3-7-2020

Implementation Potential of Light Reflective Asphalt in Oldenzaal: A Sustainable Supply Chain and Urban Perspective

University of Twente – BSc Thesis – Civil Engineering – Final Report

Author: Abrohom Demir

SUPERVISORS: DR. S.R.MILLER (UT)
M. PENA ACOSTA (UT)
J. GROOTENHUIS (TWW)

Preface

Before you lies the thesis report about the implementation potential of light reflective asphalt (LRA) in Oldenzaal. The thesis is written for my Civil Engineering Bachelor graduation at the University of Twente (UT). The research period for this thesis took place from mid-April until the end of June in 2020.

As an inhabitant of Oldenzaal, I always have wanted to contribute to the local society in some way. Because of the increasing importance of sustainability in the recent years, the intent of this report is to take one more step towards a more sustainable Oldenzaal.

First, I would like to thank all three supervisors (Seirgei Miller, Monica Pena Acosta and Jeroen Grootenhuis) who were available at all times to answer any questions I had.

Secondly, I would like to thank both Twentse Weg- en Waterbouw (TWW) and the Municipality of Oldenzaal. Without the data and staff members of these two organisations, the analysis in this thesis could not have been performed.

More specifically, I would like to thank my contact person at the municipality, Jeroen Buitenweg, for introducing me to the several experts within the municipality and providing me with enough survey respondents in order to conduct the analysis in this report.

Last but not least, I would like to thank all the expert interviewees and survey respondents for providing this study with the data for the analysis.

Hopefully, you will enjoy reading this report.

Abrohom Demir

Oldenzaal, June 16, 2020

Table of Content

Table of Figures

Table of Tables

Terminology and Abbreviations

To prevent any confusion when reading this report, the following terms have been defined (Table 1). Furthermore, the Dutch translation and abbreviation, if applicable, are given per term. The terms are ordered alphabetically.

Table 1 - Overview of all the terms and their definitions

Term	Abbreviation	Term (Dutch)	Definition
Aggregates	-	Steenslag	The stones within an asphalt mixture.
Albedo	-	Albedo	The reflective light capacity of materials, indicated by a percentage or value between 0 and 1. The higher the value or percentage, the more light can be reflected back.
Asfalt Centrale Twente	ACT	Asfalt Centrale Twente	Asphalt producer within the supply chain of ReintenInfra.
Asphalt granulate	-	Asfaltgranulaat	Asphalt mixture retrieved from already-applied asphalt.
Asphalt road/street	-	Asfalt weg/straat	Road with the purpose of transporting vehicles (and cyclists). At the very least, the surface layer is made out of asphalt. Road and street can be read and interpreted as equal.
Client	-	Opdrachtgever	The company/organization that decides a(n) (infrastructure) development project is needed. The client also decides to which contractor the project will be assigned.
Contractor	-	Aannemer	The company/organization that proposes and executes (infrastructure) plans for the client.
Criteria weights	-	Criteria gewichten	Weights that indicate the importance of criteria.
Diffusiveness	-	Diffusiviteit	Indicating to what extent incoming light rays leave at the same angle of arrival. A high diffusiveness indicates that reflected light rays scatter more.
Light reflective asphalt	LRA	Licht reflectief asfalt	The concept of asphalt surface layers, reflecting more (sun)light, due to having a higher albedo.
Light reflective asphalt alternative	LRA alternative	Licht reflectief asfalt alternatief	Achieving a higher albedo within the asphalt surface layer by replacing (a part) of the darker aggregates with lighter colored aggregates.
Los Angeles-coefficient	LA coefficient	Los Angeles-coëfficiënt	Resistance against fragmentation of the aggregates. The lower the declared value is, the more resistant the aggregates are against fragmentation.
Luminance factor	-	Luminantie factor	The whiteness of a material defined with a value between 0 and 1. The higher the value, the whiter the material.

Term	Abbreviation	Term (Dutch)	Definition
Mirror factor	-	Spiegel factor	The inverse of the diffusiveness definition. Indicates to what extent incoming light rays leave at the same angle of arrival. A low mirror factor indicates that reflected light rays scatter more.
Multi-criteria analysis	MCA	Multi-criteria analyse	An analysis tool, to determine the best alternative based on a set of criteria and their weights.
Polished stone value	PSV	Polijstgetal	Resistance against polishing by the aggregates. The higher the declared value, the more resistant against polishing.
Reclaimed asphalt	-	Asfaltgranulaat	See definition of asphalt granulate.
ReintenInfra	-	ReintenInfra	Represents the chain of contractor firms, which fall under the name of ReintenInfra.
Sustainable supply chain management	SSCM	N/A	''The creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, in-formation, and capital flows associated with the procurement production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term.'' (Ahi & Searcy, 2013)
Top/surface layers	-	Deklaag	The top (or surface) layer of an asphalt road, which is in contact with the atmosphere. Both the terms top and surface layer are defined by this definition.
Twentse Weg- en Waterbouw	TWW	Twentse Weg- en Waterbouw	Contactor firm which develops plans for the client, e.g. municipalities. TWW is a part of ReintenInfra.
UHI mitigation strategies	-	UHE mitigatie strategieën	The combined set of techniques that are used to reduce the UHI effect as effectively as possible.
UHI mitigation techniques	-	UHE mitigatie technieken	Techniques that reduce the UHI effect.
Urban heat island effect	UHI effect	Urbane hitte eiland (UHE) effect	The phenomenon of urban areas heating up more than the surrounding rural areas.
Urban heat island intensity	UHI intensity	Urbane hitte eiland intensiteit	The intensity at which the UHI effect is present (expressed in °C)
Whiteness	-	Witheid	See definition of luminance factor.

