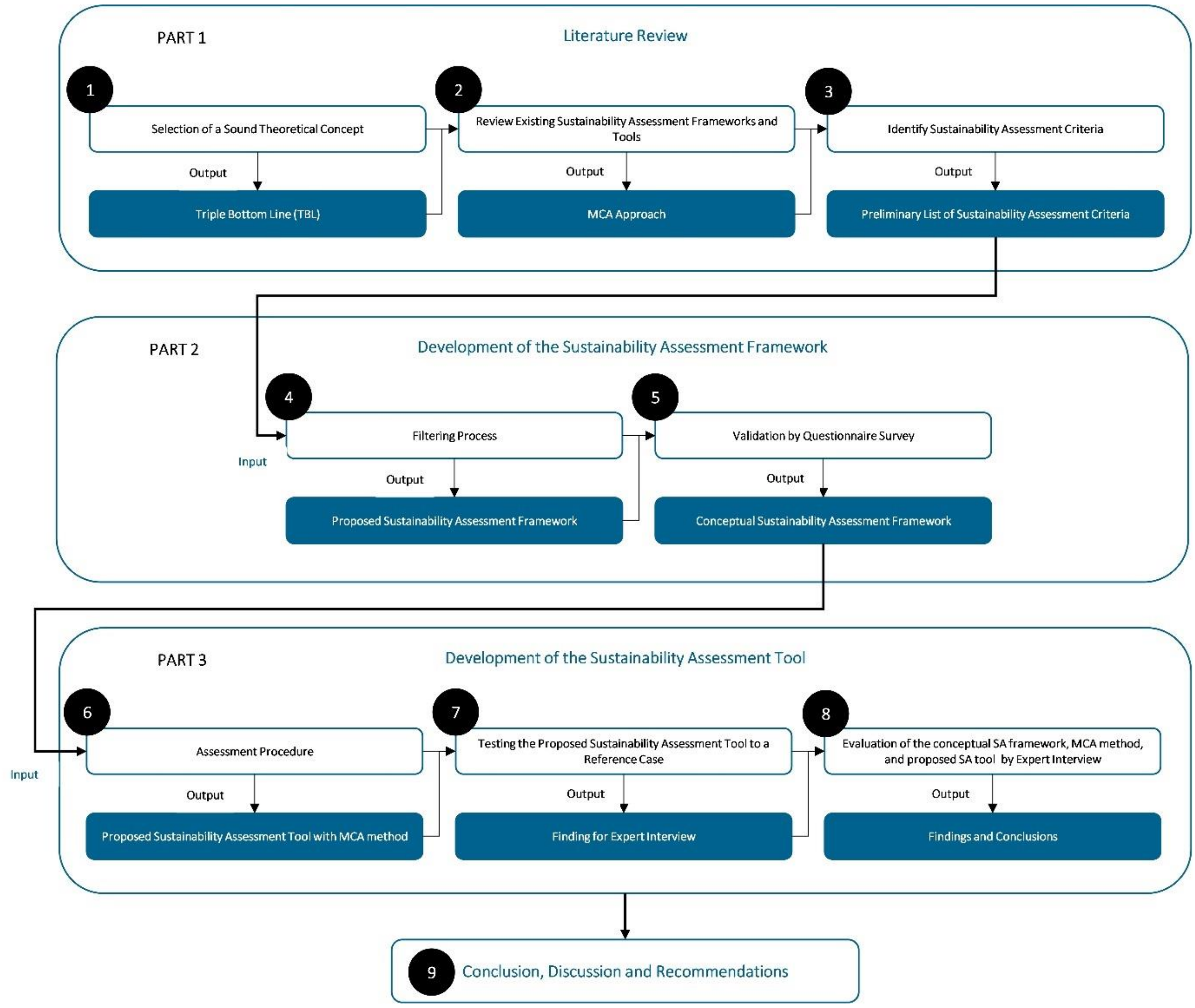


Figure 3.1 - Research Framework (own illustration)

3.2 Part 1: Form the Preliminary List of Sustainability Assessment Criteria from Literature

This section explains the methodological steps to form the preliminary list of SA criteria.

3.2.1 Literature Review

The research begins with an introduction which introduces the research topics, problem, gap and objective of the research. After that a thorough literature review followed. In-depth knowledge about sustainability, TBL, 3Ps, SA approaches and SA criteria up to now was acquired through scientific information found in scientific databases (including journals, articles, papers etc.) with the use of keywords, related to the topic of the research. To perform the search, the following keywords were used in combinations, see Table 3.1 (from 1994 to the present, because in 1994 the TBL framework of Elkington was introduced). These keywords were looked up in both single and plural forms. The author included papers that present SA criteria from other infrastructure projects such as railways, waterways, etc. in the selection.

Table 3.1 - Synonyms and replacement words for the search of keywords

Sustainability	Sustainability assessment (SA)	Highway infrastructure projects
Sustainable	Assessment tool	Transport infrastructure
Sustainable development (SD)	Assessment method	Road
Sustainable construction (SC)	Assessment framework	Freeway
Triple bottom line (TBL)	Sustainability appraisal	Motorway
People, planet, profit (PPP)	Sustainability impact assessment	Construction industry (CI)
	Sustainability evaluation	Construction project
	Sustainability rating tool	Transport project
	Decision support tool (DST)	
	Ex-ante/Ex-post evaluation	

These keywords were used in the following search engines: Scopus, ScienceDirect, ResearchGate, Web of Science and Google Scholar. Scopus, Web of Science and Google Scholar cover most scientific fields (Falagas et al., 2008). The focus was on using Scopus as a starting point, because Falagas et al. (2008) who studied the differences between PubMed, Scopus, Web of Science and Google Scholar concluded that *"Scopus is the database that indexes a larger number of journals than the other three databases studied"*. In addition, literature can be searched based on: abstracts, authors, citations in the advanced search option to get more valid results (TITLE-ABS-KEY) and a citation analysis can be performed. For these reasons, Scopus is the best available research tool with the largest database for searching electronic literature (journals-, research articles, reports, manuals, guidelines and books) that are published after 1995. Within these found sources, references and citations to other work were also reviewed when relevant. The papers found during the literature search were reviewed for their content and significance to the research objectives. The output of this part is the selection of a sound theoretical concept to be used in this research, a review of existing SA approaches and frameworks and a integrative list of preliminary SA criteria for all three dimensions of sustainability.

3.2.2 Exploratory Interviews

For gathering background information, in-depth information and starting a dialog with experts a suitable qualitative interview type can be used. There is a variety of ways qualitative interviews can be categorized. The most well-known categorization is: unstructured, semi-structured and structured (DiCicco-Bloom & Crabtree, 2006). Semi-structured interviews are the most suitable for this research, because semi-structured (in-depth) interviews are generally organized around a set of predetermined open-ended questions, with other questions emerging from the dialogue between interviewer and interviewees. According to DiCicco-Bloom & Crabtree (2006), the semi-structured interview format is the most widely used for qualitative research and in-depth interviews and can occur either with an individual or in groups. Structured interviews are useful when complete knowledge of the subject is available and data that is to be gathered is specifically determined. Unstructured interviews on the other hand are of an open-ended form, due to the absence of predetermined questions. This form is based on the interaction of the interviewer and interviewee to guide the interview. Both the unstructured and structured interview forms do not apply to this research, because this research is in the form of exploratory research, where information is searched based on in-depth questions around a certain subject.

In the following chapter, exploratory interviews are going to be conducted with experts within the Antea Group to gather background information on the design processes that Antea Group follows to help set the scope of this research. Exploratory interviews in the form of semi-structured interviews can be seen as preliminary research consisting of interviews with several experts involved in the field (Verschuren & Doorewaard, 2010). For this research, semi-structured interviews seemed suitable for the purpose of exploring the role of the engineering consultancy firm Antea Group in developing sustainable and integrated solutions, the highway design process they follow in the Netherlands, the tools and methods they use in practice and to find out how and where the intended SA framework and tool can be applied in practice.

The interviews are going to be recorded with the permission of the participants. A brief summary of the research and objective is going to be sent out prior to all of the interviews. Because of the implications of COVID-19 that occur during this research, face to face communication is not an option. Therefore, the author is going to use the business communication platform Microsoft Teams to conduct the interviews. This method of communication seems appropriate considering the situation.

3.3 Part 2: Develop and Validate the Sustainability Assessment Framework

This section explains the methodological steps to develop and validate the SA framework.

3.3.1 Filtering Process

After literature review and conducting of exploratory interviews, a filtering process will be performed on the preliminary list of SA criteria resulted from the literature review. The number of SA criteria used depends on the nature of the project being evaluated, in this case highway projects, as well as the evaluation purpose. It is critical to choose not only relevant SA criteria, but also to avoid using SA criteria that could lead to duplication. Currently there are many filtering criteria for SA criteria selection, on the basis of findings from the previous studies, four filtering criteria (approaches to reduce the number of SA criteria in the proposed SA framework) are presented below:

- *Overlapping:* merge (combine) SA criteria that are overlapping or covered by other criteria to avoid duplication, for instance on similarity and correlation between SA criteria;
- *Specific to other sectors:* SA criteria that are specific to other types of construction projects, for instance, railways will be excluded;
- *Frequency of appearance in literature:* SA criteria that are mentioned less than 5 times (<25% of the reviewed studies) will be excluded;
- *Present in transport rating systems:* SA criteria that appear in existing transport rating systems will be included. In subsection 2.3.1.3, a list of the most important transport rating systems was provided.

3.3.2 Questionnaire Survey

After the filtering process, a questionnaire survey will be conducted, because it is capable of gathering data that answers research questions and adheres to specific data types (Liu et al., 2021). A series of closed-ended and open questions are going to be asked to the respondents to reflect on and be able to give feedback. The purpose of the survey is to establish whether the SA criteria that form the proposed SA framework are relevant for the Dutch highway context. For this survey, experts with experience with sustainability and road design will be contacted via email to fill in the questionnaire on Microsoft Forms. The questionnaire is designed to assess their agreement with the SA criteria in the planning- and design phase of highway development in the Dutch context. To collect empirical evidence and opinions from different experts in the field to determine and establish which SA criteria are relevant for the specific context and should therefore be included in the conceptual SA framework. The experts also have the opportunity to suggest criteria that should be included as well. The output of this part is the development of the new conceptual SA framework.

3.3.2.1 Data Collection and Procedure

In the email a short summary of the purpose of the research is sent along with the link to the questionnaire. The questionnaire consists of a series of questions to collect information and data from experts within Antea Group. All respondents will receive the same list of SA criteria. This questionnaire is designed via Microsoft-Forms on Antea Groups SharePoint. The expert is asked whether they want to complete the list in their own time or to discuss it together, so that they can indicate their own preference. The potential experts are selected based on two reasons. Firstly, the expert are qualified and experienced professionals with rich expertise in developing construction projects within Antea Group. Second, they have a multidisciplinary background, such as sustainability, road design, energy transition, project management, etc.

The experts may complete the questionnaire within one weeks. For those who do not respond within the time limit, the links will be emailed again to remind them to complete the questionnaire. For those who completed a questionnaire with errors or missing data, further explanation will be provided and the respondent will be asked to revise or complete their answers.

3.4 Part 3: Developing the Sustainability Assessment Tool

This section explains the methodological steps to develop and evaluate the new SA tool, the application of the proposed SA tool to a reference case and the evaluation with a decision-making expert in the field of road design. This will be done to test the findings from the literature review and examine the applicability of the proposed SA tool. Clearly, the development of such a SA tool will be an iterative process requiring numerous rounds between development and testing. However, due to the scope of this research and time constraints, the applicability of the proposed SA tool will be investigated only once and the findings from applying it to the reference case and evaluating it with an expert will be used to assess the applicability and usability of the proposed SA tool.

3.4.1 Design Option Analysis

This SA tool aims to provide the project team of Antea Group with a tool to carry out a design option (alternatives & variants) analysis from the sustainability viewpoint. A design option analysis is a method for making careful design choices and ensuring that they are traceable and transparent for everyone in the future, as to which options were considered and why certain choices were made during the design process. For this analysis, a trade-off matrix (TOM) is utilized. A TOM consists of a table (matrix) in which design options are compared to each other to be able to make a carefully considered choice. The SA tool uses a combination of SA criteria to provide an overall picture of how the design options contribute to sustainability. The design option analysis as described in this method is a form of multi-criteria analysis (MCA). In this research, it means that design options are weighed against each other using different themes and SA criteria. In this SA tool, an MCA method is used to determine the weighting factors of the themes.

3.4.1.1 MCA Method

There are several MCA methods developed to acquire the weighting factors of the themes, such as the Analytic Hierarchy Process (AHP) (Saaty, 1977), Analytic Network Process (ANP) (Saaty, 2005) and best-worst method (BWM) (Rezaei, 2015, 2016) to name a few. The selection of most suitable MCA method will be based on the number of themes, SA criteria and the advantages and disadvantages of the different MCA methods. The reasoning and selection of the most suitable MCA method will take place during the development of the SA tool.

3.4.2 Evaluation of the Proposed SA Tool

After realizing the conceptual SA framework, the assessment procedure with the selected MCA method is incorporated to form the proposed SA tool. The proposed SA tool will need to be evaluated on the applicability and usability. This is done with the use of a reference case including an expert interview. Due to time constraints, the proposed SA tool will only be used once on a highway project to test its applicability and usability. Selection of a suitable reference case is based on the following requirements:

- The highway project needs to be in the design phase to ensure that the project adheres to the scope of this research; and
- The author should have access to project information of the reference case and access to an expert involved in the reference case who is familiar with the content and research topics.

CHAPTER 4
COMPANY REVIEW AND DESIGN PROCESS

4 Company Review and Design Process

This chapter provides background information based on exploratory interviews held with experts within Antea Group. These interviews were held for setting the scope of the research and to gather information about the design processes that Antea Group follows. This chapter is broken down into two sections. The first section explains the exploratory interviews (see 4.1). The second section presents the findings of the interviews (see 4.2). The exploratory interview questions and answers can be found in appendix A.1 and A.2.

4.1 Exploratory Interviews

Exploratory interviews in the form of semi-structured interviews can be seen as preliminary research consisting of interviews with several experts involved in the field (Verschuren & Doorewaard, 2010), in this case road infrastructure and sustainability. For this research, semi-structured interviews seemed suitable for the purpose of exploring the role of the engineering consultancy firm Antea Group in developing sustainable and integrated solutions, the highway design process they follow in the Netherlands, the tools and methods they use in practice and to find out how and where the intended SA tool can be applied in practice. Information was gathered through interviews with 4 experts with different expertise's. The interviews were recorded with the permission of the participants. A brief summary of the research and objective was sent out prior to all of the interviews.

Because of the implications of COVID-19 that occurred during the time of the interviews, face to face communication was not an option. Therefore, the author used the business communication platform Microsoft Teams to conduct the interviews. This method of communication seemed appropriate considering the situation. The interviews lasted about 60 minutes and were conducted in accordance with the interview protocol (see appendix A.1), which served as a guide (question list) for the interview. During the interview, discussion was not limited to these questions, instead, depending on the responses, questions from the protocol were followed by in-depth questions to encourage participants to share more information that would help in gaining a better understanding of the topics.

The potential experts for these interviews were selected based on the purpose of this research and their knowledge and experience in the research field of sustainability and road infrastructure design. The experts were contacted through email communication. To maintain confidentiality among the participants, the experts' identities are coded into numbers. Quotes from the interviewees that are given in this research will be referred to the interviewee numbers which are shown below (see Table 4.1).

Table 4.1 - Exploratory Interview Participants

Interviewee	Function	Department
Interviewee 1	Project manager	Infrastructure (roads)
Interviewee 2	Advisor for sustainability and circularity	Infrastructure (roads)
Interviewee 3	Cost expert and value engineer	Infrastructure (roads)
Interviewee 4	Coordinator preparation	Infrastructure (roads)

4.2 Exploratory Interviews Findings

This section presents the findings of the exploratory interviews. The findings are presented and structured based on the discussed topics. First, the company profile of Antea Group is presented. After that, the role of Antea Group in the design process is presented. The information presented below is either based on answers given by the experts, referral to the appropriate documentation inside the company or information found in Rijksoverheid and Rijkswaterstaat reports and publications.

4.2.1 Company Profile of Engineering Consultancy Firm Antea Group

This research is conducted in cooperation with Antea Group, which will provide empirical information, knowledge and evidence to be used and consulted in this research. Antea Group offers broad support in products, projects and services for Rijkswaterstaat, provinces, municipalities, contractors and privates parties. For this research it is important to know that Antea Group assists and advises clients in making well-informed choices and considerations within projects, based on information, experience and expert knowledge.

In (sustainability) transition issues, they connect chain partners and work towards integrated and sustainable solutions. Antea Group advises their clients at strategic level to put sustainable development on the agenda (Antea Group, 2021a). The mission of Antea Group is as followed:

"Antea Group is a leading partner in the development and application of sustainable and integrated solutions in our living environment. Sustainability is never the end point, but a continuous process with a positive impact on the living environment as the starting point. That starts with the motivations within our organisation, because sustainability comes from within and thus works through the chain. We believe in sustainable and innovative services on the one hand and socially responsible business operations on the other" (Antea Group, 2021a).

Antea Group has embedded in its mission statement that it wants to be a leading partner in developing sustainable and integrated solutions for our living environment. Of course Antea Group also takes responsibility for making its own business operations more sustainable. Finally, Antea Group wants to be an employer where people are proud and happy to help their clients and partners to realize the next step in sustainability. It is about total sustainability, i.e. continuous improvement in strengthening the balance between the environment, economy and social aspects.

Antea Group, focusses their efforts on seven SDGs, which are closest to them. This focus, a step-by-step and targeted approach, makes them more powerful and be able to create more impact. In their approach to contributing to the SDGs, they focus on their internal organization as well as on their projects, products and services. The seven SDGs Antea Group focusses on are (Antea Group, 2021a) are shown in Figure 4.1.

Figure 4.1 - SDGs Antea Group focusses on in their products and services (Antea Group, 2021b)

In addition, Antea Group offers customers 'green offers' with which they want to further develop awareness and sustainability. In this way, Antea Group stimulates and facilitates sustainability in the chain through green offers, offering sustainable solutions, alternatives or working methods (Antea Group, 2021a).

4.2.2 Highway Design Process in the Netherlands

In the Netherlands, the design of road and highway infrastructure is obliged to comply with some requirements and standards. The following guidelines apply to the Netherlands: the *MIRT-procedure* and *Kader wegontwerp 2.0.* These guidelines are considered as recommendations for any road infrastructure project under the authority the Ministry of Infrastructure and Water Management.

4.2.2.1 MIRT-process

In the Netherland, the Dutch government works together with other agencies on safety, accessibility and quality of life in the Netherlands. They do so by investing in better roads, rail connections and waterways, these investments are included in the *Meerjarenprogramma Infrastructuur, Ruimte en Transport (MIRT)*, the program that supports the major infrastructure projects of the *Ministerie van Infrastructuur en Waterstaat (IenW)*. All major infrastructure projects are found in the MIRT. Provinces work in a similar way with N-roads, but different method.

The *Tracéwet* applies to the realization of new highways or the adaptation of existing highways. The *Tracéwet* regulates which spatial procedures must be followed when adapting or expanding main roads.

In a *MIRT-process*, the involved parties work phase by phase to substantiate the tasking in increasingly concrete terms. Every MIRT phase ends with a political -administrative decision on the subsequent phase:

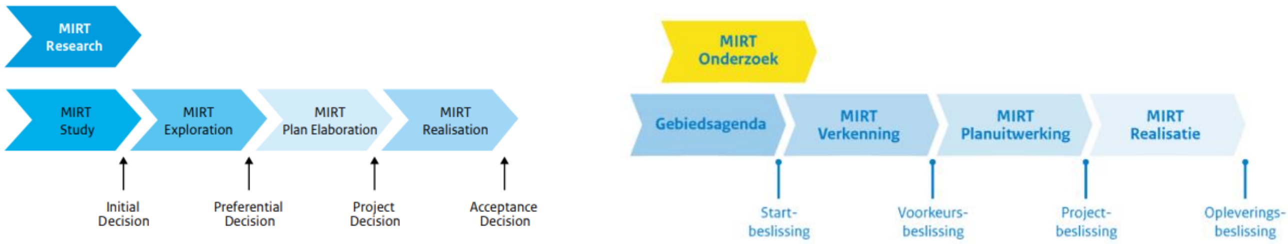


Figure 4.2 - MIRT-process (Rijkswaterstaat, 2016)

For major roads, the extensive MIRT-procedure with sectoral structural vision is followed. The regular procedure has three decision moments, namely the Initial Decision (*Startbeslissing)*, the *ontwerp-Tracébesluit ((O)TB)* and the *Tracébesluit (TB)*. In addition to the extensive procedure, a formal decision moment about the preferred alternative (*voorkeursalternatief (VKA)*) with a structural vision is added, as the conclusion of the MIRT-Exploration (*MIRT-Verkenning*). This is a step-by-step procedure. This means that a (design) structural vision is first made in which the preferred solution is included. This environmental impact assessment (EIA) (*milieueffectenrapportage (MER)*) provides the environmental information when choosing a preferred solution (*voorkeursoplossing*). After the (design) structural vision ((D)SV) (*(ontwerp-)structuurvisie ((O)SV)*), in the following MIRT-Plan Elaboration (*MIRT-Planuitwerking*) phase, the preferred solution is worked out in detail and ultimately laid down in a *ontwerp-Tracébesluit ((O)TB)*.

The *MIRT-process* explained, according to (Rijkswaterstaat, 2018):

- *MIRT-Study:* may result in a task for a MIRT-Exploration based on a *Startbeslissing*. With the *Startbeslissing* in the MIRT, taken by the Minister of Infrastructure and the Environment and the relevant administrators, the MIRT-Exploration phase begins;

- *MIRT-Exploration:* The aim of the MIRT-Exploration is to arrive at a smart, sustainable and climate-proof solution by examining a task broadly, concretising the objective and problem analysis and making an insightful assessment. In this phase, linkage opportunities (*meekoppelkansen*), measures (*maatregelen*), area information etc. need to be integrally included. The cost-benefit analysis (CBA) and plan-EIA are mandatory in the MIRT-Exploration to provide the necessary decision information with regards to the environmental consequences and cost of measures. This decision information is determined on the basis of the alternatives, the plan and study area (*plan- en studiegebied*), the assessment method and the assessment framework (mapping out the impact and cost of solutions based on criteria). This information helps substantiating the Preferential Decision (*Voorkeursbeslissing*): a well-substantiated choice for the best solution, the legal procedure and the financing method. After decision-making, the preferred alternative (*voorkeursalternatief (VKA)*) is laid down in the Preferential Decision and then further elaborated in the MIRT-Plan Elaboration phase in order to prepare the realization. The MIRT-Exploration ends with a political-administratively supported Preferential Decision.

- *MIRT-Plan Elaboration:* follows the (adaptive) preference decision from the MIRT-Exploration phase. In the MIRT-Plan Elaboration phase further elaboration of the preferred alternative will take place. Despite the fact that one preferred alternative has been chosen, several technical variants are possible. In addition, the parties substantiate the design in sufficiently concrete terms to be able to tender the project. The MIRT-Plan Elaboration is completed with a Project Decision (*Projectbeslissing*) in the form of a *Tracébesluit (TB)*. The Project Decision paves the way for its realisation;

- *MIRT-Realisation:* leads to an Acceptance Decision (*Opleveringsbeslissing*). To this end, the *Tracébesluit (TB)* that has been laid down in a Project Decision is worked out into a VO, DO and UO to carry out the work on that basis. The *Tracébesluit (TB)* is the decision arising from the Infrastructure (Planning Procedures) Act. In the procedure under the *Tracéwet*, the products that are delivered in the MIRT-Plan Elaboration phase are the *ontwerp-Tracébesluit ((O)TB)* and the EIA. The EIA is then an annex to the *ontwerp-Tracébesluit ((O)TB*. The Minister of Infrastructure and Water Management determines the *ontwerp-Tracébesluit ((O)TB* and *Tracébesluit (TB)*.