Summary

The urban heat island (UHI) effect has many negative effects on society, economy and environment and has been a recent topic in research studies. Several mitigation techniques have been proposed throughout the recent years. One of these UHI mitigating techniques is the use of light reflective asphalt (LRA). Despite the UHI mitigating capacity and other benefits it may have, LRA also has disadvantages.

The aim of this study is to take into account both the pros and cons of the LRA innovation and analyse what the implementation potential for LRA is in the context of Oldenzaal. This implementation potential is divided into two parts. The first part being the feasibility of LRA implementation from a sustainable supply chain management (SSCM) perspective. Meaning, whether or not the LRA innovation is feasible for the contractor, i.e. TWW. The second part of implementation potential is whether or not the LRA innovation fits into the urban context of Oldenzaal. Both these implementation potential perspectives are researched by answering the following research question: *To what extent does the infrastructural innovation, i.e. LRA, show implementation potential in the context of Oldenzaal?*

The four aggregate alternatives, i.e. Bestone (BS), Labradoriet (LD), Luxovit (LV) and Reflexing White (RW), were compared using a multi-criteria analysis (MCA). Literature, experts and surveys were used to form the base of the MCA. The results suggest that LRA will be more difficult to implement than the the conventional aggregate, i.e. BS, as the latter is the more dominant alternative. When comparing the three LRA alternatives, LD and RW both seem to be the best LRA alternatives within the supply chain of ReintenInfra. LD seems to be the most viable LRA option economic-wise, while LV is the whitest and most diffusive aggregate, which can help in reducing the UHI effect and energy costs the most. RW is the most all-round LRA option. LD and LV both have low re-usability and applicability potential in top layers. Taking into account these pros and cons, future research on finding the optimal LRA mixture should be conducted.

Using literature and expert interviews, the different urban factors influencing LRA potential have been identified and analysed for Oldenzaal. Results show a correlation between the location of roads and high UHI intensities zones. Furthermore, road illumination energy-savings of 560 GJ (equivalent to 53 households per year), can be achieved if LRA is to be applied for all asphalt roads. The urban canyon geometry of Oldenzaal, does not play a significant role, as only 17 out 222 asphalt roads are prohibited from LRA implementation by this factor. From a health perspective, the vulnerable groups to the additional thermal stress of the LRA innovation prevent 15 out of 222 asphalt roads from LRA implementation. Although identified, analysis regarding the construction year and traffic intensity could not be performed due to incomplete or missing data.

The model contains a final and relative score for the implementation potential per road, indicating which road is, relatively-speaking, the most LRA-suitable. The top five asphalt roads for LRA implementation have been given from high to low potential, i.e. Prossinkhof, Bisschop Balderikstraat, Stationsplein, Titus Brandsmastraat and Bleekstraat. Only the input of the model has been partly validated, as the outcome, i.e. the final scores, do not contain an external and observed set of data with which it can be compared. Hence, future research should focus on validating the model by performing parameter observations before and after LRA implementation.

Summary (Dutch)

Het urbane hitte eiland (UHE) effect heeft vele negatieve gevolgen voor maatschappij, economie en milieu en is een recent onderwerp in onderzoekstudies. Meerdere mitigatie technieken zijn voorgesteld door de jaren heen. Eén van deze mitigatie technieken focust op het gebruik van licht reflectief asfalt (LRA). Ondanks de UHE mitigerende capaciteit en andere voordelen, heeft LRA ook nadelen.