4.2.2.2 Road Design Process in the Netherlands

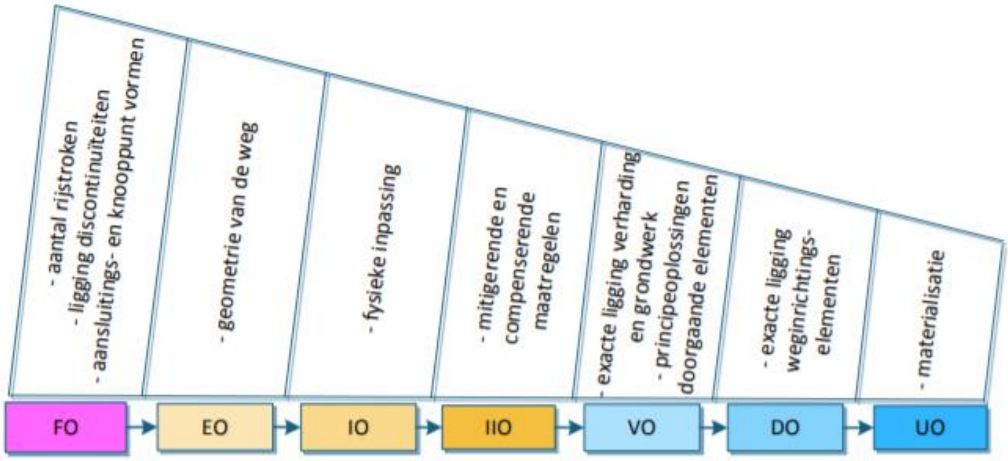


Figure 4.3 - Road design process (Rijkswaterstaat Ministery van Infrastructuur en Waterstaat, 2019)

In the road design process, choices are made in the steps from Functional Design (*Functioneel Ontwerp (FO)*) to Implementation Design (*Uitvoeringsontwerp (UO)*). All considerations and choices are recorded and made transparent in the design note (*ontwerpnota*). For each choice, it is described which consideration has been made and on the basis of what the choice was made. The following design stages in the road design process are explained (Rijkswaterstaat Ministery van Infrastructuur en Waterstaat, 2019):

- *The Functional Design (FO):* concerns longitudinal lane schemes, with metering of discontinuities. The FO is the input for traffic research (*verkeersonderzoek (NRM)*), with all traffic engineering, road safety considerations and choices recorded in the design memorandum. The FO is the basis for traffic engineering effect studies (I/C values, delay factors, travel times, etc.);

- *The Elementary Design (EO):* the geometric design is made to see what the impact of a geometric guideline-compliant road is on the environment;

- *The Fitting Design (Inpassend Ontwerp (IO)):* is a technically feasible and adaptable design that is input for impact studies. This design serves to demonstrate that the road is technically compatible and feasible. The choices about physical integration are weighed up using matrices and recorded in a bottleneck analysis (*knelpuntenanalyse*) and can influence the choices made in the FO and EO;

- *The Integral Integrating Design (Integraal Inpassend Ontwerp (IIO)):* in this the design is further elaborated into an integral design. The result is a working traffic system that is not only spatially but also legally and environmentally integrated into the environment. Choices are weighed up using matrices and recorded in a measure analysis;

- *The Preliminary Design (Voorlopig Ontwerp (VO)):* the main geometry is determined for the detailing of the road design. The result is a design in which design principles are laid down that form the basis for further detailed elaboration. Choices are made by means of matrices;

- *The Final Design (Definitief Ontwerp (DO)):* all partial designs are worked out integrally. Before and after elaboration of the partial designs, an interface analysis is performed on the interfaces between all road design elements. The result is a design in which details are laid down that form the basis for further materialization. Choices are made by means of matrices;

- *The Implementation Design (Uitvoeringsontwerp (UO)):* the DO is translated into materialization. Materialization of the DO means that for each design element it is indicated from which materials (and therefore with which physical properties) the design element will be executed outside. All details resulting from the materialization have been worked out in partial designs by the UO. The result is a design that can be implemented.

4.2.2.3 The Road Design Process in the Different MIRT Phases

The starting point is an extensive *Tracéwetprocedure* (Rijkswaterstaat Ministery van Infrastructuur en Waterstaat, 2019):

- *MIRT-Study:* in this phase, policy is funneled to a number of solution (alternatives) that are included in the Initial Decision. There is no formal road design process and/or test process involved;

- *MIRT-Exploration:* in the 1st sieve (*eerste zeef*) Exploration, the infrastructural alternatives that can reasonably be considered from the MIRT-Study are elaborated in more detail. A FO is worked out for each alternative. In the 2nd sieve (*tweede zeef*) Exploration, we are working towards a VKA. EOs and IOs are drawn up for this purpose. EOs are an important tool for recording explicit choices with regard to integration. In this phase, the drafting of EOs is explicitly taken together with the drafting of IOs in order to set up an IO that is aligned with the environment in one phase. After all, an IO cannot be set up without bottleneck analysis on an EO. After the bottleneck analysis has been completed, the IOs are drawn up for the promising solutions. These IOs show the spatial feasibility of the solutions. The IOs are then input for the assessment of effects (plan-EIA and SCBA) and overall assessment. These products ultimately lead to the establishment of a VKA.

- *MIRT-Plan Elaboration:* In the preparatory part of the MIRT-Plan Elaboration, the FO and the IO from the Exploration are updated or re-developed. The Plan Elaboration leads to a TB. To this end, the updated IO is elaborated into an IIO for a OTB and then into an IIO for a TB;

- *MIRT-Realisation:* The realization leads to an Acceptance Decision (*Opleveringsbeslissing*). To this end, the TB that is laid down in a Project Decision is worked out into a VO, DO and UO to carry out the work on that basis.

4.2.2.4 Highway Design Options

In practice, misunderstanding sometimes arises between the terms design alternative and design variant. This research focusses on both, but to clarify, the terms are explained below (Rijkswaterstaat, 2019b):

- *Alternatives:* are the main choices. MIRT projects mainly concern route and location choices. These will be investigated in the MIRT-Exploration, for example in a plan-EIA;

- *Variants:* are further elaborations of parts within alternatives. These are often more technical aspects, small differences in exact positioning or, for example, choices between possible mitigating measures.

Figure 4.4 shows the highway design process in the Netherlands and the focus of the research indicated in red:

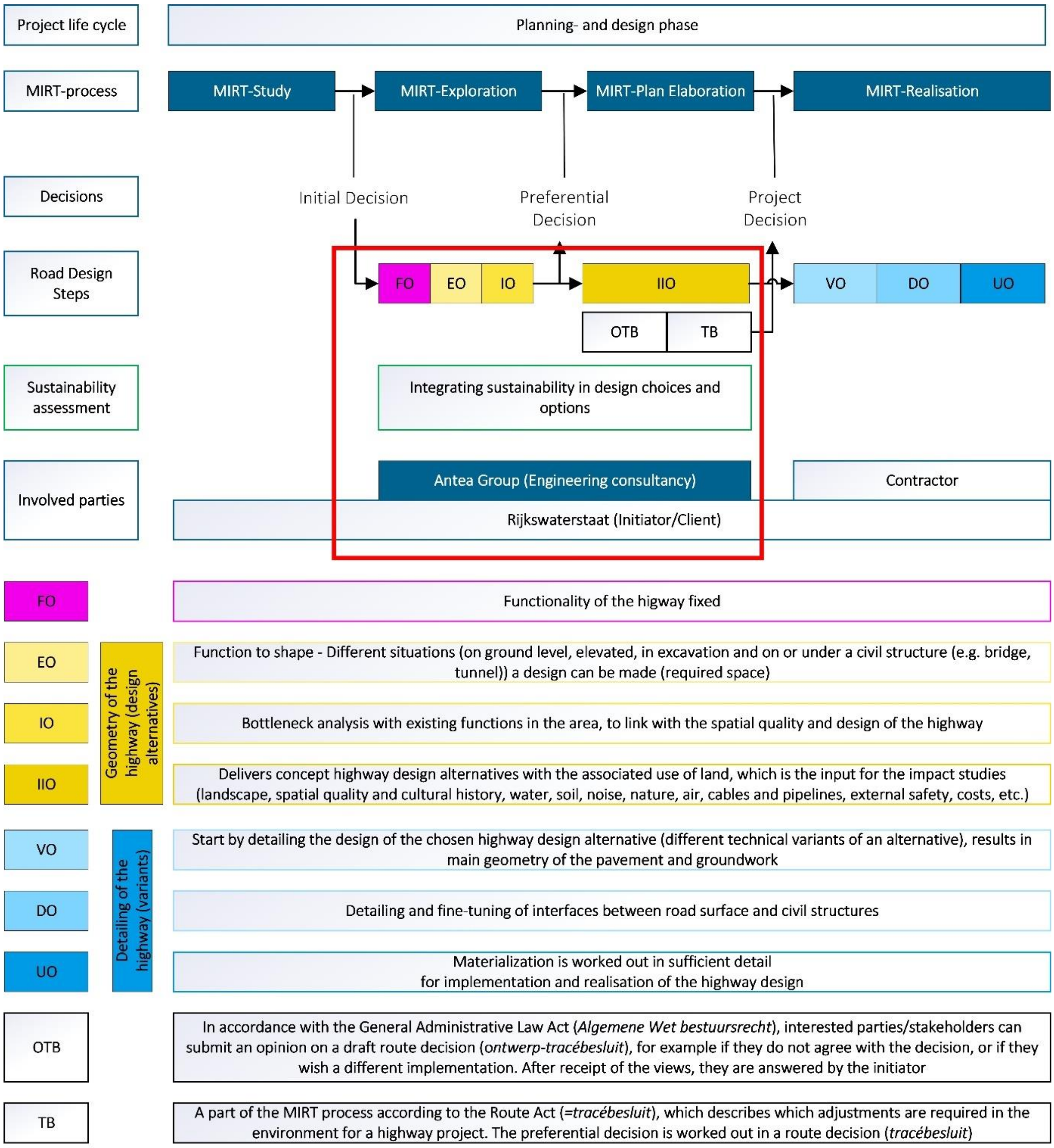


Figure 4.4 - Highway design process (focus of the research indicated in red) (adapted from (Rijkswaterstaat Ministery van Infrastructuur en Waterstaat, 2019))

4.2.3 Integral Project Team

Within this design process Antea Group uses Integrated Project Management (IPM) roles, the roles together form the integral project team:

- Project Manager (PM);
- Project Controller (PC);
- Technical Manager (TM);
- Project Environment Manager (PEM);
- Contract Manager (CM).

Antea Group's integral project team is led by the PM. The other IPM roles are his responsibility. TM is the central role within IPM and is the only role that interacts directly with all other role holders. In the next chapter the development of the SA framework is elaborated.

CHAPTER 5
DEVELOPENT OF THE SUSTAINABILITY ASSESSMENT FRAMEWORK

5 Development of the Sustainability Assessment Framework

In this chapter, the development of the SA framework takes place. This chapter is broken down into three sections. The first section explains the filtering process applied to the preliminary list of SA criteria from subsection 2.3.2 to form the proposed SA framework (see 5.1). The second section show how a questionnaire survey with experts from Antea Group was used to validate the proposed SA framework (see 5.2). The last section addresses the findings of the questionnaire survey and presents the conceptual SA framework (see 5.3). After that a suitable MCA method will be proposed to determine the importance of the themes for a specific project (see chapter 6).

5.1 Sustainability Themes and Assessment Criteria

The intended result of this section, is to propose a framework consisting of a list of SA criteria to evaluate and compare environmental, economic and social sustainability in design choices and between design options.

5.1.1 Filtering Process

For establishing the proposed SA framework it is critical to choose not only relevant SA criteria for the specific context, but also to avoid using SA criteria that could lead to duplication. As mentioned in subsection 3.3.1, the filtering process of SA criteria is carried out based on four filtering criteria (approaches to reduce the number of SA criteria in the final list) which are: overlapping, specific to other sectors, frequency of appearance in literature and present in transport rating systems. During the filtering process, the SA criteria to be included in the proposed SA framework will be indicated in green, merged will be in orange and excluded will be in red. Some examples of the filtering process are given below.

Include

"Surface and groundwater quality (Env. 11)" is included in the proposed SA framework, because the SA criteria appears in almost all of the existing frameworks, it is used in rating systems and therefore placed in the theme "Water & Climate".

Merge

"Soil consumption (Env. 17)" is mentioned eight times in literature and present in the rating systems, however, it is part of and covered by the SA criterion *"Material balance with circular economy (CE) (Env. 4)"* and therefore merged (→ Env. 4) in the proposed SA framework.

Exclude

"Vulnerability from vandalism & sabotage (Soc. 13)" is only mentioned once in the literature and not present in the analysed rating systems and therefore excluded for the proposed SA framework.

A total of 64 SA criteria identified found in the literature, were reduced to 34 SA criteria and grouped into the corresponding sustainability dimensions (economic, environmental and social) and themes (proposed heterogeneous themes based on literature and rating systems for evaluating sustainability) (see Table 5.1, Table 5.2, Table 5.3). There are 9 SA criteria dealing with economic sustainability, 18 with social sustainability and 7 with environmental sustainability. The 34 SA criteria that are the result of the filtering process are going to be presented to experts within Antea Group with the use of a questionnaire survey.

Table 5.1 - Determination of criteria to include in the SA framework (environment - Planet)

No.	Environmental (Planet) criteria	Total ref.	Used in rating system	Merge	Theme
Env. 1	Energy consumption	17	Yes	Include	Energy
Env. 2	Energy efficiency	9	Yes	→ Env. 1	
Env. 3	Generation of renewable energy	5	Yes	Include	Energy
Env. 4	Material balance with circular economy (CE)	8	Yes	Include	Materials
Env. 5	Sustainable procured materials	6		→ Env. 4	
Env. 6	Reusability	4		→ Env. 4	
Env. 7	Non-renewable materials consumption	5	Yes	→ Env. 4	
Env. 8	Life-Cycle Assessment (LCA)	2	Yes	→ Env. 4	
Env. 9	Recycled materials	9	Yes	→ Env. 4	
Env. 10	Design for disassembly	1		→ Env. 4	
Env. 11	Surface and groundwater quality	17	Yes	Include	Water & Climate
Env. 12	Buffers for ecological land	6	Yes	→ Env. 20	
Env. 13	Climate adaptation (flooding)	10	Yes	Include	Water & Climate
Env. 14	Stormwater runoff & drainage	5	Yes	→ Env. 13	
Env. 15	Climate adaptation (drought and heat stress)	8	Yes	Include	Water & Climate
Env. 16	Soil quality	12	Yes	Include	Ecology & Nature
Env. 17	Soil consumption	8	Yes	→ Env. 4	
Env. 18	Biodiversity	14	Yes	→ Env. 20	
Env. 19	Waste	10	Yes	→ Env. 4	
Env. 20	Ecosystem functions	17	Yes	Include	Ecology & Nature
Env. 21	Protected natural areas	7	Yes	Include	Ecology & Nature
Env. 22	Streams, wetlands, waterbodies and their riparian areas	5	Yes	→ Env. 20	

Table 5.2 - Determination of criteria to include in the SA framework (social - People)

No.	Social (People) criteria	Total ref.	Used in rating system	Merge	Theme
Soc. 1	Reliability	1	Yes	Include	Mobility & Accessibility
Soc. 2	Adaptability	4	Yes	Include	Mobility & Accessibility
Soc. 3	Robustness	4	Yes	Include	Mobility & Accessibility
Soc. 4	Agricultural land	5	Yes	→ Soc. 7	
Soc. 5	Development land	5	Yes	→ Soc. 7	
Soc. 6	Archeological & historic sites	5	Yes	→ Soc.19	
Soc. 7	Landscape structures	6	Yes	Include	Culture & Landscape
Soc. 8	Brownfields	5	Yes	→ Soc. 7	
Soc. 9	Wayfinding	4	Yes	Exclude	
Soc. 10	Residential, recreational and working areas	4	Yes	Include	Culture & Landscape
Soc. 11	Aesthetics & degradation	1		→ Soc. 12	
Soc. 12	Spatial and visual quality	7	Yes	Include	Health & Well-being
Soc. 13	Vulnerability from vandalism & sabotage	1		Exclude	

Soc. 14	Traffic safety	6	Yes	Include	Health & Well-being
Soc. 15	Local character	5	Yes	→ Soc. 7	
Soc. 16	Emissions and air quality	15	Yes	Include	Health & Well-being
Soc. 17	Noise pollution and vibration	12	Yes	Include	Health & Well-being
Soc. 18	Light pollution	6	Yes	Include	Health & Well-being
Soc. 19	Cultural heritage	9	Yes	Include	Culture & Landscape
Soc. 20	Stakeholder involvement & participation	7	Yes	→ Soc. 22	
Soc. 21	Connectivity between functions and communities	8	Yes	Include	Culture & Landscape
Soc. 22	Public support	3	Yes	Include	Health & Well-being
Soc. 23	Traffic flow	4	Yes	Include	Mobility & Accessibility
Soc. 24	Economic efficiency	5	Yes	→ Soc. 23	
Soc. 25	Pedestrian & bicycling facilities	2	Yes	→ Soc. 21	
Soc. 26	Flexibility	2	Yes	→ Soc. 2	
Soc. 27	External safety	3	Yes	Include	Health & Well-being
Soc. 28	Nuisance during construction	2	Yes	Include	Health & Well-being
Soc. 29	Construction safety	1	Yes	Include	Health & Well-being
Soc. 30	Utility services	1	Yes	Include	Culture & Landscape

Table 5.3 - Determination of criteria to include in the SA framework (economic - Prosperity)

No.	Economic (Prosperity) Criteria	Total ref.	Used in rating system	Merge	Theme
Econ. 1	Cost-effective design	1		→ Econ. 5	
Econ. 2	Innovation	4	Yes	Include	Economic development
Econ. 3	Infrastructure network	3	Yes	→ Econ. 11	
Econ. 4	Accessibility to employment	2	Yes	→ Econ. 11	
Econ. 5	Management and maintenance costs (LCC)	6	Yes	Include	Costs & Investments
Econ. 6	Construction costs	5	Yes	Include	Costs & Investments
Econ. 7	Financial risks	1	Yes	Include	Costs & Investments
Econ. 8	Road operating costs	4		→ Econ. 7	
Econ. 9	Social cost-benefit analysis (SCBA)	1	Yes	Include	Costs & Investments
Econ. 10	Residual value of structure	1		→ Econ. 5	
Econ. 11	Local economy	8	Yes	Include	Economic development
Econ. 12	Regional development	5	Yes	Include	Economic development

5.1.2 Sustainability Themes

Criteria are often grouped, usually on substantive grounds, in this case in themes. For each theme, it is possible to look at how a design choice or option can contribute to the sustainability objectives of RWS, like: sustainable area development, circular economy (CE), energy, etc. (described in 1.1.3). In this research, we look at sustainability from the perspective of 9 themes. These themes are the result of qualitative content analysis performed on the examined literature in chapter 2 and focused on the sustainability objectives of RWS. The themes are listed below (see Table 5.4). Each of the 9 themes has its own focus on how a highway can contribute to a more sustainable living environment. In this way, sustainability can be made explicit in highways. When the themes are deployed early in a highway project, they add the most value to the project. The description of the themes is presented below:

Table 5.4 - The sustainability themes

Theme	Description
Energy	A highway can contribute to the energy transition and a sustainable living environment, by exploiting opportunities in highway development for energy conservation and the generation of sustainable energy.
Materials	A highway can contribute to the transition of circular economy (CE), by minimizing the use of materials and negative environmental impacts arising from the use of materials in highway development. Closing material chains and limiting the production and processing of materials and raw materials for construction and maintenance play an important role in this.
Water & Climate	Water that is safe, clean and healthy in the vicinity of a highway is an essential component of a sustainable living environment. This requires extra attention for a changing climate. Reduce the vulnerability of highways to climate change by exploiting opportunities for climate adaptation, for example by taking into account the increasing risk of flooding, heat and drought and the consequences of flooding in the design.
Ecology & Nature	Well-functioning ecosystems and varied habitats are part of a sustainable living environment. It is important to preserve and, where possible, strengthen the current ecological values and natural processes around the highway. This is a precondition for a healthy biodiversity. In addition, careful handling of the soil around the highway also contributes to a sustainable living environment by taking pollution, disturbance and subsidence of the soil into account.
Culture & Landscape	Careful use of space around the highway is of great importance for a sustainable living environment. By arranging the available space as efficiently and multifunctionally as possible and by preventing the expansion of the built-up area as much as possible. In addition, a recognizable landscape and attractive use of the area and (visible) cultural, archaeological and historical values contribute to spatial quality and can serve as inspiration for the design of an area.
Health & Well-being	A safe, clean and sustainable living environment on and around the highway contributes to the well-being and health of users and local residents. In this way it protects people against illness and accidents. In addition, a sustainable living environment around the highway promotes healthy behaviour, such as exercise and recreation, a healthy lifestyle, social safety and social interactions.
Mobility & Accessibility	It is critical to develop a robust traffic system in order to improve an area's accessibility. Therefore, making efficient use of existing and new infrastructure is needed in order to achieve this and as a result, save space, fuel and time. Accessibility can continue to be increased by means of an adaptive highway. In which the possibilities to respond to future changes play an important role. Highway projects must be able to adapt to current and future traffic demands.
Costs & Investments	In sustainable development, investments of the highway are in balance with the benefits. Not only the investment costs, but all the costs and benefits for the construction and use during the life cycle of a project are important. Sustainable financing is necessary to make short-term and

	long-term developments possible and profitable. In addition to financial returns, revenues also include social benefits and future value.
Economic development	A highway can contribute to a sustainable (regional) economy by improving the business climate in the region, which relates to economic activity in the region on the one hand and the economic vitality of the population on the other. An attractive business climate is a precondition for an economically vital environment. Furthermore, integrating innovative solutions and the smart use of innovative techniques in a highway can contribute to the sustainability of a highway.

These themes and related SA criteria are integrated into one comprehensive framework shown in Table 5.5, the so-called sustainability assessment framework. The SA framework is a visual representation of the sustainability themes and the associated SA criteria, which collectively integrate the relevant sustainability aspects of the 3Ps as much as possible. The SA framework focuses on themes and SA criteria for which the design choices and options are expected to have an effect or added value on sustainability and which may be important for decision-making. The SA framework is based on an integrated approach to sustainability. By providing insight into the various facets of sustainability, it becomes clear how a highway project can have maximum contribution to realizing the vision.