Het doel van dit onderzoek is om zowel de voor- als nadelen van de LRA innovatie in beschouwing te nemen en de implementatie potentie van LRA in de context van Oldenzaal te analyseren. Deze implementatie potentie is onderverdeelt in twee delen. Het eerste deel richt zich op de haalbaarheid van LRA implementatie vanuit een zogenaamde 'sustainable supply chain management' (SSCM) perspectief. Dit perspectief focust op de haalbaarheid van de innovatie voor de aannemer, in dit geval TWW. Het tweede perspectief van de implementatie potentie focust op de haalbaarheid van LRA vanuit de urbane context van Oldenzaal. Beide implementatie potentie perspectieven zijn onderzocht door het beantwoorden van de volgende onderzoeksvraag: *In hoeverre heeft de infrastructurele innovatie, LRA, implementatie potentie in de context van Oldenzaal?*

De vier steenslag alternatieven, Bestone (BS), Labradoriet (LD), Luxovit (LV) en Reflexing White (RW), zijn met elkaar vergeleken m.b.v. een Multi-criteria analyse (MCA). Literatuur, experts en enquêtes zijn gebruikt als basis voor de MCA. De resultaten suggereren dat het moeilijker zal worden voor het implementeren van LRA dan de conventionele steenslag (BS), aangezien het laatste dominanter blijkt te zijn in de MCA. Het vergelijken van de LRA steenslagen laat zien dat LD en RW de betere LRA alternatieve steenslagen zijn binnen de keten van ReintenInfra. LD blijkt, economisch gezien, de beste LRA steenslag, terwijl LV juist de voordelen heeft van een wittere kleur en een meer diffuus oppervlak. Dit helpt met het verminderen van de UHE effect en energie kosten. RW blijkt de meest veelzijdige LRA steenslag optie. LD en LV hebben beide een laag hergebruik en toepasbaarheid potentie voor deklagen. Door zowel de voor- als nadelen in beschouwing te nemen van alle vier de steenslagen, kunnen toekomstige studies zich richten op het vinden van de optimale LRA mengsel.

Door gebruik van literatuur en expert interviews zijn de verschillende urbane factoren die de LRA potentie beïnvloeden geïdentificeerd en geanalyseerd voor Oldenzaal. Resultaten laten een verband zien tussen de locatie van de wegen en de hoge UHE intensiteitszones. Mochten alle asfalt wegen vervangen worden door LRA wegen, dan is een energiebesparing, m.b.t. weg illuminatie, van 560 GJ (gelijk aan 53 huishoudens per jaar) mogelijk. De urbane kloof geometrie speelt geen significante rol omdat slechts 17 van de 222 asfalt wegen verboden zijn door deze factor. Vanuit een gezondheid perspectief zijn de kwetsbare groepen voor extra hitte stress, gecreëerd door LRA, in beschouwing genomen. Deze factor zorgt ervoor dat 15 van de 222 asfalt wegen verboden worden voor LRA implementatie. De twee resterende factoren, constructie jaar en verkeersintensiteit, zijn geïdentificeerd, maar niet geanalyseerd door de incomplete of missende data.

Het model bevat relatieve scores voor de implementatie potentie per straat. Deze scores geven in relatieve zin aan welke wegen het meest LRA-geschikt zijn. De top vijf asfalt wegen geschikt voor LRA zijn gegeven van hoge naar lage potentie: Prossinkhof, Bisschop Balderikstraat, Stationsplein, Titus Brandsmastraat en Bleekstraat. Alleen een deel van de model input is gevalideerd omdat de output, geen externe en vergelijkbare dataset bevatte. Dus een ander uitgangspunt van dit onderzoek is dat toekomstig onderzoek zich moet richten op parameter observaties voor en na LRA implementatie om zo de model output te kunnen valideren.

1. Introduction

1.1. Background Context

As of recent there is a clear emphasis on combating climate change. For instance, Dutch authorities have set the goal to have a CO_2-neutral energy system by the year of 2050 (*Rijksoverheid Stimuleert Duurzame Energie | Duurzame Energie | Rijksoverheid.Nl*, n.d.). Sustainable innovations can help in either directly or indirectly contributing to this energy neutral system.

One of the main culprits influencing the energy consumptions in cities during warmer periods is the UHI effect (Yang et al., 2015). Model calculations for the annual average air temperature increases indicate the presence of the UHI effect among Dutch cities. For Oldenzaal, these UHI intensities can increase up to 1.7 °C according to this model (Remme, 2017). This phenomenon is known to cause higher temperatures within urban areas than surrounding rural areas. The different effects that an UHI has on a city and their inhabitants are (Ichinose et al., 2008; Synnefa et al., 2011; Yang et al., 2015):

- Increased energy cooling load and corresponding costs.
- Significant increases in peak energy consumption.
- Degradation of air quality.
- Increased thermal stress on inhabitants.
- Significant impact on the urban ecosystems.
- Degradation of the living environment.
- Significant increase in risk of morbidity or illness caused by the heat due to the UHI.