Sustainability is subdivided in the framework into the three sustainability dimensions (TBL), i.e. People, Planet, Prosperity, which in turn are collectively subdivided into 9 themes and 34 corresponding SA criteria. For the SA framework, clustering criteria in a hierarchical form, helps to check the relevance of the criteria, simplifies the process of calculating weights and facilitates the emergence of higher-level views of the issues, especially regarding trade-offs between objectives (Ward et al., 2016). In this research, the themes and SA criteria are organized in a hierarchical manner as a value tree. In this way, the following hierarchy levels can be recognized: dimension level, theme level and SA criteria level (see appendix B.2 and Table 5.5). The table below explains how each theme and SA criteria can be assessed, for further details is referred to Table 6.3:

Table 5.5 - The proposed sustainability assessment framework

Theme code	Theme	Criterion code	Assessment criteria	Creating sustainable added value
T1	Energy	C1	Energy consumption	The extent to which the design contributes to energy savings during the life cycle
		C2	Generation of renewable energy	The extent to which the design contributes to the self-generation or supply of renewable, sustainable energy in the use phase
T2	Materials	C3	Material balance with circular economy (CE)	The extent to which the design contributes to material savings, sustainability and CE during the life cycle
T3	Water & Climate	C4	Climate adaptation (flooding)	The extent to which the design contributes to the realization of a sustainable and robust water system
		C5	Surface and groundwater quality	The extent to which the design contributes to improving surface and groundwater quality
		C6	Climate adaptation (drought and heat stress)	The extent to which the design contributes to improving resilience to climate change
T4	Ecology & Nature	C7	Ecosystem functions	The extent to which the design contributes to the preservation and strengthening of biodiversity (flora and fauna), coherence between ecosystem functions and the stimulation of natural capital

		C8	Protected natural areas	The extent to which the design contributes to the protection and restoration of the protected nature areas (Natura 2000 areas and Natuurnetwerk Nederland)
		C9	Soil quality	The extent to which the design contributes to improving soil quality
T5	Culture & Landscape	C10	Cultural heritage, archaeological and historical values	The extent to which the design contributes to the preservation and protection of cultural heritage, archaeological and historical value
		C11	Landscape structures	The extent to which the design contributes to preserving and reinforcing typical features of the landscape and different areas
		C12	Residential, recreational and working areas	The extent to which the design contributes to improving the quality of life in residential, recreational and working areas
		C13	Utility services	The extent to which the design contributes to improving cable and pipeline networks for utilities
		C14	Connectivity between functions and communities	The extent to which the design contributes to improving connections and connectivity between existing functions and communities in an area
T6	Health & Well-being	C15	Noise pollution and vibrations	The extent to which the design contributes to reducing the noise level and vibration of traffic to surrounding areas in the use phase
		C16	Light pollution	The extent to which the design contributes to the reduction of unnecessary light pollution of the road and road traffic to surrounding areas and communities in the use phase
		C17	Spatial and visual quality	The extent to which the design contributes to improving spatial and visual quality in the use phase
		C18	Emissions and air quality	The extent to which the design contributes to improving air quality in the use phase
		C19	Traffic safety	The extent to which the design contributes to improving road safety
		C20	External safety	The extent to which the design contributes to reducing the risks associated with the transport of dangerous goods for people and vulnerable objects in the vicinity of the motorway
		C21	Construction safety	The extent to which the design contributes to the realization of a healthy and safe working environment for project workers for construction and operation on site
		C22	Nuisance during construction	The extent to which the design contributes to minimizing noise, dust, visual impact, nuisance, barrier effect, odor, vibration, air and light pollution during construction
		C23	Public support	The extent to which the design contributes to solving social problems for the public
T7	Mobility & Accessibility	C24	Traffic flow (network load)	The extent to which the design contributes to promoting the flow in the area
		C25	Reliability (network performance)	The extent to which the design contributes to increasing the reliability of the travel time ratios (travel time gain), vehicle loss hours and unexpected delays
		C26	Adaptability & flexibility	The extent to which the design contributes to the resilient and adaptive design of the highway
		C27	Robustness	The extent to which the design contributes to increasing the availability of the highway

T8	Costs & Investments	C28	Construction costs	The extent to which the design contributes to reducing the design's construction costs for the project life cycle
		C29	Management and maintenance costs (LCC)	The extent to which the design contributes to reducing the management and maintenance costs of the design for the life cycle of the project
		C30	Financial risks	The extent to which the design contributes to reducing financial risks
		C31	Social cost-benefit analysis (SCBA)	The extent to which the design contributes to positive effects on prosperity
T9	Economic development	C32	Local economy	The extent to which the design contributes to making the local economy more attractive to the environment and promoting economic activities
		C33	Regional economy	The extent to which the design contributes to strengthening the regional economy (economic position)
		C34	Innovation	The extent to which the design contributes to stimulating and implementing innovations

5.2 Questionnaire Survey to Form the Conceptual SA Framework

The SA criteria from the proposed SA framework need to be validated on relevance to the planning- and design phase within the Dutch highway context. For the reason that, the SA criteria should be location-specific and specific to the type and characteristics of a certain project to which they will be applied.

To validate the SA criteria and their relevance to the planning- and design phase within the Dutch highway context, a sample of 30 Dutch engineering consultancy from Antea Group with experience with sustainability and road design were selected for participating in a questionnaire survey. SA criteria identified in the literature review were presented in the questionnaire. The time needed to fill in the questionnaire was around 30 min., in general, long questionnaires get fewer responses, it could be assumed that the length of the questionnaire used in the research would not affect the response rate.

Ultimately, 10 experts responded by filling the questionnaire and two experts were interviewed based on the same questions of the survey. In the questionnaire the SA criteria from the literature were presented to the experts for review and validation, including instructions on how to complete the survey and background information on the purpose of the research (see appendix C.1). The experts were asked to specify which of the SA criteria are relevant for the planning- and design phase (MIRT-Exploration and MIRT-Plan Elaboration phase) within the Dutch highway context, by selecting "relevant", "irrelevant", "no opinion" or "already named/overlapping", with an option to justify their choice by giving an explanation or a practical example. Afterwards the experts were then asked to suggest other possible relevant SA criteria based on their knowledge and experience with regard to sustainability in road design.

The author analysed the relevance based on a calculation, $\frac{relevant}{total\ responses} = [\%]$ and compared it with the comments of the experts. Because, the response rates per SA criterion were so different from each other, the author did not draw a line for a minimum percentage score for a SA criterion to be included. Instead, the author focused on the reasoning and arguments of the experts, why a certain SA criterion is relevant. The results and analysis of the questionnaire are presented in appendix C.2, C.3 and C.4.

To maintain confidentiality among the respondents, the experts' identities are coded into numbers (see Table 5.6). Quotes from the respondents that are given in this research will be referred to the respondents numbers which are shown below:

Table 5.6 - Questionnaire survey respondents

Respondent	Function	Department
Respondent 1	Project engineer	Civil structures (roads)
Respondent 2	Project engineer	Infrastructure (roads)
Respondent 3	Cost expert and value engineer for roads	Infrastructure (roads)
Respondent 4	Project engineer	Civil structures (roads)
Respondent 5	Project engineer	Water
Respondent 6	Project engineer	Infrastructure (roads)
Respondent 7	Advisor for roads, sustainability & circularity	Infrastructure (roads)
Respondent 8	Coordinator preparation	Infrastructure (roads)
Respondent 9	Project engineer	Project control
Respondent 10	Senior advisor	Spatial strategy (roads)
Respondent 11	Senior advisor	Energy transition
Respondent 12	Cost expert & value engineering	Infrastructure (roads)

5.3 Conclusion on the Questionnaire Survey

Four additional SA criteria were suggested by two experts (Respondent 6, 7). Namely SA criteria that focusses on:

- *"Energy consumption of the realization and demolition of the project"*: CO2 production is a good value for energy. How much CO2 reduction is possible per design option? Determining the CO2 production goes hand in hand with determining the MKI-value and therefore does not require more time/costs. To measure this criterion, quantitative assessment is possible in [ton];
- *"Fuel consumption of road users"*: think of different asphalt, which reduces the rolling resistance of the cars. *"Certain types of asphalt reduce rolling resistance and thus energy consumption"* (Respondent 3). Or a design where the flow is better, which results in less stoppage and therefore less energy consumption. Another example given, *"a road design with as few height differences as possible contributes to lower fuel consumption. You can also think of an ascending slope at an exit and a descending slope at an entrance, so that gravity can be used when accelerating and decelerating. Examples of this kind can contribute to considerable fuel savings over the entire service life."* (Respondent 6). To measure this criterion, qualitative reasoning is suggested;
- *"Environmental cost indicator":* expressed in ECI-value [euros]. This means that the criterion "Material balance with circular economy (CE)" is expressed in the amount of materials re-used, refurbished, recycled and deposited in the design; and
- *"Material production":* expressed in CO2-emissions [ton CO2 eq.] from material production, calculated in DuboCalc.

These four suggested SA criteria were added to the conceptual SA framework, because the respondents are experts in the fields of sustainability and road design. In addition, the SA criteria are expected to be crucial in assessing the sustainability of highway designs, as well as having significant savings potential e.g. lowering CO2-production or CO2-emissions. In the end, 36 SA criteria were carefully chosen, based on relevance and reasoning (see Table 5.7).

The outcome of this chapter is the conceptual SA framework with 36 SA criteria that were found to be relevant for the planning- and design phase within the Dutch highway context. The conceptual SA framework presented in appendix B.4, integrates SA criteria from the social, environmental and economic dimensions of sustainability (People, Planet, Prosperity).

Table 5.7 - The conceptual SA framework

Theme code	Theme	Criterion code	Assessment criteria
T1	Energy	C1	Energy consumption
		C2	Generation of renewable energy
		C3	Energy consumption (fuel)
		C4	Energy consumption (construction & demolition)
T2	Materials	C5	Material balance with circular economy (CE)
		C6	Material production
		C7	Environmental cost indicator
T3	Water & Climate	C8	Climate adaptation (flooding)
		C9	Surface and groundwater quality
		C10	Climate adaptation (drought and heat stress)
T4	Ecology & Nature	C11	Ecosystem functions
		C12	Protected natural areas
		C13	Soil quality
T5	Culture & Landscape	C14	Cultural heritage, archaeological and historical values
		C15	Spatial quality
		C16	Residential, recreational and working areas
		C17	Utility services
T6	Health & Well-being	C18	Noise pollution and vibrations
		C19	Light pollution
		C20	Visual quality
		C21	Emissions and air quality
		C22	Traffic safety
		C23	External safety
		C24	Construction safety
		C25	Nuisance during construction
		C26	Public support
T7	Mobility & Accessibility	C27	Traffic flow (network load)
		C28	Reliability (network performance)
		C29	Adaptability & flexibility
		C30	Robustness
T8	Costs & Investments	C31	Investment costs (LCC)
		C32	Maintenance costs (LCC)
		C33	Financial risks
		C34	Social cost-benefit analysis (SCBA)
T9	Economic development	C35	Regional economy
		C36	Innovation

CHAPTER 6
DEVELOPMENT OF THE SUSTAINABILITY ASSESSMENT TOOL

6 Development of the Sustainability Assessment Tool

In this chapter, the development of the SA tool takes place. This chapter is broken down into three sections. The first section explains the purpose, aim and application of the SA tool (see 6.1). The second section presents the assessment procedure applied to the SA framework to form the proposed SA tool (see 6.2). The last section presents the developed SA tool (see 6.3). After that the proposed SA tool is applied to a reference case and evaluated with an expert (see chapter 7).

6.1 Introduction

This sustainability assessment (SA) tool aims to provide the project team of Antea Group with a tool to carry out a design option (alternatives & variants) analysis from the sustainability viewpoint. This tool serves to support the decision-making. The project team exists of experts (designers & decision-makers) involved in the design process and decision-making, during the planning- and design phase (MIRT-Exploration and MIRT-Plan Elaboration phase).

6.1.1 Purpose of a Design Option Analysis

A design option analysis is a method for making careful design choices and ensuring that they are traceable and transparent for everyone in the future, as to which options were considered and why certain choices were made during the design process. For this analysis, a trade-off matrix (TOM) is utilized. A TOM consists of a table (matrix) in which design options are compared to each other to be able to make a carefully considered choice.

6.1.2 Aim of the Sustainability Assessment Tool

The SA tool uses a combination of SA criteria to provide an overall picture of how the design options contribute to sustainability. If only one SA criteria is used, a completely sustainable design will not be achieved. The SA criteria should therefore always be used in conjunction. Qualitative methods as well as quantitative methods are also examined. In certain MIRT phases a final design is not yet established, therefore only the use of quantitative methods can give an inaccurate picture. That is why qualitative methods are also used, such as the sustainable design principles mentioned in 2.1.4. However, in the tool, a number of criteria can be quantified, including investments, social costs and benefits, energy and the environmental impact by means of an ECI-value.

6.1.3 Application of the Design Option Analysis

The design option analysis as described in this method is a form of multi-criteria analysis (MCA). In this research, it means that design options are weighed against each other using different themes and SA criteria. A design option analysis can be performed by the project team of Antea Group. The project team of RWS should be involved in this process, to determine what the objectives are within the project and what they find important.

This design option analysis can be used in any highway construction or maintenance project that requires significant design choices. It is not always desirable or necessary to conduct a thorough investigation. However, it is especially important when the design options have very different results on various sustainability themes or SA criteria.

The basis for weighing design options in this analysis is to determine how much the design options contribute to sustainability. This is determined based on the performance as measured by a set of SA criteria allocated to different themes.

6.2 Assessment Procedure

Choosing between different design options is not an easy task. To arrive at a preferred option within the MIRT-Exploration and MIRT-Plan Elaboration of a highway project, the steps presented below must be completed.

6.2.1 Incorporate Requirements into the Design Options

Before the design options are analyzed, they must first be tested to see if they meet the (client's) requirements, standards and guidelines. Critical requirements are those that must be met and included in the design options. There are also non-critical requirements, those that do not have to be met by a design. The analysis only considers the design that meet the above mentioned requirements.

6.2.2 Description and Elaboration of Design Options

After several design options have been compiled from all possible combinations of solutions and a typical name has been chosen for each of them, the generic and specific characteristics of the design options can be described. Describing here is meant that the performance, score or value is indicated for each characteristic, e.g. by expressing the cost for all design options in the same unit [euros].

6.2.3 The Choice for the Type of Trade-Off Matrix

The assessment of design options takes place in a TOM. The SA criteria determine which measurement scale is used. In this SA tool, the themes are subdivided into SA criteria, but only a weighting factor is assigned to the themes. However, assessment is done by evaluating the SA criteria, which has the advantage of providing a more nuanced assessment that can be analyzed. The SA tool only considers which themes should be prioritized. In this SA tool, an MCA approach is used to determine the weighting factors of the themes, later explained in subsection 6.2.5.

Each SA criterion is associated with a certain score, which is expressed in a certain unit value or measurement scale. Three measuring scales in which one can express the score are the: +/- scale, the number scale and the own nominal value. In the tool, the value for each criterion is mapped into its unit value. The measuring scales are explained below:

- *+/- Scale:*

\+ The advantage is that the score is displayed simply;

\- A disadvantage is that outcomes are less objective and the differences in outcomes leave a lot of room for discussion.

- *Number scale:*

\+ The advantage compared to the +/- measuring scale is that the total score per design can be determined easily and accurately;

\- A disadvantage is that too much value is placed on accuracy.

- *Own nominal value:*
  - \+ The advantage is that the options for each SA criterion can be compared accurately with each other;
  - \- A disadvantage, however, is that it is less objective and accurate to determine which design scores best because the criteria are expressed in non-comparable units.

This SA tool will use a more hybrid form by combining the measuring scales in the TOM. The reason for this is that assessing sustainability and measuring it is still in its early stages. There is no methodology available that can make all aspects of sustainability fully measurable. For this reason, the author decided to use a combination of qualitative and quantitative methods in order to gain a broad insight into sustainability.

6.2.4 Themes and SA criteria

Design options are assessed based on themes and SA criteria. The SA criteria are composed based on the results of the literature review and questionnaire survey, relevant specifically for highway projects in the Netherlands. Design options are assessed based on several themes, with associated (specific) SA criteria from a sustainability perspective.

6.2.5 Determining Weighting Factors for the Themes

Within a project, some themes can be considered more important than others. By assigning weighting factors, the project team can indicate the importance of one theme over another. After filling in and determining the score of the SA criteria, it is possible to check the consequences of a certain value of a weighting factor on the results. This is a form of sensitivity analysis.

Not only the client (RWS) can state the importance of a certain theme, but stakeholders also have their input and demands that can differ for certain areas within a project. The weighting must be determined in consultation between the project team (consisting of experts from Antea Group), RWS and stakeholders. The allocation of weights on themes is done in consultation. This is a form of collective decision-making, which is aggregation with deliberation and consensus. Recent research has shown that collective decision-making outperforms the wisdom of crowds, which refers to the aggregation of many independent judgments without deliberation and consensus (Hamada et al., 2020). The assessment of the SA criteria is done by experts from Antea Group. The assessment process to arrive at a careful consideration and advice to the client is shown below:

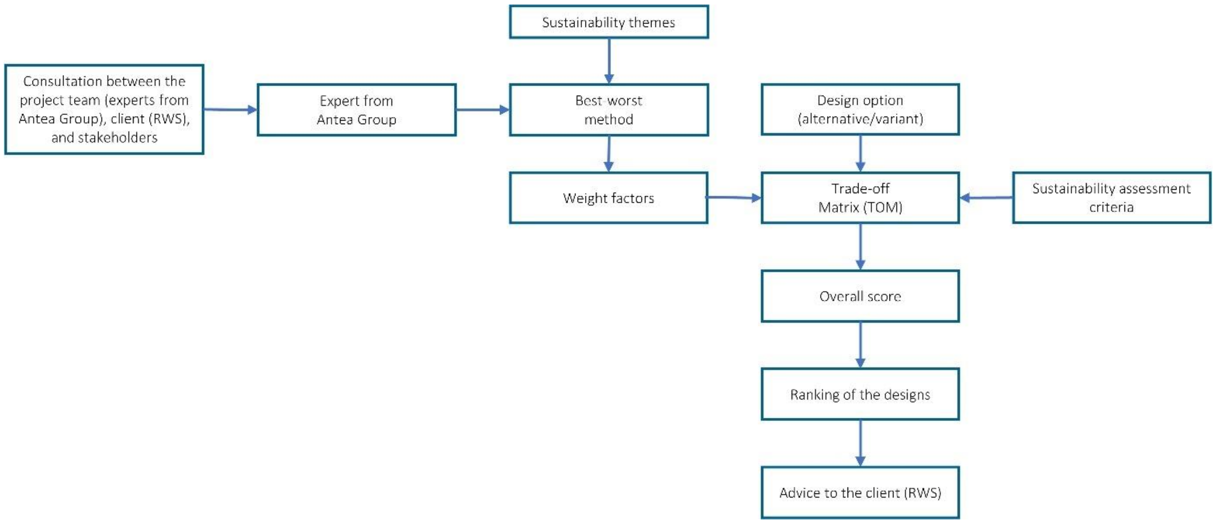


Figure 6.1 - Assessment procedure (own illustration)

Assigning a weighting factor is done as a percentage (%) using the 'best-worst method' (BWM), whereas the sum of the themes together must always be 100%.

6.2.5.1 Best-Worst Method

The selection and ranking of the preferred design (e.g., most desirable, most important) from a range of design options, is influenced by a set of SA criteria, as well as different experts, clients and stakeholders' interests. As it is clear from Table 5.7, existence of a large number of SA criteria have convinced the author to consider this assessment as an MCDM problem.

Therefore, a multi-criteria decision-making (MCDM) method is applied in this research. The goal of the MCDM is to find the preferred design from a set of design options with respect to a number of SA criteria, for example, a design with the best overall value/score.

There are different approaches to acquiring the weighting factors of the themes, such as the Analytic Hierarchy Process (AHP) (Saaty, 1977) Analytic Network Process (ANP) (Saaty, 2005) to name a few. The best-worst method (BWM) is chosen as one of the latest developed MCDM methods by Rezaei (2015), who believes using the unstructured approach in executing the pairwise comparisons is the main reason for inconsistency. The introduction of the BWM improves the consistency ratio by performing fewer pairwise comparisons (Rezaei, 2015, 2016). BWM is easy and precise because the implementation of secondary comparisons is not necessary (Ghoushchi et al., 2021; Rezaei et al., 2015). Compared to other methods, for instance, AHP and ANP, BWM has the following advantages (Li et al., 2020; Lin et al., 2021; Rezaei, 2015):

- BWM needs less pairwise comparison data compared to other methods. This reduces the complexity and time needed and eventually leads to more reliable pairwise comparisons;
- BWM is highly consistent, therefore, the obtained results by this method will be highly reliable;
- BWM is one of the most data-efficient methods which could at the same time allow a consistency check.

A review of the latest research works in the MCDM problem field shows that the BWM has been utilized successfully by researchers. Researchers applied BWM to make decisions on the different MCDM problems, such as supply chains (Ahmadi et al., 2017; Suhi et al., 2019; Zhao et al., 2018), urban transportation network evaluation (Groenendijk et al., 2018; Mahmoudi et al., 2019) and other fields

(Ahmadi et al., 2017; Kumar & Ramesh, 2020; Li et al., 2020; Pamucar et al., 2021; van de Kaa et al., 2017) etc. But few to the authors' knowledge have tried to use BWM in the field of highway infrastructure before and this is a unique advantage of this research.

These advantages and considerations convinced the author to use the BWM in this research. BWM offers designers and decision-makers an opportunity to evaluate and compare different design options.

Steps in the Best-Worst Method

The following steps of the BMW are taken to derive the weighting factors of the themes (Rezaei, 2015, 2016):

Step 1: Determine a set of themes.

This step determines a set of themes $\{T1,\ T2,\ T3 \ldots,\ Tn\}$ that should be used to arrive at an overall score from which a judgment or advice can be given. In this research, the themes are the result of the literature review and questionnaire survey, which are: Energy ($T1$), Materials ($T2$), Water & Climate ($T3$), Soil & Nature ($T4$), Culture & Landscape ($T5$), Health & Well-being ($T6$), Mobility & Accessibility ($T7$), Investments ($T8$) and Economic Development ($T9$).

Step 2: Determine the best (e.g., most desirable, most important) and worst (e.g., least desirable, least important) theme.

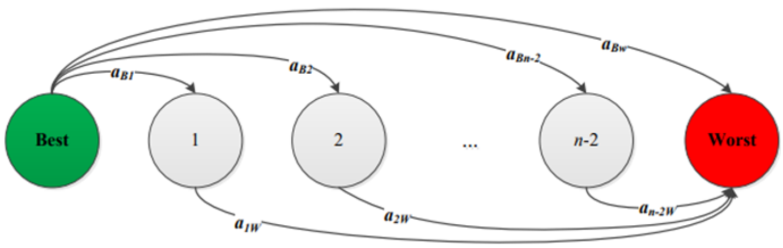
In this step, the experts identify the most important theme and the least important theme in general. No comparison is made in this step.

Step 3: Prefer the most important theme over the other themes.

Determine the preference of the main theme over the other themes using a number between 1 and 5. Note: Other scales can also be used to determine the preference, such as 1-9 (original) and 1-100. For this research, a scale 1-5 has been chosen to ease the difficulty of choosing the correct number by the expert. The following scale 1-5 is used:

Table 6.1 - Preference scale

Five-point scale	
Description	Value
Equally important	1
Moderately more important	2
Substantially more important	3
Much more important	4
Extremely more important	5



The resulting 'Best-to-Others' (BO) vector would be: $A_B = (a_{B1},\ a_{B2},\ a_{B3},\ \ldots,\ a_{Bn})$

Step 4: Determine the preference of all other themes over the least important theme using a number between 1 and 5.

The resulting 'Others-to-worst' (OW) vector would be: $A_W = (a_{1W},\ a_{2W},\ a_{3W},\ \ldots,\ a_{nW})^{\mathrm{T}}$

Step 5: Find the optimal weighting factors: $(w_1^*, w_2^*, \ldots,\ w_n^*)$.

The optimal weighting factors for the themes, is the one where, for each pair of $\frac{w_B}{w_j} = a_{Bj}$ and $\frac{w_j}{w_w} = a_{jW}$. To satisfy these conditions for all j, we have to find a solution where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_w} - a_{jW}\right|$ for all j is minimized: $\min \max_{j} \left\{\left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_w} - a_{jW}\right|\right\}$

Given the non-negativity and sum condition for the weights, this results in the following problem:

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for all } j \qquad (1)$$

Problem (1), can be transferred to the following problem:

$$\min \xi$$

Subjected to:

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \text{ for all } j$$

$$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \text{ voor alle } j$$

By solving problem (1), the optimal weight factors $W = (w_1^*, w_2^*, \dots, w_n^*)$ and ξ^* are obtained. Op deze manier kan bepaald worden waar in een specifiek project de nadruk op ligt, wat is van groot belang en wat minder van belang - wat weegt zwaarder mee. The calculation is solved in an excel template based on (Rezaei, 2015)and adapted to the context of this research. An example calculation with results is presented in appendix D.2.

Step 6: Check the consistency

The consistency of the input can be checked using ξ^*. It is important to note that the larger the ξ^*, the higher the consistency ratio (CR) and the less reliable the comparisons become.

Different values of a_{BW} determine which consistency index (max ξ) should be used for control. Since a scale of 1-5 ($a_{BW} = 5$) is applied, we must use the consistency index (max ξ) value of 2,30.

Consistency ratio (CR) ∈ 0.1. The lower the CR, the more consistent the comparisons, so the more reliable the results:

$$Consistency\ ratio\ (CR) = \frac{\xi^*}{Consistency\ index} = \frac{\xi^*}{2{,}30}$$

BMW always results in consistent (not necessarily completely consistent) equations.

6.2.6 Scoring the Sustainability Assessment Criteria

The score of the SA criterion belonging to one particular theme is assigned a score of 1-5 (based on a combination of qualitative and quantitative assessments of the SA criteria), whereby the average is multiplied by the weighting factor of the theme. This makes it possible to compare design options on each theme, but also on a total score by adding up all the scores of the themes. The measurement scale to be used +/- is converted to a scale of 1-5. So, if we have a matrix where design options are rated on a 5-point scale, the higher the score, the better. The definition of the scores that can be assigned is shown in the table below:

Table 6.2 - Measurement scale (score compared to the current/reference situation)

Definition	Score	
Very negative contribution, major deterioration	--	1
Negative contribution, deterioration	-	2
No intervention or opportunities are taken, no change	+/-	3
Achieving minimum sustainability performance, minimum improvement	+	4
Positive contribution (highest achievable performance), in addition to achieving the objectives by applying measures, sustainable added value is also created through maximum effort and taking full advantage of opportunities	++	5

6.2.6.1 Nominal Value of the Sustainability Assessment Criteria

Some of the SA criteria can be measured objectively (such as investment costs). Some other SA criteria are subjective. If the inputs in matrix are of a different scale (euro, ton) then they must first be normalized before they can be incorporated into the overall score, for this the following formula can be used (Rezaei, 2016):

$$x_k^{norm} = \begin{cases} \dfrac{x - x_{min}}{x_{max} - x_{min}}, \ if\ x\ is\ positive\ (quality) \\ \dfrac{x - x_{max}}{x_{min} - x_{max}}, \ if\ x\ is\ negative\ (costs) \end{cases}$$

For example, we look at investment costs, the cheapest design option has investment costs of 50 and the most expensive 200 and one in between of 150. Then the following formulas are applied:

$$Cheapest = \frac{50 - 200}{50 - 200} = 1 * (5\ score) = 5$$

$$In\ between = \frac{150 - 200}{50 - 200} = 0{,}333 * (5\ score) = 1{,}6665$$

$$Most\ expensive = \frac{200 - 200}{200 - 200} = 0 * (5\ score) = 0$$

6.2.6.2 Overall Score of a Design Option

Determining the final score of a design options in the trade-off matrix (TOM) with themes and SA criteria and the various scales takes place as follows:

- The nominal value for each SA criteria is converted into a score that is expressed in numbers (as shown directly above). The other SA criteria with the +/- or number scale are also assessed. This is done for all SA criteria and design options;
- Then the sum of all scores per theme and design option is calculated;
- Then this number is divided by the number of SA criteria that have been assessed in each theme. In this way the themes can be compared on scores. All the total score of the themes combined, result in the overall score. Rounding is done to two decimal places. The assigned scores, along with the weight factors determined using the BWM, give an overall score of the design options.

6.2.7 Filling in the Trade-Off Matrix

For each SA criterion, the score for all design options is filled in. When filling in the scores in the TOM, only facts, key figures, or other information on which experts or decision-makers agree (depending on the level of abstraction) is used. It is possible that more information is needed to fill in an SA criterion and that a design options needs further elaboration to determine the SA criterion.

6.2.7.1 Determining the Overall Score for Design Options

After filling the TOM, the overall score for each variant can be determined. After the overall score for all design options has been performed, a sensitivity analysis can be performed. A sensitivity analysis is performed by adjusting, the weighting factors of the themes or scores or the SA criteria. The score for all design options is then determined again and can be checked and compared to the first overall score. The overall score of the design options is determined by an expert or the project team.

6.2.7.2 Determining Preferred Design Option by the Client

The preferred design option can be determined after the overall score has been calculated. The TOM results are only used to make a decision or give advices about which design option to implement. The TOM is part of a recommendation to the client about how much the design contributes to sustainable. Following the advice, the client makes the final decision.

6.3 Proposed Sustainability Assessment Tool

The table below shows the proposed SA tool with the themes, SA criteria and type of assessment (quantitative/qualitative) depending on the available information in a certain stage in the design process. This proposed SA tool is evaluated with an expert in the next chapter to assess the applicability with the use of a reference case.

Table 6.3 - Proposed sustainability assessment tool

Theme code	Theme	Criterion code	Assessment criteria	Type of assessment
T1	Energy	EC1	Energy consumption (system)	Quantitative: • Amount of energy for use [kWh] Qualitative: • Explanation
		EC2	Generation of renewable energy	Quantitative: • Amount of energy generated [kWh] Qualitative: • Explanation
		EC3	Energy consumption (fuel)	Qualitative: • Type of asphalt • Traffic flow • Few height differences (slopes)
		EC4	Energy consumption (construction & demolition)	Quantitative: • CO_2 emissions [ton CO_2 eq.] Qualitative: • Machinery • Construction methods • Transport distances
T2	Materials	EC5	Material balance with circular economy (CE)	Qualitative: • Amount of re-use, refurbished and recycled and deposited

				• Longer life span
		EC6	Emission from materials	Quantitative: • CO2 emissions [ton CO2 eq.] Qualitative: • Explanation
		EC7	Environmental cost indicator	Quantitative: • ECI-value [euros]
T3	Water & Climate	EC8	Climate adaptation (flooding)	Qualitative: • Use of space (water storage)
		EC9	Surface and groundwater quality	Qualitative: • Composition of the water
		EC10	Climate adaptation (drought and heat stress)	Qualitative: • Use of space (paved surface)
T4	Ecology & Nature	EC11	Ecosystem functions	Qualitative: • Disturbance, damage, conservation, barrier effect, fragmentation, biodiversity, ecological connections
		EC12	Protected natural areas	Qualitative: • Effect (direct or indirect) on features or values
		EC13	Soil quality	Qualitative: • Composition of the soil
T5	Culture & Landscape	SC1	Cultural heritage, archaeological and historical values	Qualitative: • Effect on features or values
		SC2	Landscape structures	Qualitative: • Use of space (in landscape) • Rest areas, gas stations, restaurants, etc.
		SC3	Residential, recreational and working areas	Quantitative: • Amount of land to be acquired [m2] Qualitative: • Demolition of built-up areas
		SC4	Utility services	Qualitative: • Explanation
T6	Health & Well-being	SC5	Noise pollution and vibrations	Qualitative: • Noise exposure
		SC6	Light pollution	Qualitative: • Blocking light of the road and road traffic to surrounding areas
		SC7	Spatial- and visual quality	Qualitative: • View on the highway • View from the highway
		SC9	Emissions and air quality	Qualitative • Explanation
		SC9	Traffic safety	Qualitative: • Lane change (freight) traffic • Risk of car traffic accidents • Chance of traffic jams • Logic of design/ Human factors • Deviations from guidelines
		SC10	External safety	Qualitative: • Safety risks
		SC11	Construction safety	Qualitative: • Design complexity
		SC12	Nuisance during construction	Qualitative: • Complexity phasing • Availability emergency services • Construction risks
		SC13	Public support	Qualitative: • Explanation

T7	Mobility & Accessibility	SC14	Traffic flow (network load)	Quantitative: • Morning intensity/capacity [I/C] • Evening intensity/capacity [I/C] Qualitative: • Explanation
		SC15	Reliability (network performance)	Qualitative: • Travel times
		SC16	Adaptability & flexibility	Qualitative • Accommodate further traffic growth (future developments)
		SC17	Robustness	Qualitative: • Availability (less maintenance)
T8	Investments	EC1	Investment costs (LCC)	Quantitative: • Investment costs [euro] Qualitative: • Explanation
		EC2	Maintenance costs (LCC)	Quantitative: • Maintenance costs [euros] Qualitative: • Maintainability
		EC3	Financial risks	Quantitative: • Costs [euros]
		EC4	Social cost-benefit analysis (SCBA)	Quantitative • SCBA-ratio
T9	Economic development	EC5	Regional economy	Qualitative: • Accessibility, attractiveness and spatial quality of the area • Structure of the network
		EC6	Innovation	Qualitative: • Implementing innovations • Other modalities

CHAPTER 7
REFERENCE CASE

7 Reference Case

7.1 Introduction

To examine the applicability of the proposed sustainability assessment (SA) tool developed in the previous chapter, a reference case was utilized. The proposed SA tool has been applied by the author to a highway project currently in the design phase to find out the functioning, applicability and implications.

After the author applied the proposed SA tool and evaluated the findings, an expert on highway design involved in the realization of the project was interviewed to evaluate the finding, applicability, practical use and implementation within Antea Group. During the interview, the conceptual SA framework, MCA method and proposed SA tool were discussed and evaluated.

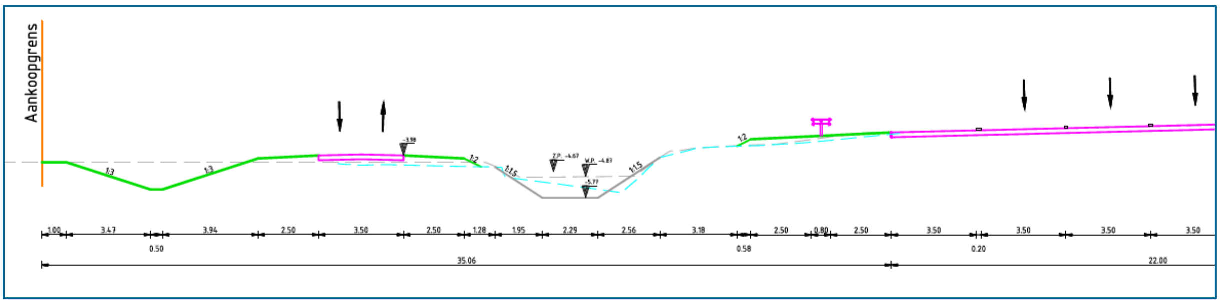
The application and the evaluation of the proposed SA tool on the reference case was done in four sequential steps:

1. *Project information:* Antea Group's content server was used to acquire project information of the reference case. This was done to get an understanding of how sustainability is addressed and how design options were analyzed in the reference case;
2. *Applying the proposed SA tool:* the assessment procedure was applied by the author on the reference case;
3. *Formulating the interview questions:* once the assessment produce was applied and the information of the reference case processed in the proposed SA tool, the findings were processed to be evaluated by interview questions;
4. *Interview with the expert:* the finding were evaluated with the expert involved in the reference case. During the interview, the conceptual SA framework, MCA method and proposed SA tool were discussed and evaluated with the expert and the possibility of incorporating it within Antea Group was explored.

7.2 Step 1: Project Information

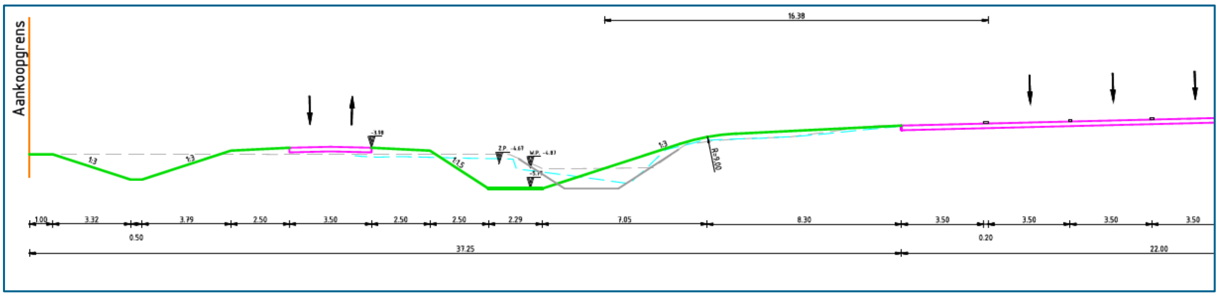
In the first step, the reference case is presented. The selected reference case is a highway project in the Netherlands, which is currently in the design phase *(Inpassend Ontwerp (IO))*, in which a number of variants of the preferred alternative (VKA) are assessed. This case is chosen, because it is currently in the design process (MIRT-Plan Elaboration phase) and the expert's memories and details regarding the project are still fresh.

Variant 0 (VKA)



The current situation does not offer sufficient space for the construction of an extra lane on the outside of the reference highway, which makes it necessary to move and displace the parallel road and the waterway. The integration of a ‘new’ parallel road and waterway can be elaborated in various ways. The VKA assumes that the parallel road will be moved to the other side of the waterway, which will be retained at its current location. The following variants were compared with the variant 0 (VKA):

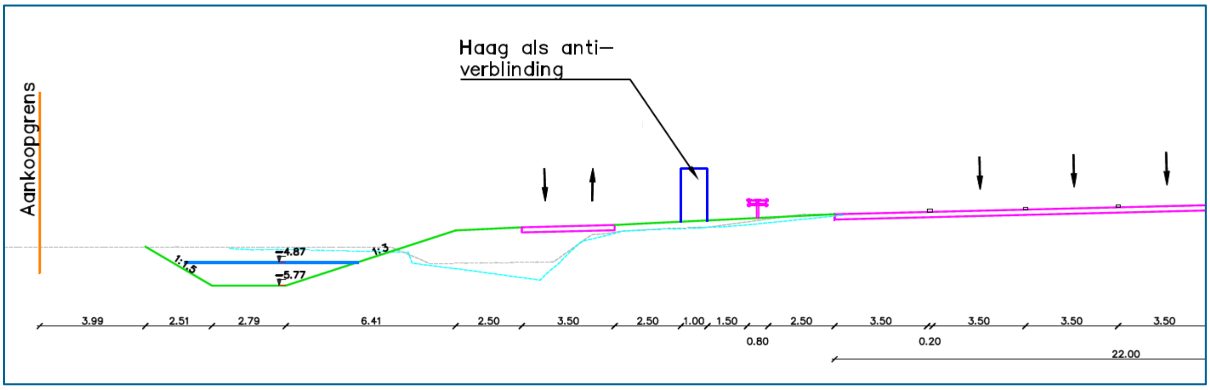
Variant 3



The parallel road has been integrated into the other side of the existing A-waterway (waterways with an important water supply or drainage function) in accordance with the VKA. Due to the widening of the reference highway, there is insufficient space available in the existing berm for the preservation of the parallel road. On the road side, the existing A-watercourse has been provided with a slope of 1:3, so that the waterway meets the requirements of a safe object in accordance with the *Veilige Inrichting van Bermen* guideline. The placement of a guide rail construction is not necessary in this situation. A new waterway will be constructed between the parallel road and the private properties. This waterway has the following functions:

- realize the necessary water compensation;
- separation between 'public' and 'private' properties;
- drainage function: the waterways perpendicular to the reference highway are connected to this waterway and at a limited number of locations by means of a culvert connected to the existing A-waterway.

Variant 6c



In contrast to the VKA, the parallel road has been integrated next to the reference highway. Due to the widening of the reference highway, there is insufficient space available in the existing berm for the preservation of the parallel road and the existing A-waterway. The existing A-waterway will be relocated to accommodate the parallel road. Because of the necessary water compensation, the A-waterway must be widened. The parallel road is located within the obstacle-free zone (13.00 m) of the reference highway and is protected by a guide rail construction. In order to prevent approaching traffic and light nuisance being misled, a hedge with a height of approximately 1.00m will be positioned between the reference highway and the parallel road.

7.3 Step 2: Applying the Proposed SA Tool

In the second step, the findings of applying the proposed SA tool on the reference case are presented. Application of the proposed SA tool on the reference case is presented in appendix D.4. Within the proposed SA tool, the author assessed and compared two design options to the reference situation on the themes and SA criteria mentioned in appendix C.4. By means of assessment, it is indicated for each SA criterion whether the design option concerned has a positive contribution to sustainability or a negative contribution compared to the reference situation. Per design option, the scores of all themes and SA criteria were added up to provide the overall score per design option.

7.4 Step 3: Formulating the Interview Questions

In the third step, the interview questions are formulated. After applying the proposed SA tool to the reference case, the findings were processed to be evaluated by interview questions. In appendix D.1 an overview of the list with interview questions is provided.

7.5 Step 4: Expert Interview

After formulating the interview questions, the author contacted an experts involved in the case to evaluate the conceptual SA framework, MCA method and proposed SA tool. The expert interviewed within Antea Group, works as a project leader, has experience with decision-making and is part of the design team who are responsible for the integral design of highways in the Netherlands. In addition, the expert involved in the reference case has knowledge about and experience with the content and research topics.

First, the author had introduced himself to the expert and explained the goal of the research and purpose of the interview. After that, the author presented the conceptual SA framework to be discussed and evaluated. Next, the best-worst method (MCA approach) was explained, filled in by the expert and discussed (see 6.2.5 for explanation of the method). Lastly, the application of the proposed SA tool on the reference case was evaluated to understand the use and the added value of the proposed SA tool. The review of the proposed SA tool is presented below. Interview questions asked and answers given during the interview are presented in appendix D.1 and D.5.

7.5.1 Evaluating the Conceptual Sustainability Assessment Framework

To evaluate the conceptual SA framework, the author went through the framework together with the expert and asked some questions about the description, definition and the added value of the SA criteria.

The expert indicated that (1) the descriptions of the SA criteria are insightful and clearly defined, (2) provide a good picture of how a design can make a positive contribution and thus create sustainable added value and (3) there is a clear distinction between the SA criteria.

Furthermore, the expert stated that this conceptual SA framework provides a clear reference during the design phase to steer toward sustainable solutions and what is required for this, thereby challenging the designer to arrive at sustainable solutions. It is a very extensive and therefore also a complete framework. For some design phases, it can be useful to be more specific about a theme and thereby including more criteria, which is an advantage of this framework. The framework, according to the expert, can be used as an overview or reference during the design process when the focus is on sustainability.

7.5.2 Applying the MCA Method and Discussing the Results

To evaluate the use and applicability of the best-worst method, the author asked the expert to use and fill in the method, based on his experience. The author asked which themes are usually found most important and least important in highway projects. From filling in the method, the following conclusions were drawn.

The expert indicated that 'Mobility & Accessibility' is often considered the most important theme and is often the reason for the initiative of a project. There is often a need for better traffic flow. With 'Materials' there is generally not much difference between the designs, so this makes little difference in the total score. 'Investments' actually scores very high in every project, the budget for each project is often already determined in the past, without taking into account extra investments for sustainability. The least important is often the 'Economic development'. The results from using the best-worst method are provided in appendix D.3. However, this will not be discussed further in this research, it was only applied to test the usability and applicability of the method.

Regarding the use of the method, the expert stated that (1) it is an efficient method for objectively determining the weighting factors, (2) also not that labour-intensive, (3) fairly easy to apply in practice and (4) an easy way to determine per location/area or phase what is considered important, because at a different location within the project there may be other aspects that are considered more important according to the client or stakeholders. However, the expert also mentioned that it is always subjective, but it is a good way to compare the themes. You always have an idea of what it will look like, but this confirms it with fewer mutual comparisons. In addition, the expert stated that it is useful to apply the method on a specific area within a project, because at a different location there may be other aspects that are considered more important according to the client or stakeholders.

To conclude, the experts mentioned that this method is a good way to record the weighting factors. With the weighting factors, one can also mutually assess the themes between design options. For example, the focus within this project is on this theme, this design scores the best, it is recommended to further develop this design. This helps to determine the distribution of your weighting factors. If you do not use this method, you will determine together, for example costs are included for 20%, we choose these weightings. Only then there is less consideration of how you determine a value, there is less comparison.

7.5.3 Evaluation of the Proposed Sustainability Assessment Tool

By filling in the proposed SA tool using the reference case, the author encountered a number of things. These points have been discussed with the expert for feedback.

The following SA criteria were missing or had not been assessed in the reference case: 'Energy consumption (system)', 'Energy generation', 'Climate adaptation (drought and heat stress)', 'Light pollution', 'External safety', 'Building safety', 'Nuisance during construction', 'Reliability (network performance)', 'Adaptability & flexibility' and 'Societal cost-benefit analysis (SCBA)', 'Regional economy' and 'Innovation'. According to the expert certain SA criteria cannot always be assessed in every phase and the level of detail (qualitative and quantitative) can still differ. Some SA criteria can only be distinguished in the later phases, for example differences in the availability of information between the MIRT-Exploration and MIRT-Plan Elaboration phase to assess the SA criteria. However, these SA criteria can be of added value if the information is available and when there is a distinctive difference between the design options.

The proposed SA tool provides insight into how designs can contribute to sustainability and to visualize the added value, this new framework can indicate how added value can be strived for. In addition, the addition of the weighting factors can certainly add value. It helps and prevents discussions. This allows you to make the choice for the design more objectively, now it often still happens instinctively. Furthermore, the criteria that Antea Group uses are all there and this tool offers additional criteria as a supplement to enable an even more specific assessment. It does make it more extensive, however, you can select which ones to include and thus make it clearer again. Lastly, approaching a design from the perspective of life cycle costs is also an added value that is often not yet taken into account by RWS. Especially when we look at sustainability, this can ensure that we arrive at a better solution.

According to the expert, the proposed SA tool makes it possible to visualize the added value to give a thorough assessment and advice to the client when you are talking about sustainability. For example, if there are designs with the same investment costs, it can certainly help to be able to give advice based on the proposed SA tool to go for the most sustainable solution.

The assigning of a score for a SA criteria was found to be clear and user-friendly with a +/- scale and 1-5 score. In addition, the method for determining the weighting factors is a handy and simple application and not time-consuming if you have the necessary information. The assessment results are clearly presented and it is also a good to hide the total score at first so you can assess it objectively, otherwise you will allocate to a certain preferred design the moment you fill in an assessment. You only have to add weighting factors after the assessment. Besides, because you can collapse the table, you can broadly assess the scores per design on the themes, which makes it more clear. The proposed SA tool can be used and implemented without any problems.

Lastly, the expert indicated that the proposed SA tool could also be relevant and applicable for road projects, because in those projects you also have to deal with the same themes. However, the description of the SA criteria has to be adapted according to the specific characteristics of these projects.

7.6 Findings from the Reference Case and Interview

The interview with the expert with the intention to evaluate the conceptual SA framework, MCA method and proposed SA tool resulted in the following findings and conclusions.