Twentse Weg- en Waterbouw (TWW), part of ReintenInfra, would like to help in mitigating the UHI effect and contribute to the 2050 energy neutral system by acting on a local scale, i.e. Oldenzaal. The innovation of LRA can in potential reduce the UHI effect by making pavements absorb less sunlight. By doing so, peak energy consumptions can be reduced in intensity, as this is one of the effects of the UHI effects (Ichinose et al., 2008; Synnefa et al., 2011; Yang et al., 2015). Therefore, TWW would like to get a better understanding of the implementation potential of LRA in Oldenzaal. However, the actual potential of LRA in an urban context depends on the local characteristics of this urban area and thus requires local research (Qin, 2015a; Santamouris, 2013). The current state of knowledge regarding the UHI effect and the LRA innovation are discussed in Sections 2.1 and 2.2 respectively.

Sustainable innovations, such as LRA, are mostly new to the market and require extra expenses from the contractor. Besides, the economical disadvantages, there may even be other drawbacks as well. For instance, new products often experience consumer resistance (Cornescu & Adam, 2013). To determine whether other not LRA is feasible for the supply chain of ReintenInfra, the sustainable supply chain management (SSCM) perspective needs to be taken into account.

From this SSCM perspective, LRA does not only need to be feasible within the urban context, but also from within the supply chain of ReintenInfra. If other conventional, so non-LRA, mixtures show to be more feasible within this supply chain, than the niche, i.e. LRA, will get overshadowed by the dominant conventional mixtures currently applied by ReintenInfra. The present state of knowledge regarding SSCM is elaborated in Section 2.3.

1.2. Research Aim and Questions

The aim of this research is to determine the implementation potential of LRA in the context of Oldenzaal. Objectives related to this aim are:

- Identifying the hindering factors from a SSCM perspective for the implementation of LRA within ReintenInfra.

- Identifying the urban factors and analysing their influence on the potential implementation of LRA in Oldenzaal.

Based on the research aim and objectives, the main research question is determined:

> *Main research question: To what extent does the infrastructural innovation, i.e. LRA, show implementation potential in the context of Oldenzaal?*

In order to answer the main question, the following sub research questions are determined:

1. *What are the possible alternatives for LRA, within the supply chain of TWW?*
2. *Based on what environmental, economic and social criteria, and corresponding weights, will the best LRA alternative be chosen?*
3. *What are the pros and cons of these alternatives based on the criteria?*
4. *What are the different urban factors in general and their influence on the potential implementation of LRA in Oldenzaal?*

An overview of how the aims and questions are linked to each other is given in the flowchart depicted in Figure 1.

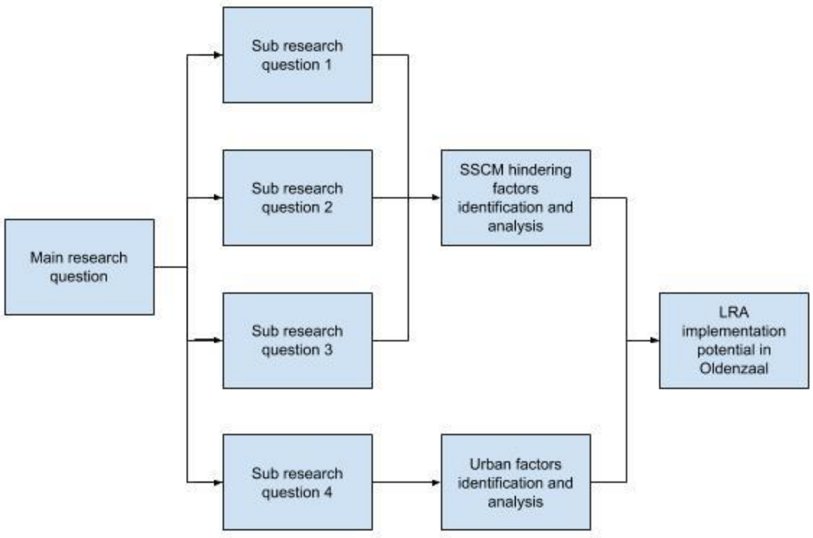

Figure 1 - Flowchart showing the link between research questions, objectives and aim.

1.3. Research Scope

The implementation potential of LRA in Oldenzaal is analysed for asphalt roads that can be used by vehicles. Asphalt paths/roads that can solely be used for cyclists or pedestrians are not taken into account. The study area of Oldenzaal and the above defined asphalt roads are illustrated in Figure 2.