With the SA framework and tool, sustainability is secured and given an important place in making integral design choices and evaluating design options, that help support improved sustainability practices within Antea Group. The SA framework provides an overview and frame of reference when making integral design choices, when ambitions are focussed on sustainability and the SA tool tackles the issue of assessing, comparing and ranking of design options regarding their contribution to sustainability from the early phases of a project (ex-ante evaluation). The SA tool can also be applied in the different stages with the design phase.

In addition, the best-worst method is found to be time efficient, effective and an easy to use tool for determining the weighting factors of the themes. As a result, design options can also be compared on the themes instead of just a final score. This ensures that Antea Group can provide advice more objectively for the choice of a preferred design option.

Furthermore, the SA criteria identified in this research can potentially be applied to a variety of other infrastructure projects. The SA framework and tool can be adapted to other types of projects and they allow flexibility for the addition of new criteria in the future.

Lastly, the SA tool provides flexibility because the analysis can be done at a higher level of abstraction, in a more qualitative manner for criteria and aspects for which there is insufficient information or data. Besides, the analysis can also be performed more quantitatively, although quantitative data is not always available or costs a lot more time/money to gather. The next chapter will discuss the conclusion, discussion and recommendations and provide an answers to main research question.

CHAPTER 8
CONCLUSION, DISCUSSION AND RECOMMENDATIONS

8 Conclusion, Discussion and Recommendations

The conclusion, discussion and recommendations are discussed in this chapter. Based on the knowledge gained from the sub research questions, the conclusion section provides an answer to the main research question. The challenges that were encountered during the implementation of the research, as well as the limits of the conceptual sustainability assessment framework and proposed sustainability assessment tool are highlighted in the discussion section. Finally, several recommendations are given to Antea Group, as well as some suggestions for future research.

8.1 Conclusion

In order to answer the main research question, the answers to the sub research questions are provided first in sequence, then based on the knowledge acquired from these questions the main research question can be answered.

8.1.1 Answers to the Sub Research Questions

SQ1: What are the existing sustainability assessment approaches used in the construction industry and infrastructure sector that attempt to integrate the three dimensions of sustainability?

In order to answer this sub-research question, a literature review on sustainability and sustainability assessment approaches was conducted. First, the TBL (3Ps) theory coined by John Elkington, a well-known concept in sustainable development (SD) was selected as a sound theory regarding the three interdependent dimensions of sustainability. Subsequently the literature review and analysis of the existing sustainability assessment approaches took place. The findings showed that despite the numerous sustainability assessment approaches available, none of them address sustainability as a whole. While there are positive characteristics associated with each approach, some practical issues remain unsolved. The literature review showed that there is no simple solution for the assessment of projects, specifically when tackling sustainability of highway projects. In other words, all sustainability assessment approaches have their strengths and weaknesses, but none of the tools and methods analysed are suitable for a comprehensive assessment of the sustainability of highway design options that are currently available. However, the MCA approach seemed to be the most suitable for developing an new sustainability assessment tool that integrates criteria from the three dimensions of sustainability. In line with the results of the analysis of existing sustainability assessment approaches, the author concludes that combining results from existing sustainability assessment approaches and sustainability assessment criteria in one comprehensive MCA sustainability assessment framework could be beneficial for effectively integrating and balancing all dimensions of sustainability (TBL) in the assessment of design choices and options.

SQ2: What are the sustainability assessment criteria from literature that cover all the three dimensions of sustainability to form a preliminary list?

In order to answer this sub research question, a literature review on sustainability assessment criteria in the context of the construction and infrastructure sector was conducted. The review of existing assessment frameworks and rating systems shows that, a large number of studies propose frameworks with sustainability assessment criteria but fail to integrate them into a unified and more comprehensive framework. In addition, only a few studies have looked at highways, but not at identifying relevant sustainability assessment criteria specific for the planning- and design phase (ex-ante evaluation) and specific for the Dutch highway context, which is exactly the gap this research aims to fill. A total of 64 sustainability assessment criteria (22 environmental, 30 social and 12 economic respectively) from the construction and infrastructure sector were identified through surveying recent literature, which formed the preliminary list of criteria. The list is presented in appendix B.1. The list with 64 sustainability assessment criteria provide the answer to the second sub research question.

SQ3: Which sustainability assessment criteria are relevant for the Dutch highway context to form the comprehensive sustainability assessment framework?

In order to answer this sub research question, a filtering process on the sustainability assessment criteria was conducted and subsequently a questionnaire survey was held to establish which are relevance to the Dutch highway context. The following steps were applied during the filtering process: (1) criteria with similar context (overlapping) were merged, while sector specific criteria were excluded and (2) criteria presented in rating systems were included in de proposed sustainability assessment framework. The filtering process resulted in a reduction to 34 sustainability assessment criteria. After this process a questionnaire survey was sent to experts within Antea Group to check the relevance of the sustainability assessment criteria during the planning- and design phase of the Dutch highway context. With the help of 12 experts from Antea Group, the proposed sustainability assessment framework with 34 criteria was validated and while two criteria were excluded from the list, an additional of four criteria (namely: energy consumption (construction & demolition), energy consumption (fuel), environmental cost indicator, material production) were added based on expert opinions and experience. The survey resulted in the development of the conceptual sustainability assessment framework. This framework consists of 36 sustainability assessment criteria, which are categorised in their corresponding social, environmental and economic (3Ps) dimensions of sustainability and related 9 themes, presented in appendix C.4. The conceptual assessment framework which integrates the 36 sustainability assessment criteria for the Dutch highway context provides the answer to the third sub research question.

SQ4: How can the sustainability assessment tool be applied practice?

In order to answer this sub research question, an assessment procedure is provided for the conceptual sustainability assessment framework, to form the proposed sustainability assessment tool. The tool is basically a design option analysis in which the design choices and options are assessed on their contribution to the sustainability. For this analysis, a trade-off matrix is utilized. The trade-off matrix consists of the themes and sustainability assessment criteria presented in the conceptual sustainability assessment framework. In this sustainability assessment tool, the best-worst method (MCA approach) is used to determine the weighting factors of the themes. For each project, the weighting must be determined in consultation between the project team (consisting of experts from Antea Group), RWS and stakeholders. The weights are not fixed in the tool. Each design option can be assessed on the sustainability assessment criteria, so that a score is provided. In the sustainability assessment tool, design options are compared to each other to be able to give well-informed advice to RWS and make a carefully considered choice.

After developing the proposed sustainability assessment tool, the tool is tested by applying it to a reference case (highway project). Based on the results from the reference case, the functioning, applicability and possible implications of the proposed tool were evaluated with an expert involved in the project. From the evaluation of the tool with the experts, some recommendations followed that need further research. The evaluated SA tool provides answers to fourth sub research question, presented in appendix D.4.

8.1.2 Answer to the Main Research Question

"How can the three dimensions of sustainability be integrated into one comprehensive sustainability assessment tool for making integral design choices and assessing design options during the planning- and design phase in the Dutch highway context?"

Based on the knowledge and results acquired through answering the sub research questions, the main research question can now be answered. In the developed sustainability assessment tool, the social, environmental and economic dimensions of sustainability (People, Planet, Prosperity) are integrated into one comprehensive framework specific for the Dutch highway context. The tool can assess, compare, evaluate and rank design options based on the relevant sustainability assessment criteria. The criteria assess to what extent a design choice and option contributes to the creation of sustainable added value and the realization of sustainability objectives of RWS aimed at realizing a sustainable living environment and rank them accordingly. In this tool, design options can be explicitly weighed up on all dimensions of sustainability, related themes and corresponding sustainability assessment criteria which can support the decision-making.

The conceptual sustainability assessment framework can be used as an overview and frame of reference when making integral design choices. With the aim to help substantiated design choices and tackling sustainability from the very first phases to the implementation of a project. The framework offers a practical way to secure that sustainability is an integral part in the design choices, considerations and effect determination during the regular design process. This helps designers make a choice that leads to more sustainability. As a result, Antea Group can realize that RWS (can) make integral decisions regarding sustainability, so that sustainable solutions can be included in the design options.

The added value of the conceptual sustainability assessment framework is that it provides a systematic overview of all possible aspects of sustainability that can be taken into account during the planning- and design phase (MIRT-Exploration and MIRT-Plan Elaboration phase) of a highway project. In addition, it can help designers and decision-makers understand how the environmental, economic and social dimensions of sustainability (People, Planet, Prosperity) can be used to decrease the negative impacts of highway projects and embrace the principles of sustainability with respect to environmental protection, economic profitability and human well-being, to make their highway designs more sustainable and to contribute towards sustainable development (SD).

8.2 Discussion

8.2.1 Contribution to the Literature

The sustainability assessment framework and tool can deliver an important contribution to making highways in the Netherlands more sustainable and move towards sustainable development (SD). They can ensure that design issues are exposed from a completely new perspective, in this research from the sustainability viewpoint.

8.2.2 Scientific Contribution

The main scientific contribution of this research is that the comprehensive sustainability assessment framework based on the concept of sustainability (TBL) helps tackle the research gap in the literature with regard to sustainability integration into highway projects and the effectiveness of existing SA approaches. Ultimately, the conceptual assessment framework and proposed sustainability assessment tool integrate the principles of sustainability and enables new practical and theoretical solutions to help enhance the integration of sustainability within the highway infrastructure sector.

There are six ways in which this research contributes to the literature:

1. Results of this research, present ways for designers and decision-makers to secure sustainability in future design choices. The framework may be used during the design process to guide designers toward sustainable solutions and to understand what is required, so that they are challenged to come up with sustainable designs;
2. This is the first research which has focused on identifying sustainability assessment criteria for the Dutch highway context in all three dimensions including environmental, economic and social dimensions (People, Planet, Prosperity);
3. This research is one of the limited researches focussing on the Dutch highway context that considered and integrated the social, economic and environmental dimensions of sustainability (People, Planet, Prosperity), also known to as triple bottom line (TBL) into a comprehensive sustainability assessment framework. This research combines an integral overview of themes and criteria with a method for properly weighing and applying them;
4. Although the focus of this research was on the Dutch highway context, the framework can potentially be used for other types of projects in the Netherlands, as well as highway projects in other nations. Because most criteria were found in studies focussing on the construction industry and infrastructure sector. However, the criteria should carefully be adapted to the specific characteristics of other projects and the ways in which those projects can contribute to sustainability;
5. The questionnaire survey resulted in an additional of four criteria (namely: energy consumption (construction & demolition), energy consumption (fuel), environmental cost indicator, material production) based on expert opinions and experience, which were not found in literature; and
6. For the first time the best-worst method is applied in a sustainability assessment tool specific for highway infrastructure to assess and evaluate the sustainability of highway design options and ranking them.

8.2.3 Practical Contribution

This research provides engineering consultancy firm Antea Group with a new sustainability assessment framework and tool that aims to support in evaluating, comparing and assessing highway design options from the sustainability viewpoint, based on sustainability assessment criteria. This sustainability assessment tool is not biased towards one sustainable dimension, but fully address all the dimensions of sustainability (People, Planet, Prosperity) that help enhance the decision-making. With this sustainability assessment tool Antea Group could give even more body to sustainability, so that Antea Group can support its clients in making well-informed choices regarding highway design options. The sustainability assessment tool provides connection to the essence of the TBL principle, sustainable development (SD) as well as integrating sustainability more explicitly into the design process and assessment practice.

There are six ways in which this research contributes the current practices:

1. With the sustainability assessment framework and tool, sustainability is secured and given an important place in making integral design choices and evaluating design options, which is essential for sustainability-driven decision-making and help support improved sustainability practices within the construction industry, particularly the highway infrastructure sector;

2. The sustainability assessment tool tackles the issue of assessing, comparing and ranking of design options regarding their contribution to sustainability from the early phases of a project (ex-ante evaluation). In addition, the tool allows flexibility for the addition of new criteria in the future;
3. The best-worst method is time efficient compared to other methods, effective and an easy to use tool for determining the weighting factors of the themes. As a result, design options can also be compared on the themes instead of just a final score. This ensures that Antea Group can provide advice more objectively for the choice of a preferred design option;
4. The description of the sustainability assessment criteria identified in this research can possibly be revised to a variety of other infrastructure projects. However, much detail must be given to the way in which other types of projects can contribute to sustainability, based on its specific characteristics. In this way the sustainability assessment framework and tool can perhaps be adapted to other types of projects;
5. The concept of sustainable development is constantly evolving and governments and public clients are regularly introducing new law and regulations in order to promote progress toward sustainability objectives, goals and targets. With this framework and tool, Antea Group is prepared to act sustainably and gain a competitive advantage in the market, because they can successfully integrate the social, economic and environmental dimensions of sustainability (People, Planet, Prosperity) in their highway designs;
6. Assessing sustainability and measuring it is still in its infancy. There is yet no methodology available that can make all aspects of sustainability fully measurable. In the sustainability assessment tool it was therefore decided to use a combination of qualitative and quantitative methods in order to gain a broad insight into the degree of sustainability. This gives flexibility, because the analysis can be performed at a somewhat higher level of abstraction, in a more qualitative way instead of quantitative data that is not always available or costs a lot of time/money to make.

8.2.4 Limitations of the Research

This section acknowledges the limitations of conducted research.

- This research limits the pairwise comparisons and use of best-worst method only to the themes. This is done because not all criteria are relevant for each phase in the design process. So if the sustainability assessment criteria used, constantly change, it would become a complex, more time-consuming assessment procedure and determination of the weights. Far more labour and comparison are required, that is why this research has this limitation. And now that only the themes are determined, the decision-maker can better keep a full picture in mind before conducting the pairwise comparison. In addition, subjectivity is always part of decision-making;
- The use of a reference case was restricted to only one project. However, it is safe to consider that applying the tool to the reference case and evaluating this with the project leader involved in the assessment and decision-making, resulted in useful research findings. The expert present in the evaluation of the sustainability assessment framework and tool was the project leader of the project team that was realizing the highway project and had close, direct contact with the client (RWS).

8.3 Recommendations

This section consists of recommendation for Antea Group and for future research. Based on the findings from this research, the following recommendations are suggested.

8.3.1 Recommendations for Antea Group

- Antea Group is recommended and encouraged to apply the tool on other highway projects to evaluate and enhance the tool for further improvements;
- The sustainability assessment framework could also be very valuable for the MIRT-Realisation phase, as sustainable benefits can also be achieved in this phase by continuing to weigh the various criteria integrally;
- It is important that the client provides room in their budget for implementing sustainable solutions. Antea Group should therefore always discuss and address this with the client as early as possible. Because now, in many cases, a sustainable design is not chosen due to a lack of investment. As a result, it often becomes a trade-off with other investments and sustainability repeatedly turns out to be the least important compared to other objectives within the project;
- The expected outcomes of applying the sustainability assessment tool in practice are not yet certain. There is not enough time to apply the tool in a new project within the scope of this research. The tool should be applied in a future project, so that new insights and experience can be gained in practice and to embed the tool in the practice of Antea Group. So that the tool and sustainability are given a place in Antea Group and everyday work; and
- With this tool, experts within Antea Group not only know how to think sustainably, for instance, what is needed to for a design to be sustainable, but they also know how to act and put it into practice. This helps to promote awareness for sustainability within Antea Group.

8.3.2 Recommendations for Future Research

- The considered sustainable assessment criteria were taken from the construction and infrastructure sector. Based on the findings of this research, the conceptual sustainability assessment framework might also be applicable and relevant to road or other infrastructure projects, because they also deal with the same themes and subjects. The adaptation of this framework to such infrastructure projects would be the next critical step;
- It is recommended to look at civil engineering structures (bridges, tunnels), where the assessment can differ significantly compared to highways. Whereas highways often revolve around the project's use of space, civil engineering structures are often concerned with which materials are use and applied in the structure that make the most impact. This means that also within civil engineering structures a lot of sustainability benefits can be achieved;
- This research developed the sustainability assessment tool within a engineering consultancy firm. It is recommended to validate the sustainability assessment tool from Rijkswaterstaat (RWS), client's point of view and consultancy's point of view in conjunction;
- This research did not take into account the interrelationships between the sustainability assessment criteria. Many researchers argue that sustainability is a multifaceted issue with sometimes conflicting interests. Positive contributions to specific sustainability assessment criteria may have a negative impact on another assessment. In light of this, it is recommended that the interrelationship between the sustainability assessment criteria integrated in the sustainability assessment be further investigated in order to help designers and decision-makers to make well-informed decisions; and
- Examine whether the identified sustainability assessment criteria are also relevant or useful in other phases of highway projects. The identified sustainability assessment criteria are relevant for the planning- and design phase (FO to UO phases of the road design process and the MIRT-Exploration and MIRT-Plan Elaboration phase) of highway projects. However, it is wise to take them into account as early as possible in a project. Therefore, the sustainability assessment criteria could be considered as a starting point, for research in other phases of a highway project.

8.4 Reflection

In this section I reflect on the graduation process and what I have learned. In appendix E.1, the graduation process is described in detail.

In the beginning of the process I was really struggling to find a research topic and did not really know how research was conducted. To gain a better understanding of what is expected during the graduation period, I should have followed interesting research and publications of lecturers, read previous thesis and watched graduation presentations before conducting my own thesis. This would have provided me with a clearer picture of what was expected of me.

I personally found that writing my thesis from home was not the best way to make the most progress. However, during the process this was sometimes the only option due to COVID-19 and lockdown. To get the most out of the thesis period, I would advise others to work from a more social setting, such as an office or the TU Library if possible, in order to build a network, socialize and interact with professionals or other students to receive tips, feedback and advice.

The most difficult part of the research was the preparation phase in which the practical problem and theoretical gap are translated to a research problem, objective, main question, choice of methods (data collection and analysis procedures) and intended result. I have learned that it is very important to know what problem the research is going to tackle, by asking myself: *"What is the issue?"*, *"What do we know about the issue?"* and *"What is missing?"*. This is crucial for communicating the objective of the research and ensuring that all committee members and supervisors are on the same page.

For a long time during the process, I was not holding on to a schedule, which resulted in slow progress and not having any planned milestones. This caused for confusion by the supervisors, because they had no idea what I was doing or how I was progressing. I would advise others, including myself, to make a detailed plan with milestones, including weekly meetings, the kick-off meeting, mid-term meeting(s), and the green light meeting. In addition, send work-in-progress, like sections, chapters, parts of the report and agendas to supervisors before the meetings to let them know what the purpose of the meeting is and what you want feedback on. I also noticed that having a planning put more pressure on me, which significantly accelerated my progress. More pressure worked for me, but that does not mean it will work for everyone.

In the past months I have learned a lot from my committee members, supervisors and other professionals from Antea Group. As I progressed through the graduation process, I gained valuable knowledge and received positive feedback that I had matured and developed a more professional attitude toward others. I would like to express my appreciation and thanks to the committee members and supervisors for these valuable lessons and experiences.

[This page is intentionally left blank]

References

Abdel-Raheem, M., & Ramsbottom, C. (2016). Factors affecting social sustainability in highway projects in Missouri. *Procedia Engineering*, *145*, 548–555.

Abidin, N. Z. (2010). Investigating the awareness and application of sustainable construction concept by Malaysian developers. *Habitat International*, *34*(4), 421–426.

Adshead, D., Thacker, S., Fuldauer, L. I., & Hall, J. W. (2019). Delivering on the Sustainable Development Goals through long-term infrastructure planning. *Global Environmental Change*, *59*. https://doi.org/10.1016/j.gloenvcha.2019.101975

Ahmadi, H. B., Kusi-Sarpong, S., & Rezaei, J. (2017). Assessing the social sustainability of supply chains using Best Worst Method. *Resources, Conservation and Recycling*, *126*, 99–106.

Amiril, A., Nawawi, A. H., Takim, R., & Latif, S. N. F. A. (2014). Transportation infrastructure project sustainability factors and performance. *Procedia-Social and Behavioral Sciences*, *153*, 90–98.

Antea Group. (2020). *Kunstwerkenbeheer in de praktijk*.

Antea Group. (2021a). *Informatie WerkBewust! en duurzaamheid t.b.v. het tenderproces*.

Antea Group. (2021b, April 21). *Duurzaamheid*. https://anteagroup.nl/duurzaamheid

Berardi, U. (2012). Sustainability assessment in the construction sector: rating systems and rated buildings. *Sustainable Development*, *20*(6), 411–424.

Beria, P., Maltese, I., & Mariotti, I. (2012). Multicriteria versus Cost Benefit Analysis: a comparative perspective in the assessment of sustainable mobility. *European Transport Research Review*, *4*(3), 137–152.

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2017). *Cost-benefit analysis: concepts and practice*. Cambridge University Press.

Bond, A., Pope, J., & Morrison-Saunders, A. (2012). *The state of the art of impact assessment in 2012*. Taylor & Francis.

Broniewicz, E., & Ogrodnik, K. (2020). Multi-criteria analysis of transport infrastructure projects. *Transportation Research Part D: Transport and Environment*, *83*, 102351. https://doi.org/https://doi.org/10.1016/j.trd.2020.102351

Bueno, C., & Fabricio, M. M. (2018). Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in. *Automation in Construction*, *90*, 188–200.

Bueno, C., Pereira, L. M., & Fabricio, M. M. (2018). Life cycle assessment and environmental-based choices at the early design stages: an application using building information modelling. *Architectural Engineering and Design Management*, *14*(5), 332–346.

Bueno, C., Vassallo, J. M., & Cheung, K. (2013). Road infrastructure design for optimizing sustainability. *Final Report. European Investment Bank. StareBEI Programme*.

Bueno Cadena, P. C., & Vassallo Magro, J. M. (2015). Setting the weights of sustainability criteria for the appraisal of transport projects. *Transport*, *30*(3), 298–306.

Bueno, P. C., Vassallo, J. M., & Cheung, K. (2015). Sustainability Assessment of Transport Infrastructure Projects: A Review of Existing Tools and Methods. *Transport Reviews*, *35*(5), 622–649. https://doi.org/10.1080/01441647.2015.1041435

Ciegis, R., Ramanauskiene, J., & Martinkus, B. (2009). The concept of sustainable development and its use for sustainability scenarios. *Engineering Economics*, *62*(2).

Clevenger, C. M., Ozbek, E., & Simpson, S. (2013). *Review of Sustainability Rating Systems used for Infrastructure Projects*.

Damart, S., & Roy, B. (2009). The uses of cost–benefit analysis in public transportation decision-making in France. *Transport Policy*, *16*(4), 200–212.

DiCicco-Bloom, B., & Crabtree, B. F. (2006). The qualitative research interview. In *Medical Education* (Vol. 40, Issue 4, pp. 314–321). https://doi.org/10.1111/j.1365-2929.2006.02418.x

Dimitriou, H. T., Ward, E. J., & Dean, M. (2016). Presenting the case for the application of multi-criteria analysis to mega transport infrastructure project appraisal. *Research in Transportation Economics*, *58*, 7–20.

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment*, *123*, 243–260.

Elkington, J. (1994). Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development. *California Management Review*, *36*(2). https://doi.org/10.2307/41165746

Elkington, J. (1997). *Cannibals with forks The Triple bottom line of 21ste century business*.

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of Science and Google Scholar: strengths and weaknesses. *The FASEB Journal*, *22*(2), 338–342. https://doi.org/10.1096/fj.07-9492lsf

Fernández-Sánchez, G., & Rodríguez-López, F. (2010). A methodology to identify sustainability indicators in construction project management—Application to infrastructure projects in Spain. *Ecological Indicators*, *10*(6). https://doi.org/10.1016/j.ecolind.2010.04.009

Gasparatos, A., & Scolobig, A. (2012). Choosing the most appropriate sustainability assessment tool. *Ecological Economics*, *80*(0), 1–7.