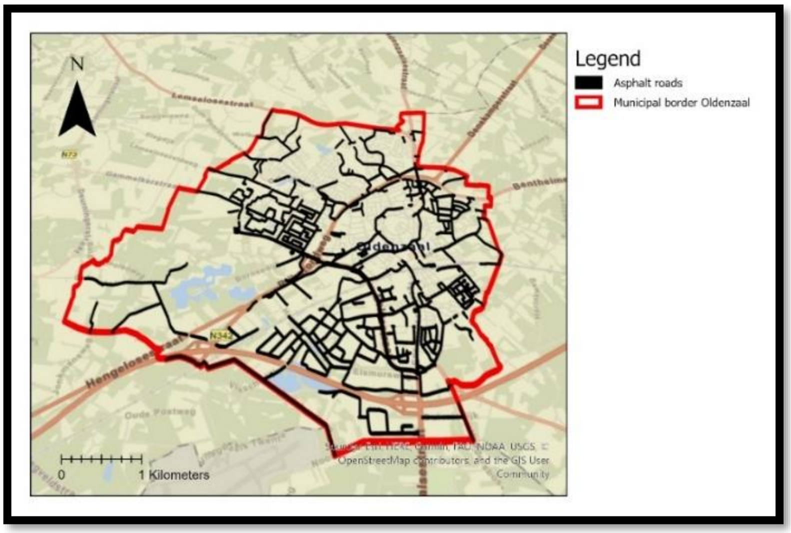

Figure 2 – The study area consisting of all the asphalt roads within Oldenzaal.

1.4. Thesis Outline

This report consist of a Multi-Criteria Analysis (MCA) in order to determine the best possible LRA alternative within the supply chain of ReintenInfra. Also, the MCA is used compare the LRA alternatives with the standard asphalt mixture used. The potential LRA implementation from an urban perspective, i.e. Oldenzaal, is analysed and will be visualized using geo-spatial data.

Chapter 2 elaborates on the current state of knowledge regarding the theoretical frameworks used in this report. Chapter 3 describes the research methodology. Chapter 4 provides the reader with the results of the sub research questions. Chapter 5 gives the answer to the main research question. Chapter 6 elaborates on discussion points of the study and recommendations for future research.

2. Theoretical Framework

In order to answer the research questions proposed in Section 1.2, the current state of knowledge in literature surrounding the main concepts is elaborated in this chapter. The main concepts are the UHI effect and its mitigation (Section 2.1), LRA (Section 2.2) and SSCM (Section 2.3).

2.1. Urban Heat Island (UHI) Effect and its Mitigation

The first concept and also one of the problems on which this thesis revolves around, is the UHI effect. To apply it to its context, i.e. Oldenzaal, the general theory which forms the basis of the UHI effect will first be elaborated.

The phenomenon was first discovered in the beginning of the 19th century by Luke Howard (Howard, 1818). In his works he discovered how the concept of an UHI actually worked. Although a definition study on UHI is currently missing in literature, the concept of an UHI (effect) in this thesis is defined as: *the phenomenon of urban areas heating up more than the surrounding rural areas.* Figure 3 gives a visualization of the UHI effect.

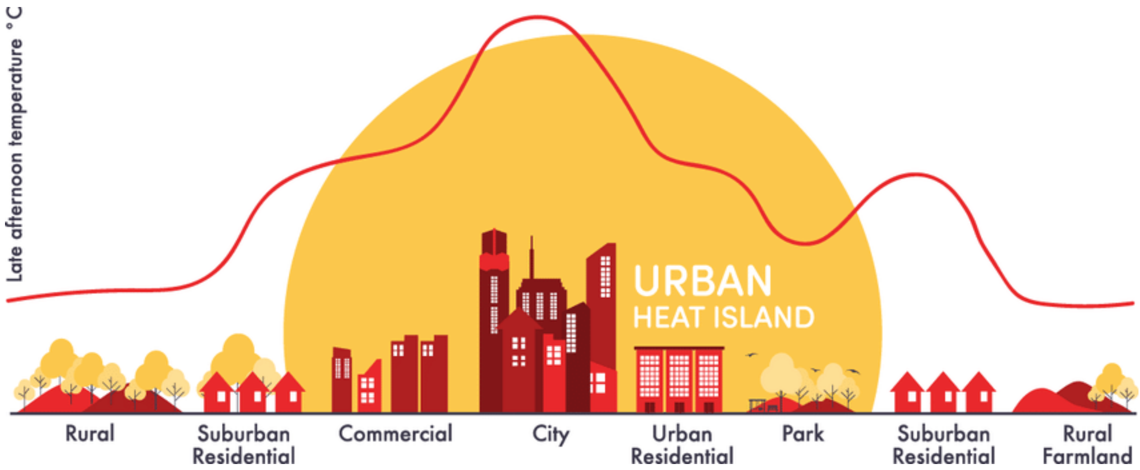

Figure 3 - The UHI effect illustrated (Fuladlu et al., 2018).

As already described in Section 1.1, more recent studies have researched the impact the UHI effect has on the environment, economy and society of an urban area. As already stated in the introduction, the results of these studies indicate the following effects of the UHI (Ichinose et al., 2008; Synnefa et al., 2011; Yang et al., 2015);

- Increased energy cooling load and corresponding costs.
- Significant increases in peak energy consumption.
- Degradation of air quality.
- Increased thermal stress on inhabitants.
- Significant impact on the urban ecosystems.
- Degradation of the living environment.
- Significant increase in risk of morbidity or illness caused by the heat due to the UHI.