Ghoushchi, S. J., Dorosti, S., Khazaeili, M., & Mardani, A. (2021). Extended approach by using best–worst method on the basis of importance–necessity concept and its application. *Applied Intelligence*, 1–15.

Gibson, B., Hassan, S., & Tansey, J. (2005). *Sustainability assessment: criteria and processes*. Routledge.

Goh, C. S. (2018). Towards an Integrated Approach for Assessing Triple Bottom Line in the Built Environment. *Proceedings of 2017 International Conference on Advances on Sustainable Cities and Buildings Development, Porto Portugal, 15-17 November 2017*.

Goh, C. S., Chong, H. Y., Jack, L., & Mohd Faris, A. F. (2020). Revisiting triple bottom line within the context of sustainable construction: A systematic review. In *Journal of Cleaner Production* (Vol. 252). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2019.119884

Green Deals. (2021, April 21). *Aanpak*. https://www.greendeals.nl/aanpak

Griffiths, K., Boyle, C., & Henning, T. F. P. (2018). Sustainability rating tools for highway projects: the nature and outcomes of use. *Infrastructure Asset Management*, *5*(2), 35–44.

Groenendijk, L., Rezaei, J., & Correia, G. (2018). Incorporating the travellers' experience value in assessing the quality of transit nodes: A Rotterdam case study. *Case Studies on Transport Policy*, *6*(4), 564–576.

Gudmundsson, H., Marsden, G., & Josias, Z. (2016). *Sustainable transportation: Indicators, frameworks and performance management*.

Gühnemann, A., Laird, J. J., & Pearman, A. D. (2012). Combining cost-benefit and multi-criteria analysis to prioritise a national road infrastructure programme. *Transport Policy*, *23*, 15–24.

Hacking, T., & Guthrie, P. (2008). A framework for clarifying the meaning of Triple Bottom-Line, Integrated and Sustainability Assessment. *Environmental Impact Assessment Review*, *28*(2–3), 73–89.

Hamersma, M., Heinen, E., Tillema, T., & Arts, J. (2017). New highway development in the Netherlands: A residents' perspective. *Transportation Research Part D: Transport and Environment*, *51*, 326–339.

Ibrahim, A. H., & Shaker, M. A. (2019). Sustainability index for highway construction projects. *Alexandria Engineering Journal*, *58*(4), 1399–1411. https://doi.org/10.1016/j.aej.2019.11.011

Inti, S., & Tandon, V. (2021). Towards precise sustainable road assessments and agreeable decisions. *Journal of Cleaner Production*, *323*, 129167.

Jackson, L. P., Grinsted, A., & Jevrejeva, S. (2018). 21st Century sea-level rise in line with the Paris accord. *Earth's Future*, *6*(2), 213–229.

Jørgensen, A., le Bocq, A., Nazarkina, L., & Hauschild, M. (2008). Methodologies for social life cycle assessment. *The International Journal of Life Cycle Assessment*, *13*(2), 96–103.

Kibert, C. (1994). *Final Session of First International Conference of CIB TG 16 on Sustainable Construction*.

Kivilä, J., Martinsuo, M., & Vuorinen, L. (2017). Sustainable project management through project control in infrastructure projects. *International Journal of Project Management*, *35*(6), 1167–1183. https://doi.org/10.1016/j.ijproman.2017.02.009

Koo, D.-H., Ariaratnam, S. T., & Kavazanjian, E. (2009). Development of a sustainability assessment model for underground infrastructure projects. *Canadian Journal of Civil Engineering*, *36*(5). https://doi.org/10.1139/L09-024

Kumar, A., & Ramesh, A. (2020). An MCDM framework for assessment of social sustainability indicators of the freight transport industry under uncertainty. A multi-company perspective. *Journal of Enterprise Information Management*.

Labuschagne, C., Brent, A. C., & van Erck, R. P. G. (2005). Assessing the sustainability performances of industries. *Journal of Cleaner Production*, *13*(4), 373–385.

Lee, J. C., Edil, T. B., Benson, C. H., & Tinjum, J. M. (2011). Evaluation of variables affecting sustainable highway design with BE2ST-in-Highways system. *Transportation Research Record*, *2233*(1), 178–186.

Li, Q., Rezaei, J., Tavasszy, L., Wiegmans, B., Guo, J., Tang, Y., & Peng, Q. (2020). Customers' preferences for freight service attributes of China Railway Express. *Transportation Research Part A: Policy and Practice*, *142*, 225–236.

Lin, S.-H., Zhao, X., Wu, J., Liang, F., Li, J.-H., Lai, R.-J., Hsieh, J.-C., & Tzeng, G.-H. (2021). An evaluation framework for developing green infrastructure by using a new hybrid multiple attribute decision-making model for promoting environmental sustainability. *Socio-Economic Planning Sciences*, *75*, 100909.

Liu, B., Xue, B., & Chen, X. (2021). Development of a metric system measuring infrastructure sustainability: Empirical studies of Hong Kong. *Journal of Cleaner Production*, *278*, 123904.

Liu, X., Schraven, D., de Bruijne, M., de Jong, M., & Hertogh, M. (2019). Navigating transitions for sustainable infrastructures-The case of a new high-speed railway station in Jingmen, China. *Sustainability (Switzerland)*, *11*(15). https://doi.org/10.3390/su11154197

Liu, Y., van Nederveen, S., Wu, C., & Hertogh, M. (2018). Sustainable Infrastructure Design Framework through Integration of Rating Systems and Building Information Modeling. *Advances in Civil Engineering*, *2018*. https://doi.org/10.1155/2018/8183536

Mahmoudi, R., Shetab-Boushehri, S.-N., Hejazi, S. R., & Emrouznejad, A. (2019). Determining the relative importance of sustainability evaluation criteria of urban transportation network. *Sustainable Cities and Society*, *47*, 101493.

Mangili, P. v, Santos, L. S., & Prata, D. M. (2019). A systematic methodology for comparing the sustainability of process systems based on weighted performance indicators. *Computers & Chemical Engineering*, *130*, 106558.

Mansell, P., Philbin, S. P., Broyd, T., & Nicholson, I. (2019). Assessing the impact of infrastructure projects on global sustainable development goals. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, *173*(4), 196–212.

Mansourianfar, M. H., & Haghshenas, H. (2018). Micro-scale sustainability assessment of infrastructure projects on urban transportation systems: Case study of Azadi district, Isfahan, Iran. *Cities*, *72*, 149–159.

Marcelino-Sádaba, S., González-Jaen, L. F., & Pérez-Ezcurdia, A. (2015). Using project management as a way to sustainability. from a comprehensive review to a framework definition. In *Journal of Cleaner Production* (Vol. 99, pp. 1–16). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2015.03.020

Mattinzioli, T., Sol-Sánchez, M., Martínez, G., & Rubio-Gámez, M. (2020). A critical review of roadway sustainable rating systems. *Sustainable Cities and Society*, 102447.

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., & Verbeeck, G. (2018). Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Building and Environment*, *133*, 228–236.

Molaei, M., Hertogh, M. J. C. M., Bosch-Rekveldt, M. G. C., & Tamak, R. (2021). Factors affecting the integration of sustainability in the early project phases in an integrated project management model. *Research on Project, Programme and Portfolio Management*, 25–39.

Mouter, N., Bueno, P. C., & Vassallo, J. M. (2021). *New methods, reflections and application domains in transport appraisal*. Academic Press.

Omura, M. (2004). Cost-benefit analysis revisited: is it a useful tool for sustainable development. *Kobe University Economic Review*, *50*, 43–58.

Pakzad, P., & Osmond, P. (2016). Developing a sustainability indicator set for measuring green infrastructure performance. *Procedia-Social and Behavioral Sciences*, *216*, 68–79.

Pamucar, D., Iordache, M., Deveci, M., Schitea, D., & Iordache, I. (2021). A new hybrid fuzzy multi-criteria decision methodology model for prioritizing the alternatives of the hydrogen bus development: A case study from Romania. *International Journal of Hydrogen Energy*, *46*(57), 29616–29637.

Pellicer, E., Sierra, L. A., & Yepes, V. (2016). Appraisal of infrastructure sustainability by graduate students using an active-learning method. *Journal of Cleaner Production*, *113*. https://doi.org/10.1016/j.jclepro.2015.11.010

PIANOo. (2016). *Levenscycluskosten als gunningscriterium: Een praktische aanzet tot gebruik*.

PIANOo. (2020). *Stappenplan: Inkopen doen met de mileukostenindicator*.

PIANOo. (2022, February 24). *Meten en monitoren van circulair en klimaatneutraal aanbesteden voor de GWW-sector (leernetwerk GWW, 26 september 2019)*. https://www.pianoo.nl/nl/meten-en-monitoren-van-circulair-en-klimaatneutraal-aanbesteden-voor-de-gww-sector-leernetwerk-gww

Pope, J., & Morrison-Saunders, A. (2013). *Pluralism in practice*. Routledge, Taylor & Francis Group.

Reid, L. M., Davis, A. J., & Bevan, T. (2013). *Approach for Integrating Sustainability into Roadway Project Development*.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega*, *53*, 49–57.

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega*, *64*, 126–130.

Rezaei, J., Wang, J., & Tavasszy, L. (2015). Linking supplier development to supplier segmentation using Best Worst Method. *Expert Systems with Applications*, *42*(23), 9152–9164.

Rijkswaterstaat. (2016). *Spelregels van het Meerjarenprogramma Infrastructuur, Ruimte en Transport (MIRT)*.

Rijkswaterstaat. (2018). *Summary: The Dutch Multi-Year Programme for Infrastructure, Spatial Planning and Transport (MIRT)*. www.rijksoverheid.nl

Rijkswaterstaat. (2019a). *Circulaire Economie voor MIRT-projecten*.

Rijkswaterstaat. (2019b). *MIRT en m.e.r., verkenning en planuitwerking*.

Rijkswaterstaat. (2020). *Energie en klimaat*. https://www.rijkswaterstaat.nl/zakelijk/duurzame-leefomgeving/energie-en-klimaat

Rijkswaterstaat. (2021a). *Duurzaam inkopen GWW*. https://magazines.rijksoverheid.nl/ienw/duurzaamheidsverslag/2018/01/duurzaam-inkopen-gww#:~:text=Als%20grote%20opdrachtgever%20in%20de,reductie%20in%202025%20te%20realiseren

Rijkswaterstaat. (2021b). *Duurzaam waterbeheer*. https://magazines.rijksoverheid.nl/ienw/duurzaamheidsverslag/2018/01/duurzaam-waterbeheer#:~:text=Bij%20het%20werken%20aan%20water,wateren%20voor%20planten%20en%20dieren

Rijkswaterstaat. (2021c). *Duurzame gebiedsontwikkeling*. https://magazines.rijksoverheid.nl/ienw/duurzaamheidsverslag/2018/01/duurzame-gebiedsontwikkeling#:~:text=Duurzame%20gebiedsontwikkeling%20betekent%20dat%20we,we%20ruimte%20aan%20duurzame%20initiatieven

Rijkswaterstaat. (2021d). *Gezondheid*. https://magazines.rijksoverheid.nl/ienw/duurzaamheidsverslag/2018/01/gezondheid#:~:text=Naast%20de%20klassieke%20gezondheidsthema's%2C%20zoals,met%20parken%20op%20het%20dak

Rijkswaterstaat. (2021e). *Natuurlijk kapitaal en biodiversiteit*. https://magazines.rijksoverheid.nl/ienw/duurzaamheidsverslag/2018/01/natuurlijk-kapitaal-en-biodiversiteit#:~:text=We%20proberen%20natuurlijk%20kapitaal%20al,om%20de%20biodiversiteit%20te%20beschermen

Rijkswaterstaat. (2021f). *Duurzame mobiliteit*. https://rwsduurzamemobiliteit.nl/praktijk/vergroenen/personen-goederenvervoer/#:~:text=Duurzame%20mobiliteit%20gaat%20over%20het,tegelijk%20de%20bereikbaarheid%20te%20verbeteren.

Rijkswaterstaat. (2021g). *Circulaire economie*. https://magazines.rijksoverheid.nl/ienw/duurzaamheidsverslag/2018/01/circulaire-economie-rws

Rijkswaterstaat Ministery van Infrastructuur en Waterstaat. (2019). *Kader wegontwerpproces 2.0*.

Rogers, M., & Duffy, A. (2012). *Engineering project appraisal*. John Wiley & Sons.

Rogers, M., & Enright, B. (2016). *Highway engineering*. John Wiley & Sons.

Rooshdi, R. R. R. M., Abd Majid, M. Z., Sahamir, S. R., & Ismail, N. A. A. (2018). Relative importance index of sustainable design and construction activities criteria for green highway. *Chemical Engineering Transactions*, *63*, 151–156.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, *15*(3), 234–281.

Saaty, T. L. (2005). *Theory and applications of the analytic network process: decision making with benefits, opportunities, costs and risks*. RWS publications.

Sabini, L., Muzio, D., & Alderman, N. (2019). 25 years of 'sustainable projects'. What we know and what the literature says. *International Journal of Project Management*, *37*(6), 820–838. https://doi.org/10.1016/j.ijproman.2019.05.002

Sahely, H. R., Kennedy, C. A., & Adams, B. J. (2005). Developing sustainability criteria for urban infrastructure systems. *Canadian Journal of Civil Engineering*, *32*(1), 72–85.

Sala, S., Ciuffo, B., & Nijkamp, P. (2015). A systemic framework for sustainability assessment. *Ecological Economics*, *119*, 314–325.

Shen, L., Wu, Y., & Zhang, X. (2011). Key Assessment Indicators for the Sustainability of Infrastructure Projects. *Journal of Construction Engineering and Management*, *137*(6). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000315

Sierra, L. A., Yepes, V., & Pellicer, E. (2018). A review of multi-criteria assessment of the social sustainability of infrastructures. In *Journal of Cleaner Production* (Vol. 187, pp. 496–513). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2018.03.022

Silvius, A. J. G., & Schipper, R. P. J. (2014). Sustainability in project management: A literature review and impact analysis. *Social Business*, *4*(1), 63–96. https://doi.org/10.1362/204440814x13948909253866

Sjostrom, C., & Bakens, W. (1999). CIB Agenda 21 for sustainable construction: why, how and what. *Building Research & Information, 27(6)*, 347–353.

Soltani, A., Hewage, K., Reza, B., & Sadiq, R. (2015). Multiple stakeholders in multi-criteria decision-making in the context of municipal solid waste management: a review. *Waste Management*, *35*, 318–328.

Suhi, S. A., Enayet, R., Haque, T., Ali, S. M., Moktadir, M. A., & Paul, S. K. (2019). Environmental sustainability assessment in supply chain: an emerging economy context. *Environmental Impact Assessment Review*, *79*, 106306.

Suprayoga, G. B., Bakker, M., Witte, P., & Spit, T. (2020). A systematic review of indicators to assess the sustainability of road infrastructure projects. *European Transport Research Review*, *12*(1), 1–15.

Tamak, R. (2017). *Use of Critical Success Factors in an Integrated Project Management Model to Improve the Chances of Project Success of a Sustainability Oriented Highway Project during the Exploration and Planning Phase*.

Taselaar, F. (2009). *Inleiding Kabels & leidingen*. COB.

Torres-Machi, C., Chamorro, A., Yepes, V., & Pellicer, E. (2014). Current models and practices of economic and environmental evaluation for sustainable network-level pavement management. *Revista de La Construcción. Journal of Construction*, *13*(2), 49–56.

Tsai, C. Y., & Chang, A. S. (2012). Framework for developing construction sustainability items: the example of highway design. *Journal of Cleaner Production*, *20*(1). https://doi.org/10.1016/j.jclepro.2011.08.009

Ugwu, O. O., & Haupt, T. C. (2007). Key performance indicators and assessment methods for infrastructure sustainability-a South African construction industry perspective. *Building and Environment*, *42*(2), 665–680. https://doi.org/10.1016/j.buildenv.2005.10.018

Ugwu, O. O., Kumaraswamy, M. M., Wong, A., & Ng, S. T. (2006). Sustainability appraisal in infrastructure projects (SUSAIP): Part 1. Development of indicators and computational methods. *Automation in Construction*, *15*(2), 239–251. https://doi.org/10.1016/j.autcon.2005.05.006

UN World Commission on Environment. (1987). *Report of the World Commission on Environment and Development: Our Common Future Towards Sustainable Development 2. Part II. Common Challenges Population and Human Resources 4*. https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf

United Nations. (2022). *Conferences Environment and sustainable development*. https://www.un.org/en/conferences/environment

van de Kaa, G., Kamp, L., & Rezaei, J. (2017). Selection of biomass thermochemical conversion technology in the Netherlands: A best worst method approach. *Journal of Cleaner Production*, *166*, 32–39.

van Eldik, M. A., Vahdatikhaki, F., dos Santos, J. M. O., Visser, M., & Doree, A. (2020). BIM-based environmental impact assessment for infrastructure design projects. *Automation in Construction*, *120*. https://doi.org/10.1016/j.autcon.2020.103379

Verheem, R. (2002). Recommendations for sustainability assessment in the Netherlands. *Commission for EIA. Environmental Impact Assessment in the Netherlands. Views from the Commission for EIA In*.

Verschuren, & Doorewaard. (2010). *Designing a Research Project, 2nd edition*.

Ward, E. J., Dimitriou, H. T., & Dean, M. (2016). Theory and background of multi-criteria analysis: Toward a policy-led approach to mega transport infrastructure project appraisal. *Research in Transportation Economics*, *58*, 21–45.

Yu, W. der, Cheng, S. T., Ho, W. C., & Chang, Y. H. (2018). Measuring the sustainability of construction projects throughout their lifecycle: A Taiwan Lesson. *Sustainability (Switzerland)*, *10*(5). https://doi.org/10.3390/su10051523

Zakaria, R., Seng, F. K., Majid, M. Z. A., Zin, R. M., Hainin, M. R., Puan, O. C., Yaacob, H., Derin, N., Ainee, F., & Hamzah, N. (2013). Energy efficiency criteria for green highways in Malaysia. *Jurnal Teknologi*, *65*(3).

Zhao, H., Guo, S., & Zhao, H. (2018). Comprehensive benefit evaluation of eco-industrial parks by employing the best-worst method based on circular economy and sustainability. *Environment, Development and Sustainability*, *20*(3), 1229–1253.

Appendices

Appendix A: Exploratory Interviews

Appendix A.1: Exploratory Interview Question List

Topic: Design processes within Antea Group

Date: 20-10-2021 & 21-10-2021

Introduction to the research

The following questions relate to the highway design process:

- Question: What does the design process look like and which phases are there?
- Question: Where is Antea Group involved in the MIRT-process?
- Question: What does the road design process look like?
- Question: What are the steps in the design phase?
- Question: Where in the design process is Antea Group involved?

The following questions relate to the assessment of design options:

- Question: How are highway infrastructure design options assessed?
- Question: Is the weighting of certain criteria/indicators/aspects determined in advance?
- Question: Which tools and methods are applied in the design process with regard to sustainability?
- Question: Are certain criteria/indicators assessed when choosing a design option?

The following questions relate to the sustainability:

- Question: Which considerations are made and is sustainability taken into account?
- Question: Is Antea Group proactive in applying sustainability in projects or is this due to the attitude and requirements of the client and whether it falls within the scope?
- Question: How is the transition to sustainable infrastructure going?
- Question: In which infrastructure projects does sustainability play a role?

The following question relates to the roles within Antea Group:

- Question: Which roles are present in the road design process and/or make the choices (project manager, designer, project engineer, consultant, client)?

The following questions relate to the scope of the research:

- Question: To define the scope, at what phases is it most relevant for Antea Group to look at with regard to applying and comparing sustainability in design options?
- Question: In view of the conversation we have had, it is relevant in your eyes to delve into defining the aspect of sustainability in a MCA, make it more tangible to be able to compare, evaluate and measure sustainability in different design options?

Appendix A.2: Original Transcript of the Answers

CONFIDENTIAL

Appendix B: Literature Study

Appendix B.1: Preliminary List of Sustainability Assessment Criteria found in Literature

Table B.1 - Preliminary list of sustainability assessment criteria found in literature

			Academic Literature																			Transport rating systems					RWS Documents	
		Sector	Highway infrastructure	Urban transportation infrastructure	Railway infrastructure	Transportation infrastructure	Transport infrastructure	Urban transportation infrastructure	Infrastructure	Road infrastructure	Construction	Highway infrastructure	Underground infrastructure	Infrastructure	Infrastructure	Infrastructure	Highway infrastructure	Infrastructure	Infrastructure	Construction	Construction	Highway	Road	Road	Road	Road	Social cost-Benefit analyse (CBA)	Environmental Impact Assessment (EIA)
		Source	(Inti & Tandon, 2021)	(Mahmoudi et al., 2019)	(Amiril et al., 2014)	(Broniewicz & Ogrodnik, 2020)	(Bueno & Vassallo, 2015)	(Mansourianfar & Haghshenas, 2017)	(Sierra et al., 2018)	(Suprayoga et al., 2020)	(Fernández-Sánchez & Rodríguez-López, 2010)	(Ibrahim & Shaker, 2019)	(Koo et al., 2009)	(Liu et al., 2021)	(Lin et al., 2021)	(Pakzad & Osmond, 2016)	(Rooshdi et al., 2018)	(Shen et al., 2011)	(Ugwu & Haupt, 2007)	(Yu et al., 2018)	(Sahely et al., 2005)	BE2ST-in-Highways	CEEQUAL	GreenRoads	GreenLITES	Envision	(Rijkswaterstaat: Werkwijzer MKBA bij MIRT-verkenningen, 2018b)	(Rijkswaterstaat: MIRT en m.e.r., verkenning en planuitwerking, 2018b)
No.	Criteria (environement-social-economic)	Total \ No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	Energy consumption	17	x	x	x		x	x		x	x	x	x	x	x	x					x	x		x	x	x		
2	Energy efficiency	9								x	x	x			x		x					x		x	x	x		

3	Generation of renewable energy	5								x	x				x										x	x		
4	Material balance with circular economy (CE)	9			x					x	x	x	x	x	x					x						x		
5	Sustainable procured materials	6									x											x		x	x	x		x
6	Reusability	4			x					x		x							x									
7	Reliability	5		x																			x	x		x	x	
8	Non-renewable materials consumption	5		x						x			x		x											x		
9	Cost-effective design	1								x																		
10	Life-Cycle Assessment (LCA)	2									x															x		
11	Recycled materials	9								x	x		x						x		x	x		x	x	x		
12	Design for disassembly	1									x																	
13	Adaptability	5			x					x	x	x														x		
14	Robustness	7			x					x	x	x											x	x		x		
15	Surface and groundwater quality	17		x	x	x				x	x	x	x	x		x		x	x	x		x		x	x	x		x
16	Buffers for ecological land	6								x	x			x		x	x									x		
17	Climate adaptation (flooding)	10								x	x	x		x		x	x			x			x		x	x		
18	Stormwater runoff & drainage	6								x	x			x		x	x									x		
19	Climate adaptation	8								x	x			x		x	x						x		x	x		
20	Soil quality	12			x	x					x	x	x	x		x		x						x	x	x		x
21	Innovation	6							x		x			x							x			x		x		
22	Soil consumption	8								x	x	x		x						x				x	x	x		
23	Agricultural land	7								x	x			x		x	x									x		x
24	Development land	6								x	x			x		x	x									x		
25	Archeological & historic sites	7		x						x		x	x					x								x		x
26	Biodiversity	14			x	x					x	x	x	x		x		x				x	x	x	x	x		x
27	Landscape structures	12					x		x	x	x				x				x			x	x	x	x	x		x
28	Brownfields	6								x	x			x		x	x									x		
29	Waste	10			x					x	x			x		x		x	x	x	x					x		
30	Ecosystem functions	17			x	x	x			x	x	x		x	x	x		x	x			x	x	x	x	x		x
31	Protected natural areas	7								x	x			x		x	x									x		x
32	Wayfinding	6		x						x		x	x											x		x		
33	Streams, wetlands, waterbodies and their riparian areas	5				x				x					x				x							x		
34	Residential, recreational and working areas	6				x						x	x					x								x		x
35	Aesthetics & degradation	2							x																			x