However, research also suggest that magnitude and intensity of these UHI effects depend on the climate conditions of a city and also affect the choice for various UHI mitigation strategies (Kim et al., 2018). These mitigation strategies could involve the following techniques (Gago et al., 2013; Mohajerani et al., 2017; Santamouris, 2015):

- Adding more greenery to urban areas in the form of;
  - Planting trees or creating green areas, e.g. parks.
  - Green roofs.
- Increasing the albedo of cities by;
  - Applying albedo materials to building facades.
  - Applying albedo alternatives to pavements, i.e. LRA.
- Increasing the evaporative capacity of pavements in the form of;
  - Porous pavements.
  - Permeable pavements.

The case can be made that the above mentioned UHI effects and mitigation strategies can be applied to the context of Oldenzaal, as the problem of the UHI effect is also present there. In the city of Oldenzaal, the average annual air temperature can increase up to 1.7 °C according to model calculations (Remme, 2017). The model takes into account different local characteristics influencing the UHI intensity, which is turned into an UHI intensity raster map with cell sizes of 10 by 10 meters. So by finding the implementation potential of LRA in Oldenzaal, an incentive towards mitigating the UHI effect proposed by this model may be created from a municipal point of view.

The potential of these mitigation techniques are related to the urban characteristics of the cities. Consequently, localized research for Oldenzaal is needed, in order to find the UHI reducing potential per mitigation strategy, e.g. LRA (Gago et al., 2013; Mohajerani et al., 2017; Qin, 2015a; Santamouris, 2013, 2015; Yang et al., 2015).

2.2. Light Reflective Asphalt (LRA)

The concept is that LRA, due to its lighter-colored surface, will have a higher albedo. Albedo is measured between the values of 0 and 1 and indicates what percentage of the total light rays falling onto a surface is reflected back. What this means for LRA is that more sunlight will be reflected back, rather than absorb and store it in the form of heat (see Figure 4). The latter is the case now, because of the darker pigmented surfaces of roads. These conventional pavements are considered as one of the main causes of intensifying the UHI effect (Qin, 2015a; Santamouris, 2013). Hence, by increasing the albedo of pavements, the UHI intensity can generally be reduced.

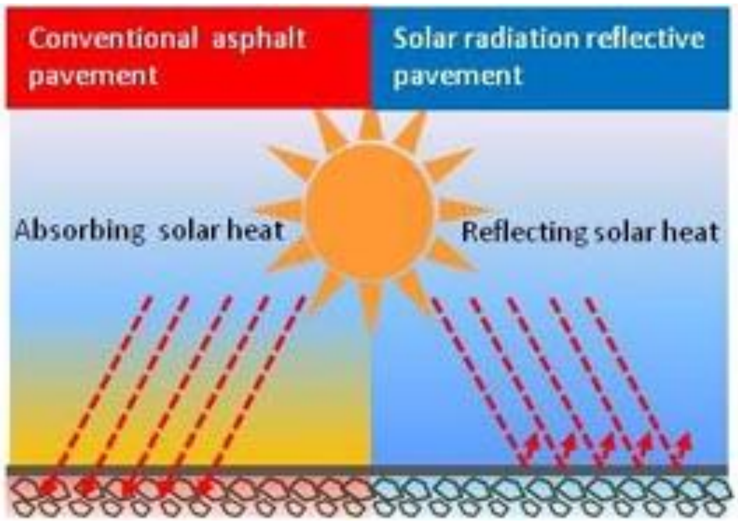

Figure 4 - The concept of LRA visualized.

Research determining the role and sensitivity of the parameters influencing the daily maximum surface temperature of pavements also confirms that albedo is one of the parameters, as shown in Eq. 1 (Qin, 2015a).

$$T_{smax} = \Gamma \frac{(1-R)I_0}{P\sqrt{\omega}} + T_0 \qquad \text{(Eq. 1)}$$

- T_{smax} is the daily maximum surface temperature.
- Γ is the percentage of the thermal absorption to the thermal conduction.
- R is the albedo.
- I_0 $(\frac{W}{m^2})$ is the daily peak solar irradiation.
- P is the thermal inertia of the pavement.
- ω $(\frac{1}{s})$ is the angular frequency.
- T_0 $(°C)$ is a regressed constant.

Of these parameters, albedo is the easiest to change (Mohajerani et al., 2017). Consequently, LRA is one of the most-well studied and most cost-effective mitigation measure for combatting the UHI effect by reducing the maximum surface temperature of the pavement (Rossi et al., 2014; Synnefa et al., 2011).

Another study confirms that albedo influences surface temperature and adds to this that, besides colour, surface roughness also affects surface temperature of materials, i.e. that smoother material surfaces have higher cooling effects than rough material surfaces (Doulos et al., 2004).