36	Spatial and visual quality	12		x	x			x			x		x	x					x			x		x	x	x		x
37	Vulnerability from vandalism & sabotage	1											x															
38	Traffic safety	9		x	x					x		x							x		x	x		x	x			
39	Local character	7								x	x			x		x	x									x		x
40	Emissions and air quality	20	x	x	x	x	x	x		x	x		x	x		x		x	x	x	x	x		x	x	x		x
41	Noise pollution and vibration	17	x	x	x	x	x	x		x		x				x		x	x	x		x		x	x	x		x
42	Light pollution	10		x		x				x	x	x		x										x	x	x		x
43	Cultural heritage	12		x	x	x					x	x		x				x	x	x				x		x		x
44	Stakeholder involvement & participation	8			x				x		x	x		x						x	x					x		
45	Connectivity between functions and communities	8		x			x		x	x				x		x		x								x		
46	Public support	4			x				x				x													x		
47	Traffic flow	7		x				x		x									x			x		x		x		
48	Economic efficiency	6		x	x			x		x											x					x		
49	Infrastructure network	4							x		x			x												x		
50	Accessibility to employment	3		x						x																x		
51	Pedestrian & bicycling facilities	3									x					x										x		
52	Flexibility	3												x			x									x		
53	Management and maintenance costs (LCC)	8			x					x	x	x		x					x							x	x	
54	Financial risks	4			x																		x			x	x	
55	Construction costs	8			x		x		x				x								x	x				x	x	
56	Road operating costs	4			x		x						x								x							
57	Social cost-benefit analysis (SCBA)	3								x																x	x	
58	Residual value of structure	1											x															
59	Local economy	11		x			x		x	x			x	x		x			x				x	x		x		
60	Regional development	8					x		x	x				x		x							x	x		x		
61	External safety	6											x				x		x					x		x		x
62	Nuisance during construction	4											x				x							x		x		
63	Construction safety	3											x											x		x		
64	Utility services	3											x													x		x

Appendix B.2: Proposed Sustainability Assessment Framework

Table B.2 - Proposed sustainability assessment framework

Dim	Theme code	Theme	Criterion code	Assessment criteria	Creating sustainable added value	Objective	Practical examples
Environment (Planet)	T1	Energy 	C1	Energy consumption	The extent to which the design contributes to energy savings during the life cycle	- Climate and energy neutral - Healthy living environment	- Apply LED lighting, energy-efficient installations (energy saving); - Use of renewable generated energy.
			C2	Generation of renewable energy	The extent to which the design contributes to the self-generation or supply of renewable, sustainable energy in the use phase	- Climate and energy neutral - Healthy living environment - Sustainable area development - Circular	- Use light poles or noise barriers with solar collectors (integrated in e.g. road furniture or civil structures); - Around the highway (e.g. junctions or exits), facilitate renewable, sustainable energy generation by third parties (assign space for e.g. solar panels and windmills). - Striving for a circular economy (connecting different energy flows).
	T2	Materials 	C3	Material balance with circular economy (CE)	The extent to which the design contributes to material savings, sustainability and CE during the life cycle	- Climate and energy neutral - Healthy living environment - Sustainable area development - Circular - Natural capital and biodiversity	- Application of new materials of sustainable origin, with attention to the entire production chain; - Lowering the Environmental Cost Indicator value (ECI-value), calculated with DuboCalc; - Focus on (high-quality) reuse, both at the front and after the end of life (closing the circular cycle); - Limit and reduce material use (material saving); - Striving for the lowest possible life cycle costs (LCC); - Use local secondary and renewable materials from the study area (extracted or produced in the vicinity).

	T3	Water & Climate	C4	Climate adaptation (flooding)	The extent to which the design contributes to the realization of a sustainable and robust water system	- Sustainable water management - Sustainable area development	- Creating new connections (waterways); - When the pavement surface is increased, also realize additional water storage (prevent the water system from being more heavily loaded which also ensures better flow due to less nuisance from water on the road); - Placing the highway on a higher elevated level (preventing flooding, evacuation route); - Avoid subsidence and flood-prone areas; - Increase water storage capacity of the soil; - Increase rainwater drainage system capacity (such as more swirls, larger pipe diameter, more closed/open water storage or installing gutters along the entire length of the road) for sufficient collection capacity at peak load.
			C5	Surface and groundwater quality	The extent to which the design contributes to improving surface and groundwater quality	- Sustainable water management- Healthy living environment	- Improve berm infiltration for the retention of contaminants in the topsoil (preventing run-off of contaminated water (such as metal particles due to wear, soot particles from exhaust gases, oil or zinc from road furniture) into surface and groundwater).- Separation of water drainage systems for clean and dirty water.
			C6	Climate adaptation (drought and heat stress)	The extent to which the design contributes to improving resilience to climate change	- Sustainable water management - Climate proof	- Prevent increase in paved surface (prevention of dehydration and decrease in water retention); - Realization of the highway outside the cores of urban areas; - Construction of sufficient greenery, shade and storage to relieve the drought and heat stress (less warming and radiation of heat to the environment).

	T4	Ecology & Nature 	C7	Ecosystem functions	The extent to which the design contributes to the preservation and strengthening of biodiversity (flora and fauna), coherence between ecosystem functions and the stimulation of natural capital	- Natural capital and biodiversity - Healthy living environment	- Apply ecological connection zones and fauna passages (e.g. ecoducts, wildlife tunnels and fish ladders) for migration or increase the capacity of existing passages (limiting fragmentation); - Providing space between ecological areas and the highway in the form of buffer zones, vegetation and soil protection zones; - Protect natural habitat to preserve or restore biodiversity (preventing the disappearance of plants, reduction in the population of animal species); - Planting trees along the highway for CO2 storage and limiting noise pollution, also benefits nature and recreation and provides an improved view for local residents, with less or even no decrease in value of homes near highways; - Application of an ecological verge design and ecological verge management (strengthening the technical and traffic functions but also the nature function of the verges); - Apply fauna grid along the highway (prevent animals from crossing the highway and causing accidents).
			C8	Protected natural areas	The extent to which the design contributes to the protection and restoration of the protected nature areas (Natura 2000 areas and Natuurnetwerk Nederland)	- Natural capital and biodiversity - Healthy living environment	- Adapting the design of the highway, so that a protected area is not affected by the project (prevention of surface loss, fragmentation, pollution, disturbance by noise, disturbance by light, disturbance by vibration, optical disturbance and change in population dynamics); - Connecting nature reserves to each other; - Develop new nature elsewhere or improve existing nature (compensation for nature affected on site by the project, required by law).
			C9	Soil quality	The extent to which the design contributes to improving soil quality	- Natural capital and biodiversity - Healthy living environment	- Prevent run-off of contaminated water (such as metal particles due to wear, soot particles from exhaust gases, oil or zinc from road furniture) into the soil; - Apply obstacle-free outer verge or nature-friendly road furniture; - Soil remediation; - Making the soil resistant to erosion (e.g. by planting).

Social (People)	T5	Culture & Landscape 	C10	Cultural heritage, archaeological and historical values	The extent to which the design contributes to the preservation and protection of cultural heritage, archaeological and historical value	- Sustainable area development	- Increase visibility of remains; - Apply soil drilling and possibly test trenches to systematically check whether traces and / or finds are present (limiting threats from earthworks); - Prevent damage to values by adapting existing project plans (e.g. by relocating the road); - Accentuating water systems and cultural-historical lines.
			C11	Landscape structures	The extent to which the design contributes to preserving and reinforcing typical features of the landscape and different areas	- Healthy living environment - Sustainable area development	- Preserving rows of trees, vegetation and open meadow landscapes (keeping landscape structures recognizable); - Strengthening desirable views, landscapes and vistas; - Prevent agricultural land from being used for verges and ditches; - Reuse of developed land and built-up land (existing paved surface and in a petrified environment); - Prevention of road widening, larger space requirements, intersection and deterioration of landscape values.
			C12	Residential, recreational and working areas	The extent to which the design contributes to improving the quality of life in residential, recreational and working areas	- Sustainable area development	- Prevent encroachment on residential plots, buildings, buildings and recreational areas by adapting existing project plans (e.g. by relocating the road); - Creating or improving walking paths, cycling routes, recreational areas and sports fields to stimulate movement and healthy behaviour.
			C13	Utility services	The extent to which the design contributes to improving cable and pipeline networks for utilities	- Sustainable area development	- Prevent damage and relocation of utilities (cables and pipelines) by adapting existing project plans (e.g. by relocating the road);- In the event of interventions, immediately improve the underground infrastructure or realize new utilities.
			C14	Connectivity between functions and communities	The extent to which the design contributes to improving connections and connectivity between existing functions and communities in an area	- Sustainable area development	- Preventing deteriorations for bicycle traffic, public transport & pedestrians (including loss of travel time, barrier effect, attractive routes); - Construction of access roads to surrounding neighborhoods.

	T6	Health & Well-being 	C15	Noise pollution and vibrations	The extent to which the design contributes to reducing the noise level and vibration of traffic to surrounding areas in the use phase	- Healthy living environment	- Increase distance between living, recreational and working areas; - Apply green noise barriers and noise barriers (more environmentally friendly and often cheaper), noise barriers with solar cells (energy generation), slopes, speed limits, double layer zoab (quieter), silent joint transitions or sound gutters.
			C16	Light pollution	The extent to which the design contributes to the reduction of unnecessary light pollution of the road and road traffic to surrounding areas and communities in the use phase	- Climate and energy neutral - Healthy living environment	- Limit and reduce disruption by lowering the highway; - Apply interactive lighting (only turns on when someone drives by) or a control system to use the right amount of light at busy times, such as rush hour.
			C17	Spatial and visual quality	The extent to which the design contributes to improving spatial and visual quality in the use phase	- Healthy living environment	- Improve the integration of the highway within the harmony of the environment (e.g. tracing and altitude, cross-section, roadside design, design of works of art and spatial coherence); - Strengthening the image quality plan; - Reducing the contrast between the environment and the civil works of art (aesthetic function); - Improving the amenity value (the experience of the highway and the environment by users); - Limit visual urbanization and impairment of openness; - Minimize unwanted views; - Limiting and reducing the barrier effect by lowering the highway (sunken location); - Apply land tunnel so that people do not see, hear or smell the highway itself.
			C18	Emissions and air quality	The extent to which the design contributes to improving air quality in the use phase	- Climate and energy neutral- Healthy living environment	- Improving the flow and limiting congestion and thereby reducing CO2 emissions;- Application of fuel-saving asphalt or screens that limit emissions to the environment;- Planting green for CO2 storage;- Stimulating the use of EVs by installing fast charging stations along the highway;- Reduce speed limit on the highway.

			C19	Traffic safety	The extent to which the design contributes to improving road safety	- Healthy living environment	- Apply detection and alarming of ghost drivers on exits, traffic signs, signage, matrix signs, markings, guide constructions, lighting etc. to reduce road injuries and accident risks; - Protect obstacles that may pose a danger in the event of a collision with guardrails or remove them.
			C20	External safety	The extent to which the design contributes to reducing the risks associated with the transport of dangerous goods for people and vulnerable objects in the vicinity of the motorway	- Healthy living environment	- Reducing the risk of accidents with hazardous substances consisting of a Site-specific Risk (PR) and a Group Risk (GR); - Prevent new companies that generate and transport hazardous substances from establishing themselves in the area.
			C21	Construction safety	The extent to which the design contributes to the realization of a healthy and safe working environment for project workers for construction and operation on site	- Healthy living environment	- Apply active safety systems (e.g. equipping vehicles with cameras and alarms) to help drivers and improve the safety of project workers working at night or in bad weather.
			C22	Nuisance during construction	The extent to which the design contributes to minimizing noise, dust, visual impact, nuisance, barrier effect, odor, vibration, air and light pollution during construction	- Healthy living environment	- Minimize disruption to traffic flows and road diversions by carrying out roadworks and highway maintenance at night; - Apply equipment and work processes that cause less nuisance to surrounding communities and nature.
			C23	Public support	The extent to which the design contributes to solving social problems for the public	- Sustainable area development - Healthy living environment	- Increase support from (future) users, local residents, stakeholders and other stakeholders (involving in the earliest possible phase); - Solve societal problems of congestion, safety, air pollution, traffic noise and vibrations, which are now caused by road traffic.
	T7	Mobility & Accessibility	C24	Traffic flow (network load)	The extent to which the design contributes to promoting the flow in the area	- Climate and energy neutral (including sustainable mobility)- Sustainable area development	- Separating urban traffic from regional traffic;- Widening the road with new asphalt (increasing capacity);- Permanently use rush hour lanes.

			C25	Reliability (network performance)	The extent to which the design contributes to increasing the reliability of the travel time ratios (travel time gain), vehicle loss hours and unexpected delays	- Climate and energy neutral (including sustainable mobility) - Healthy living environment	- Widen the road with new asphalt (increase capacity); - Expand the main and secondary road network into a more cohesive network.
			C26	Adaptability & flexibility	The extent to which the design contributes to the resilient and adaptive design of the highway	- Climate and energy neutral (including sustainable mobility) - Sustainable area development	- Improving the future value (reserving space for future plans and changes of functions).
			C27	Robustness	The extent to which the design contributes to increasing the availability of the highway	- Climate and energy neutral (including sustainable mobility) - Sustainable area development	- Apply sustainable solutions that require less maintenance.
Economic (Prosperity)	T8	Costs & Investments 	C28	Construction costs	The extent to which the design contributes to reducing the design's construction costs for the project life cycle	- Sustainable area development	- Strive for the lowest possible investments and construction costs.
			C29	Management and maintenance costs (LCC)	The extent to which the design contributes to reducing the management and maintenance costs of the design for the life cycle of the project	- Sustainable area development	- Striving for the lowest possible life cycle costs (LCC).
			C30	Financial risks	The extent to which the design contributes to reducing financial risks	- Sustainable area development	- Strive for the smallest possible chance of occurrence; - Take control measures.
			C31	Social cost-benefit analysis (SCBA)	The extent to which the design contributes to positive effects on prosperity	- Sustainable area development	- Striving for social benefits > social costs (SCBA ratio); - Not only looking at financial costs and benefits, but also social effects on noise pollution or nature.
	T9	Economic development 	C32	Local economy	The extent to which the design contributes to making the local economy more attractive to the environment and promoting economic activities	- Sustainable area development	- Improving the accessibility of business parks, recreational areas, etc. through new infrastructure connections. - Improve cooperation, coherence and integration between existing infrastructure networks (e.g. between main and underlying road network or road network and public transport).

			C33	Regional economy	The extent to which the design contributes to strengthening the regional economy (economic position)	- Sustainable area development	- Increasing the accessibility, attractiveness and spatial quality of the area for both existing and potential new businesses;- Improve cooperation, coherence and integration between existing infrastructure networks (e.g. between main and underlying road network or road network and public transport).
			C34	Innovation	The extent to which the design contributes to stimulating and implementing innovations	- Sustainable area development	- Anticipating self-driving cars (including size of road sections, data traffic, signpost, matrix signs); - Apply innovative and sustainable solutions to save on maintenance and replacement costs; - Integrate input from market participants to fully exploit synergies, savings and opportunities for innovation.

Appendix C: Questionnaire Survey

Appendix C.1: Structure of the Questionnaire Survey

The online questionnaire is designed to validate the SA criteria from the literature review. The aim is to collect expert opinions on the relevance of the SA criteria for the planning- and design phase (MIRT-Exploration & MIRT-Plan elaboration) in the Dutch highway context.

The questionnaire is divided into three parts:

1. Proposal round: This section asks for general information;
2. Relevance of the SA criteria: This section asks about the relevance of the SA criteria to evaluate the sustainability of highway design options in practice.
3. Evaluation of the proposed SA framework: This section asks some questions for evaluation;

1. Proposal round

The following questions are intended to acquire general information.

1. What is your name?
2. How much experience do you have with the highway design process?
3. Does sustainability play a role in your daily work? If so, how?

2. Relevance of the SA criteria

The following questions are intended to establish the relevance of the SA criteria for the Dutch highway context.

4. Are the following SA criteria included in the Environmental theme 'T1 - Energy' relevant for assessing the sustainability of highways design options in the Netherlands?
5. Can you provide an explanation or concrete example?

These questions are asked for all nine themes till question 21.

3. Evaluation of the proposed SA framework

The following questions are intended for evaluation purposes.

22. Do you think this list of SA criteria is a good indication of what makes a highway design option sustainable?
23. Is there an assessment criterion missing?
24. Do you have any questions or tips for my research or about the use of your data?

I would like to thank you for your time and contribution to this questionnaire and my graduation research. With the help of your input I am one step closer to realizing my research objective.

Appendix C.2: Results from the Questionnaire Survey

CONFIDENTIAL

Appendix C.3: Analysis of the Questionnaire Survey

CONFIDENTIAL

Appendix C.4: Conceptual Sustainability Assessment Framework

Table C.4 - Conceptual Sustainability Assessment Framework

Dimension	Theme code	Theme	Criterion code	Assessment criteria	Creating sustainable added value	Objective	Practical examples
Environmental *(Planet)*	T1	Energy	C1	Energy consumption (system)	The extent to which the design contributes to energy savings during the life cycle	- Climate and energy neutral - Healthy living environment	- Apply LED lighting, energy-efficient installations (energy saving); - Use of renewable generated energy.
			C2	Generation of renewable energy	The extent to which the design contributes to the self-generation or supply of renewable, sustainable energy in the use phase	- Climate and energy neutral - Healthy living environment - Sustainable area development - Circular	- Use light poles or noise barriers with solar collectors (integrated in e.g. road furniture or civil structures); - Around the highway (e.g. junctions or exits), facilitate renewable, sustainable energy generation by third parties (assign space for e.g. solar panels and windmills). - Striving for a circular economy (connecting different energy flows).
			C3	Energy consumption (fuel)	The extent to which the design contributes to less fuel consumption by cars in the use phase	- Climate and energy neutral - Healthy living environment	- Apply asphalt, which reduces the rolling resistance of the cars; - Improve the traffic flow, which results in less stoppage and therefore less energy consumption; - Design with as few height differences as possible, contributes to lower fuel consumption (ascending slope at an exit and a descending slope at an entrance, so that gravity can be used when accelerating and decelerating.
			C4	Energy consumption (construction & demolition)	The extent to which the design contributes to less energy consumption during construction and demolition phase	- Climate and energy neutral - Healthy living environment	- Applying green energy during implementation; - Use different machinery; - Limit transport distances.
	T2	Materials	C5	Material balance with circular economy (CE)	The extent to which the design contributes to material savings, sustainability and CE during the life cycle	- Climate and energy neutral - Healthy living environment - Sustainable area development - Circular - Natural capital and biodiversity	- Striving for the lowest possible life cycle costs (LCC); - Focus on (high-quality) reuse, both at the front and after the end of life (closing the circular cycle); - Limit and reduce material use (material saving); - Striving for the lowest possible life cycle costs (LCC); - Use local secondary and renewable materials from the study area (extracted or produced in the vicinity).

		C6	Material production	The extent to which the design contributes to less energy consumption for material production	- Climate and energy neutral	- Application of new materials of sustainable origin, with attention to the entire production chain.
		C7	Environmental cost indicator (ECI)	The extent to which the design contributes to lowering the environmental impact of the project	- Climate and energy neutral - Healthy living environment	- Lowering the Environmental Cost Indicator value (ECI-value), calculated with DuboCalc;
T3	Water & Climate	C8	Climate adaptation (flooding)	The extent to which the design contributes to the realization of a sustainable and robust water system	- Sustainable water management - Sustainable area development	- Creating new connections (waterways); - When the pavement surface is increased, also realize additional water storage (prevent the water system from being more heavily loaded which also ensures better flow due to less nuisance from water on the road); - Placing the highway on a higher elevated level (preventing flooding, evacuation route); - Avoid subsidence and flood-prone areas; - Increase water storage capacity of the soil; - Increase rainwater drainage system capacity (such as more swirls, larger pipe diameter, more closed/open water storage or installing gutters along the entire length of the road) for sufficient collection capacity at peak load.
		C9	Surface and groundwater quality	The extent to which the design contributes to improving surface and groundwater quality	- Sustainable water management - Healthy living environment	- Improve berm infiltration for the retention of contaminants in the topsoil (preventing run-off of contaminated water (such as metal particles due to wear, soot particles from exhaust gases, oil or zinc from road furniture) into surface and groundwater). - Separation of water drainage systems for clean and dirty water.
		C10	Climate adaptation (drought and heat stress)	The extent to which the design contributes to improving resilience to climate change	- Sustainable water management - Climate proof	- Prevent increase in paved surface (prevention of dehydration and decrease in water retention); - Realization of the highway outside the cores of urban areas; - Construction of sufficient greenery, shade and storage to relieve the drought and heat stress (less warming and radiation of heat to the environment).

	T4	Soil & Nature	C11	Ecosystem functions	The extent to which the design contributes to the preservation and strengthening of biodiversity (flora and fauna), coherence between ecosystem functions and the stimulation of natural capital	- Natural capital and biodiversity - Healthy living environment	- Apply ecological connection zones and fauna passages (e.g. ecoducts, wildlife tunnels and fish ladders) for migration or increase the capacity of existing passages (limiting fragmentation); - Providing space between ecological areas and the highway in the form of buffer zones, vegetation and soil protection zones; - Protect natural habitat to preserve or restore biodiversity (preventing the disappearance of plants, reduction in the population of animal species); - Planting trees along the highway for CO2 storage and limiting noise pollution, also benefits nature and recreation and provides an improved view for local residents, with less or even no decrease in value of homes near highways; - Application of an ecological verge design and ecological verge management (strengthening the technical and traffic functions but also the nature function of the verges); - Apply fauna grid along the highway (prevent animals from crossing the highway and causing accidents).
			C12	Protected natural areas	The extent to which the design contributes to the protection and restoration of the protected nature areas (Natura 2000 areas and Natuurnetwerk Nederland)	- Natural capital and biodiversity - Healthy living environment	- Adapting the design of the highway, so that a protected area is not affected by the project (prevention of surface loss, fragmentation, pollution, disturbance by noise, disturbance by light, disturbance by vibration, optical disturbance and change in population dynamics); - Connecting nature reserves to each other; - Develop new nature elsewhere or improve existing nature (compensation for nature affected on site by the project, required by law).
			C13	Soil quality	The extent to which the design contributes to improving soil quality	- Natural capital and biodiversity - Healthy living environment	- Prevent run-off of contaminated water (such as metal particles due to wear, soot particles from exhaust gases, oil or zinc from road furniture) into the soil; - Apply obstacle-free outer verge or nature-friendly road furniture; - Soil remediation; - Making the soil resistant to erosion (e.g. by planting).