However, whether or not increasing the albedo of asphalt pavements in Oldenzaal will have implementation potential, is to be determined in this research. Research on the developments regarding LRA, are also suggesting that localized research is needed, to determine the effects with regards to mitigating the UHI effect on a local scale (Qin, 2015a; Santamouris, 2013; Yang et al., 2015).

2.3. Sustainable Supply Chain Management

As LRA is a sustainable innovation, the three pillars of sustainability surrounding this innovation must be in balance for it to successfully applied in a business setting (Dyllick & Hockerts, 2002). The three pillars are known as the environmental (planet), economic (profit) and social (people) pillar, which are shown in Figure 5.

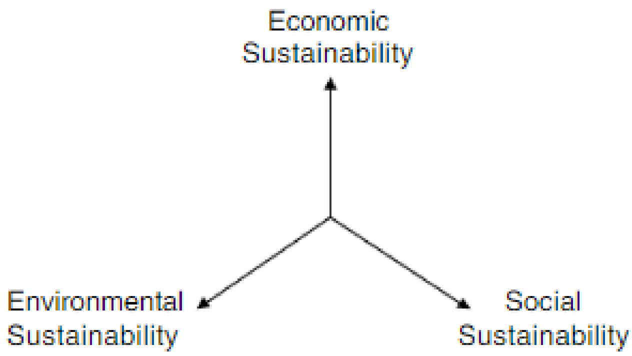

Figure 5 - The three pillars of sustainability (Dyllick & Hockerts, 2002).

What this tells us is that not only the innovation suitability from an urban perspective must be taken into consideration, but also that from the sustainable supply chain management (SSCM) perspective (Seuring & Müller, 2008). According to a literature study, the definition of SSCM is (Ahi & Searcy, 2013):

"The creation of coordinated supply chains through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, in-formation, and capital flows associated with the procurement production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short- and long-term."

By taking into account the three pillars of SSCM, the hindering factors for the implementation of LRA from a supply chain perspective will be identified. Hence, the balance or imbalance of the three pillars of sustainability, with regards to LRA, will be evaluated by taking into account these pillars in a multi-criteria analysis (MCA). The MCA will then provide an analysis of which criteria are the hindering factors in successfully applying the LRA alternative from a sustainable supply chain perspective. The identification may help ReintenInfra to better understand these factors and may even help to tackle them more effectively.

3. Research Methodology

The research questions proposed in Section 1.2, are to be elaborated using the methodology explained in this chapter. First an overview of the research methods and tools per research question is given in Figure 6. After which, Sections 3.1-3.5 give a more detailed elaboration on the research and methods per research question.

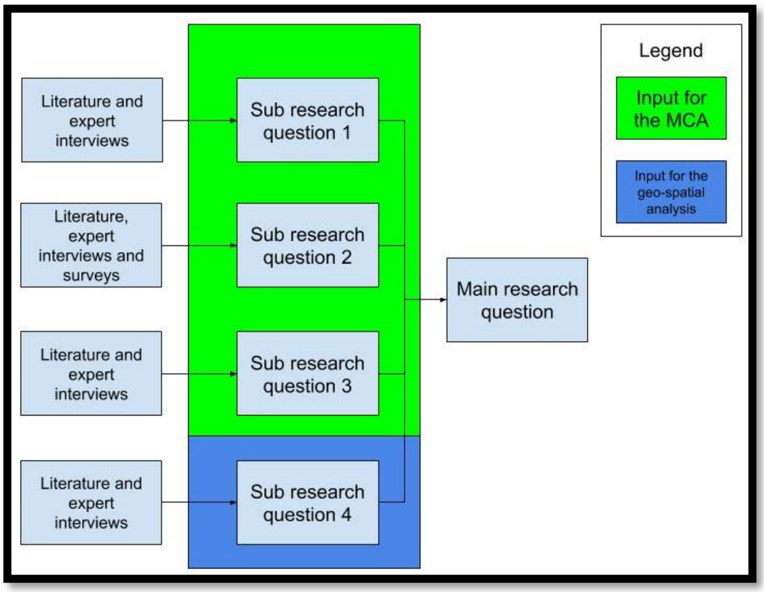

Figure 6 – Overview of the research methods and tools to be used.

3.1. Methodology SRQ1

The different alternatives have been determined by first finding literature regarding the different elements within an asphalt mixture and their potential influence on increasing the albedo of the total asphalt mixture. The findings in literature are compared with that of experts, for justification. Finally, in order to determine the final set of alternatives, an expert within the local supply chain was asked about the set of alternatives and their data availability. By doing so, data limitations are prevented as much as possible. The final set of alternatives will be compared within the MCA.