Social (People)	T5	Culture & Landscape	C14	Cultural heritage, archaeological and historical values	The extent to which the design contributes to the preservation and protection of cultural heritage, archaeological and historical value	- Sustainable area development	- Increase visibility of remains; - Apply soil drilling and possibly test trenches to systematically check whether traces and / or finds are present (limiting threats from earthworks); - Prevent damage to values by adapting existing project plans (e.g. by relocating the road); - Accentuating water systems and cultural-historical lines.
			C15	Landscape structures	The extent to which the design contributes to preserving and reinforcing typical features of the landscape and different areas	- Healthy living environment - Sustainable area development	- Preserving rows of trees, vegetation and open meadow landscapes (keeping landscape structures recognizable); - Strengthening desirable views, landscapes and vistas; - Prevent agricultural land from being used for verges and ditches; - Reuse of developed land and built-up land (existing paved surface and in a petrified environment); - Prevention of road widening, larger space requirements, intersection and deterioration of landscape values.
			C16	Residential, recreational and working areas	The extent to which the design contributes to improving the quality of life in residential, recreational and working areas	- Sustainable area development	- Prevent encroachment on residential plots, buildings, buildings and recreational areas by adapting existing project plans (e.g. by relocating the road); - Creating or improving walking paths, cycling routes, recreational areas and sports fields to stimulate movement and healthy behaviour.
			C17	Utility services	The extent to which the design contributes to improving cable and pipeline networks for utilities	- Sustainable area development	- Prevent damage and relocation of utilities (cables and pipelines) by adapting existing project plans (e.g. by relocating the road); - In the event of interventions, immediately improve the underground infrastructure or realize new utilities.
	T6	Health & Well-being	C18	Noise pollution and vibrations	The extent to which the design contributes to reducing the noise level and vibration of traffic to surrounding areas in the use phase	- Healthy living environment	- Increase distance between living, recreational and working areas; - Apply green noise barriers and noise barriers (more environmentally friendly and often cheaper), noise barriers with solar cells (energy generation), slopes, speed limits, double layer zoab (quieter), silent joint transitions or sound gutters.

			C19	Light pollution	The extent to which the design contributes to the reduction of unnecessary light pollution of the road and road traffic to surrounding areas and communities in the use phase	- Climate and energy neutral - Healthy living environment	- Limit and reduce disruption by lowering the highway; - Apply interactive lighting (only turns on when someone drives by) or a control system to use the right amount of light at busy times, such as rush hour.
			C20	Spatial and visual quality	The extent to which the design contributes to improving spatial and visual quality in the use phase	- Healthy living environment	- Improve the integration of the highway within the harmony of the environment (e.g. tracing and altitude, cross-section, roadside design, design of works of art and spatial coherence); - Strengthening the image quality plan; - Reducing the contrast between the environment and the civil works of art (aesthetic function); - Improving the amenity value (the experience of the highway and the environment by users); - Limit visual urbanization and impairment of openness; - Minimize unwanted views; - Limiting and reducing the barrier effect by lowering the highway (sunken location); - Apply land tunnel so that people do not see, hear or smell the highway itself.
			C21	Emissions and air quality	The extent to which the design contributes to improving air quality in the use phase	- Climate and energy neutral - Healthy living environment	- Improving the flow and limiting congestion and thereby reducing CO2 emissions; - Application of fuel-saving asphalt or screens that limit emissions to the environment; - Planting green for CO2 storage; - Stimulating the use of EVs by installing fast charging stations along the highway; - Reduce speed limit on the highway.
			C22	Traffic safety	The extent to which the design contributes to improving road safety	- Healthy living environment	- Apply detection and alarming of ghost drivers on exits, traffic signs, signage, matrix signs, markings, guide constructions, lighting etc. to reduce road injuries and accident risks; - Protect obstacles that may pose a danger in the event of a collision with guardrails or remove them.

		C23	External safety	The extent to which the design contributes to reducing the risks associated with the transport of dangerous goods for people and vulnerable objects in the vicinity of the motorway	- Healthy living environment	- Reducing the risk of accidents with hazardous substances consisting of a Site-specific Risk (PR) and a Group Risk (GR); - Prevent new companies that generate and transport hazardous substances from establishing themselves in the area.
		C24	Construction safety	The extent to which the design contributes to the realization of a healthy and safe working environment for project workers for construction and operation on site	- Healthy living environment	- Apply active safety systems (e.g. equipping vehicles with cameras and alarms) to help drivers and improve the safety of project workers working at night or in bad weather.
		C25	Nuisance during construction	The extent to which the design contributes to minimizing noise, dust, visual impact, nuisance, barrier effect, odor, vibration, air and light pollution during construction	- Healthy living environment	- Minimize disruption to traffic flows and road diversions by carrying out roadworks and highway maintenance at night; - Apply equipment and work processes that cause less nuisance to surrounding communities and nature.
		C26	Public support	The extent to which the design contributes to solving social problems for the public	- Sustainable area development - Healthy living environment	- Increase support from (future) users, local residents, stakeholders and other stakeholders (involving in the earliest possible phase); - Solve societal problems of congestion, safety, air pollution, traffic noise and vibrations, which are now caused by road traffic.
T7	Mobility & Accessibility 	C27	Traffic flow (network load)	The extent to which the design contributes to promoting the flow in the area	- Climate and energy neutral (including sustainable mobility) - Sustainable area development	- Separating urban traffic from regional traffic; - Widening the road with new asphalt (increasing capacity); - Permanently use rush hour lanes.
		C28	Reliability (network performance)	The extent to which the design contributes to increasing the reliability of the travel time ratios (travel time gain), vehicle loss hours and unexpected delays	- Climate and energy neutral (including sustainable mobility) - Healthy living environment	- Improving the future value (reserving space for future plans and changes of functions).
		C29	Adaptability & flexibility	The extent to which the design contributes to the resilient and adaptive design of the highway	- Climate and energy neutral (including sustainable mobility) - Sustainable area development	- Improving the future value (reserving space for future plans and changes of functions).

			C30	Robustness	The extent to which the design contributes to increasing the availability of the highway	- Climate and energy neutral (including sustainable mobility) - Sustainable area development	- Apply sustainable solutions that require less maintenance.
Economic *(Prosperity)*	T8	Investments	C31	Investment costs (LCC)	The extent to which the design contributes to reducing the design's construction costs for the project life cycle	- Sustainable area development	- Strive for the lowest possible investments and construction costs.
			C32	Maintenance costs (LCC)	The extent to which the design contributes to reducing the management and maintenance costs of the design for the life cycle of the project	- Sustainable area development	- Striving for the lowest possible life cycle costs (LCC).
			C33	Financial risks	The extent to which the design contributes to reducing financial risks	- Sustainable area development	- Strive for the smallest possible chance of occurrence; - Take control measures.
			C34	Social cost-benefit analysis (SCBA)	The extent to which the design contributes to positive effects on prosperity	- Sustainable area development	- Striving for social benefits > social costs (SCBA ratio); - Not only looking at financial costs and benefits, but also social effects on noise pollution or nature.
		Economic development	C35	Regional economy	The extent to which the design contributes to strengthening the regional economy (economic position) and promoting economic activities	- Sustainable area development	- Increasing the accessibility, attractiveness and spatial quality of the area for both existing and potential new businesses; - Improve cooperation, coherence and integration between existing infrastructure networks (e.g. between main and underlying road network or road network and public transport).
			C36	Innovation	The extent to which the design contributes to stimulating and implementing innovations	- Sustainable area development	- Anticipating self-driving cars (including size of road sections, data traffic, signpost, matrix signs); - Apply innovative and sustainable solutions to save on maintenance and replacement costs; - Integrate input from market participants to fully exploit synergies, savings and opportunities for innovation.

Appendix D: Reference Case

Appendix D.1: Interview Question List with Expert

CONFIDENTIAL

Appendix D.2: Best-Worst Method (Example)

Voorbeeld:

In dit blad ziet u hoe een 'best-worst method' (BWM) probleem wordt geconstrueerd en opgelost volgens de instructie. Voor verdere uitleg over de MCA methode wordt verwezen naar het artikel van de ontwikkelaar van de tool: Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega, 64, 126-130.

Vereisten:

Als u "Oplosser" niet in de werkbalk van uw Excel heeft, moet u deze eerst installeren (volg de onderstaande stappen):
Ga naar "Bestand", dan "Opties", dan "Invoegtoepassingen". Bij de knop (Excel Add-Ins, klik op Go..."), Selecteer "Solver Add-in" en druk op "OK". Je zou Solver nu moeten kunnen zien in je "Data" tab.

Dimensie	Milieu (Planet)				Sociaal (People)			Economisch (Prosperity)	
Aantal Thema's = 9	Thema 1	Thema 2	Thema 3	Thema 4	Thema 5	Thema 6	Thema 7	Thema 8	Thema 9
Namen van Thema's	Energie	Materialen	Water & Klimaat	Bodem & Natuur	Cultuur & Landschap	Gezondheid & Welzijn	Mobiliteit & Bereikbaarheid	Investeringen	Economische ontwikkeling

Voor *Stap 1* zijn de thema's al ingevuld.

Meest Belangrijke Thema	Materialen
Minst Belangrijke Thema	Gezondheid & Welzijn

Selecteer het 'meest belangrijkste' en het 'minst belangrijke' thema (*Stap 2*).

Belangrijkste Thema over de andere Thema's	Energie	Materialen	Water & Klimaat	Bodem & Natuur	Cultuur & Landschap	Gezondheid & Welzijn	Mobiliteit & Bereikbaarheid	Investeringen	Economische ontwikkeling
Materialen	4	1	2	4	5	5	3	2	3

Andere Thema's over de Minst Belangrijke	Gezondheid & Welzijn
Energie	2
Materialen	5
Water & Klimaat	3
Bodem & Natuur	2
Cultuur & Landschap	2
Gezondheid & Welzijn	1
Mobiliteit & Bereikbaarheid	4
Investeringen	2
Economische ontwikkeling	5

Bij *Stap 4* zal de grijze cel automatische worden ingevuld o.b.v. de invoer bij *Stap 2*. Tijdens *Stap 4* wordt de vergelijking gemaakt tussen het **'minst belangrijke'** thema t.o.v. de overige thema's. Dit wordt gedaan middels het toekennen van de cijfers 1-5 weergegeven in de 'Vijfpuntsschaal' tabel. Hierbij geeft een **5** aan dat u het 'minst belangrijkste' thema **heel veel minder belangrijk** vindt dan het linker thema. Een **1** geeft aan dat u het 'minst belangrijkste' thema **even belangrijk** vindt dals het linker thema. Let op wanneer u het zelfde thema met elkaar vergelijkt, dient altijd **1** te worden ingevuld!

Vijfpuntsschaal	
Omschrijving	Waarde
Even belangrijk	1
Iets meer belangrijk	2
Substantieel meer belangrijk	3
Veel meer belangrijk	4
Heel veel meer belangrijk	5

Bij *Stap 3* zal de grijze cel automatisch worden ingevuld o.b.v. de invoer bij *Stap 2*. Tijdens *Stap 3* wordt de vergelijking gemaakt tussen het **'meest belangrijke'** thema t.o.v. de overige thema's. Dit wordt gedaan middels het toekennen van de cijfers 1-5 weergegeven in de 'Vijfpuntsschaal' tabel. Hierbij geeft een **5** aan dat u het 'meest belangrijkste' thema **heel veel meer belangrijker** vindt dan bovenstaande thema. Een **1** geeft aan dat u het 'meest belangrijkste' thema **even belangrijk** vindt als het bovenstaande thema. Let op wanneer u het zelfde thema met elkaar vergelijkt, dient altijd **1** te worden ingevuld!

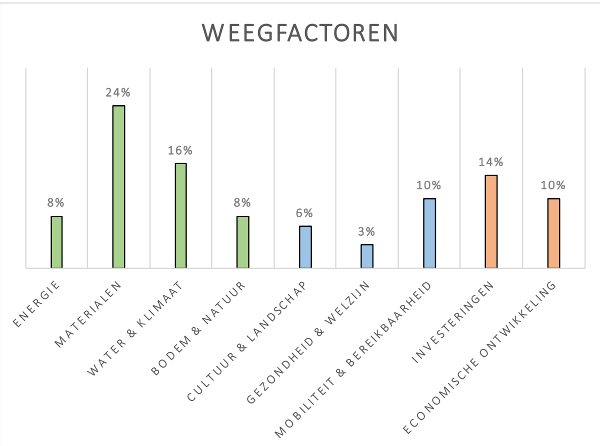
Weegfactoren	Energie	Materialen	Water & Klimaat	Bodem & Natuur	Cultuur & Landschap	Gezondheid & Welzijn	Mobiliteit & Bereikbaarheid	Investeringen	Economische ontwikkeling
	0,08	0,24	0,16	0,08	0,06	0,03	0,10	0,14	0,10
	8%	24%	16%	8%	6%	3%	10%	14%	10%

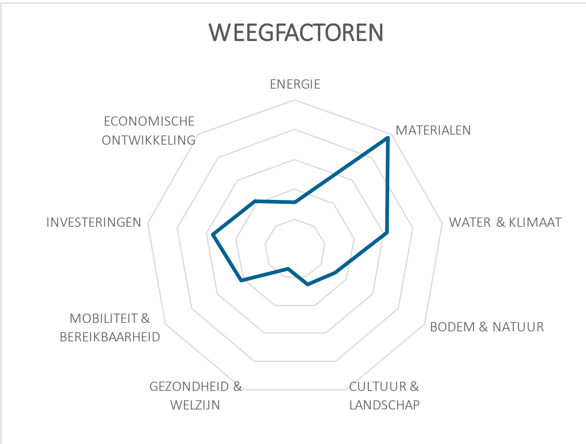
Ksi* [ξ*]	0,07
Max Ksi [ξ]	2,30
CR [ratio]	0,03

Met behulp van Ksi* [ξ*] kan de consitentie van de input worden gecontroleerd. Hierbij is het belangrijk te melden dat, hoe groter de Ksi* [ξ*], hoe hoger de Consistentie ratio (CR), en hoe minder betrouwbaar de vergelijkingen worden. Deze wordt berekendt tijdens *Stap 5*.

Ga nu naar het tabblad "Gegevens", zoek naar "Analyse" en klik op "Oplosser" (*Stap 5*). De gewichten worden automatisch verkregen en weergegeven in de gele cellen. Als u enkele groene delen wijzigt, moet u stap 5 opnieuw uitvoeren om de nieuwe resultaten te krijgen.

Omdat een schaal van 1-5 wordt toegepast, moeten we de Consistentie-index (max ξ) waarde van 2,30 gebruiken. Voor de Consistency ratio (CR) ∈ 0, 1 geldt, hoe lager de CR, hoe consistenter de vergelijkingen, dus hoe betrouwbaarder de resultaten. Deze wordt berekendt tijdens *Stap 5*.





Appendix D.3: Best-Worst Method (Reference Case)

CONFIDENTIAL

Appendix D.4: Application of the Proposed Sustainability Assessment Tool (Reference Case)

CONFIDENTIAL

Appendix D.5: Reference Case Interview (Original Transcript of the Answers in Dutch)

CONFIDENTIAL

Appendix E: Reflection

Appendix E.1: Reflection on the Graduation Process

In this appendix, I reflect on the graduation process.

Period till the Kick-off Meeting

In the first period of my research till the kick-off meeting, I was really struggling to find a topic and intended result of the research that would be relevant for the scientific literature and practice. Things like, what was my research going to contribute to the body of knowledge, what is new, different or surprising. I frequently changed my research design, as well as the methods I intended to use, causing confusion and misunderstanding among the committee members.

During the kick-off meeting I got a lot of comments that needed to be taken into consideration for continuing the research. I needed to explain certain words, definitions and terminology so that all committee members knew what I was talking about. In addition, I had to provide background information in terms of what I meant, what my intended result was going to be and with what kind of methods I was going achieve my research objective. It was not very clear what I wanted to investigate, especially in using a case and how to gather data and information. It was recommended by the committee to read more articles about integration and sustainability, to do some exploratory interviews for narrowing down my scope and to specify what I was going to look at and to establish the direction of the research. I remember that the first period during COVID-19 and the lockdown was a challenging first time experience.

Period till the 1st Mid-term Meeting

After the kick-off meeting I had troubles and issues with making a choice about what kind of result I envisioned in the research. The problem was that I was choosing a research method while my research problem, gap and questions were not well designed and elaborated. So it was recommended by the committee to start with forming the research objective that I wanted to achieve, given this objective a certain method is then a useful way to try to get an answer to my problem or to my question. I had to make a pragmatic choice in what I wanted to achieve with my research. Some tips I got from my committee were to clearly state what the research objective was, only then the method could be motivated for, there is an objective before there is a method. The research problem and objective were dependent for the method I would chose and the limitations of that method. Eventually I chose to develop a sustainability assessment tool in my research, so the research problem, gap and questions had changed accordingly. Designing the research was still a work in progress during the second period until the 1st mid-term meeting, which was something I wanted the committee to focus on and get feedback on during the 1st mid-term meeting.

I was aiming to finish the introduction, literature review and research methodology before the 1st mid-term meeting. However, during that period I had some unproductive weeks, holidays and focus/concentration problems at home. I was behind schedule and could not go to the office due to COVID-19 and lockdown. Because of the slow progress in that period, it was decided to meet again for a 2nd mid-term meeting in December.

Period till the 2nd Mid-term Meeting

After the 1st Mid-term Meeting, I looked at what methods were appropriate for achieving my research objective. For operationalizing my tool, the committee gave some tips on what methods to use. During the meeting it was recommended to look at the best-worst method, this method is new and has been explicitly developed in criticism of AHP. Some other students had used it and found it to be quite useful. This was taken into consideration when comparing different methods later on. It was also recommended to use the term 'reference case' for the case (project). This was discussed to get over the debate of, is it a tool development or is it a case study that I was going to do. The research was about developing a tool and the case was simply a reference to use, to test and see the applicability.

At that time, I had finished the introduction, literature review and was progressing towards identifying the sustainability assessment criteria. I was also able to go the office which resulted in much more progress compared to doing the research at home.

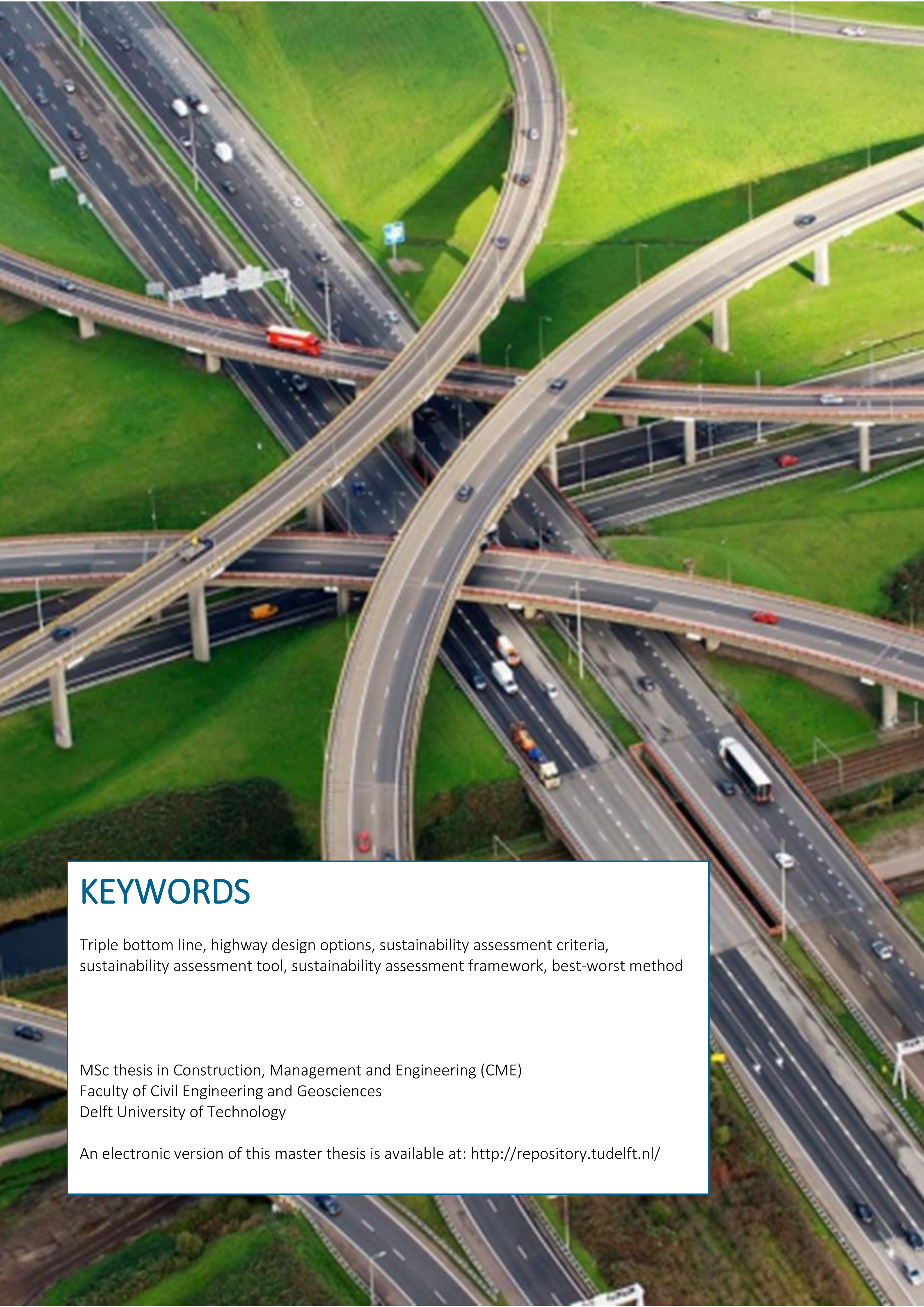
Period till the Green Light Meeting

After the 2nd mid-term meeting and discussing the last important changes, I finally knew what I wanted to accomplish and how to get there. During that period, I put a lot of effort and time in developing the sustainability assessment framework by doing interviews, a filtering process on the criteria and a validation of the framework by conducting a questionnaire survey. After these steps I developed the sustainability assessment tool, which I applied on the reference case to test the applicability. After analysing the finding, I contacted an expert from the case to evaluate the results and finding of applying the tool. All results and findings combined led to my conclusion, discussion and recommendations of the research. For the Green Light Meeting I processed all the information and results in a draft report (95% version) to be discussed during the meeting.

Period till the Thesis Defence

The Green Light Meeting was originally scheduled for April 25th, however, due to the availability and holidays of the committee members, it was rescheduled for April 20th. Paul and Maedeh attended this meeting, however, Daan was abroad since April 15th, thus he was unable to attend the Green Light Meeting. The change in the scheduled date, as well as my grandmother's funeral two weeks earlier, had an impact on my planning, and as a result, the intended submitting day could not be met. The Green Light report was submitted on April 14th a day after the scheduled date.

During the Green Light Meeting, I presented the results of my research and evaluated and discussed them with the committee members. After receiving a Green Light from the committee, the committee gave some final remarks and comments which needed to be addressed and revised in the final report. The most import one was about the structure of the research. A clearer separation of the chapters and contents was needed to provide a more logical approach. In addition, in some parts more explanation was required for transparency of the process. After combining all the comments I prioritized what to revise based on the degree of importance. Therefore, I adapted and improved the text which needed most attention and added the chapter 'research methodology' to reorganize and explain the methods used in the research including a flowchart. Finally, after significant revisions had been made, the final thesis report could be submitted in time for the thesis defence.



KEYWORDS

Triple bottom line, highway design options, sustainability assessment criteria, sustainability assessment tool, sustainability assessment framework, best-worst method

MSc thesis in Construction, Management and Engineering (CME)
Faculty of Civil Engineering and Geosciences
Delft University of Technology

An electronic version of this master thesis is available at: http://repository.tudelft.nl/