3.2. Methodology SRQ2

The set of criteria to be used in the MCA was at first determined using literature. After three expert interviews, an iteration was performed to determine the final set of criteria. Hence, a combination of literature research and expert interviews were used to complement each other, in order to find the final set of criteria to be used in the MCA.

The importance of the criteria is still to be determined. By conducting two expert interviews, the stakeholders which should influence the importance of criteria are determined. In order to determine the weight of each criteria, the literature is used to assign weights to the main criteria. For the other criteria, surveys were send to nine municipal employees active in the field of civil engineering and climate. Four out of nine respondents filled out the surveys. The surveys consisted of a pairwise comparison of the criteria, in order to determine, the relative importance. The Analytical Hierarchy Process (AHP) was used to translate the survey data to the weights per criteria (Saaty, 2008).

3.3. Methodology SRQ3

The pros and cons of each alternative based on the criteria was mainly determined by conducting three expert interviews, each having their own expertise, e.g. light characteristics or supply chain knowledge. Biased opinions may result in inaccuracy. In order to remove bias in these interviews, first the properties that should be used in determining the score of the alternatives were asked for. Afterwards, if possible, quantification of the criteria was given. If this was not possible, a qualitative score on the scale of 1 to 5 was given using the following definitions per score:

- 1: Poor
- 2: Insufficient
- 3: Mediocre
- 4: Sufficient
- 5: Excellent

If the scores of the experts do not correspond with that of the aggregate property, the score will be largely based on the aggregate property instead. The final scores of all the criteria are given in the above mentioned scale as well. The reason being that comparison will become possible between the different criteria. If possible, these scores will be based on quantification provided by experts.

3.4. Methodology SRQ4

Using literature and experts interviews, the different urban factors, which can influence the potential of LRA within an urban area, are identified. Using geo-spatial data acquired from the municipality, these urban factors have been mapped for Oldenzaal using ArcGIS Pro software. Two out of six urban factors, could not be retrieved in the form of geo-spatial data, which forms a model limitation in this study.

3.5. Methodology MRQ

The methodologies of SRQ1 until SRQ3 allow for the MCA to be performed. This results in a conclusion based on the implementation potential of LRA from a SSCM perspective. The methodology of SRQ4 results in a conclusion based on the implementation potential of LRA from an urban perspective. These two conclusions together form the answer to the MRQ.

4. Results

In this chapter the answers to the different research questions proposed in Section 1.2 are elaborated. Section 4.1 covers the first sub-research question, i.e. the different alternatives found and to be used in the MCA. Section 4.2 elaborates on the second and third sub-research question, i.e. the criteria, corresponding weights, and scores of the different LRA alternatives to be used in the MCA. Section 4.3 covers the urban characteristics that influence the potential of LRA in general and what their implications are in the context of Oldenzaal.

4.1. LRA Alternatives

One of the components of an MCA is the set of alternatives. The LRA alternatives in this MCA study are determined by first identifying the different elements within an asphalt mixture. The potential influence these elements have on the albedo of the asphalt mixture is determined as well. The albedo of a material and LRA mixture indicates the percentage of light being reflected back instead of being absorbed. By analysing which element has the highest influence on the albedo of the total asphalt mixture, a more specific set of alternatives can be created within this element category. This specific set of element alternatives will be used in the MCA.

An asphalt mixture typically consists of the binder, aggregates and additives. Besides these three components, most of the time an asphalt mixture also consists of reclaimed asphalt (NEN-EN 13108-1, 2016), which again consist of the three components mentioned above (NEN-EN 13108-8, 2005). The aggregates are categorized into coarse aggregates, fine aggregate, all-in aggregates and added filler. Depending on the type of asphalt mixture that is required, e.g. asphalt concrete (AC) (NEN-EN 13108-1, 2016) or Stone Mastic Asphalt (SMA) (NEN-EN 13108-5, 2016), the requirements for the composition of the asphalt mixture will differ.

4.1.1. The Role of the Binder on Asphalt Albedo

Traditional asphalt binders are black in colour and give the asphalt an initial black colour. These binders are referred to as bitumen and give the asphalt layer a low albedo for the initial life-phase. The albedo of fresh AC pavements has been recorded to be around 0.04-0.05 (Pomerantz & Pon, 2000), meaning it absorbs up to 95-96% of the sunlight falling onto the surface. It was also found by the same research that after five years of road usage, the albedo of these AC pavements increased to a value of 0.09-0.15 (Pomerantz & Pon, 2000), as a result of the bitumen layer wearing off and the oxidation of the binder (Qin, 2015a). However, the amount of time it takes for the bitumen to wear off is estimated to be one year according to a more recent study (see Figure 7) (Sen & Roesler, 2016). The relative short life-span of the bitumen film would lead to a low potential on influencing the albedo, as increasing the albedo of the bitumen would only affect the albedo in the initial life-phase of the asphalt road.

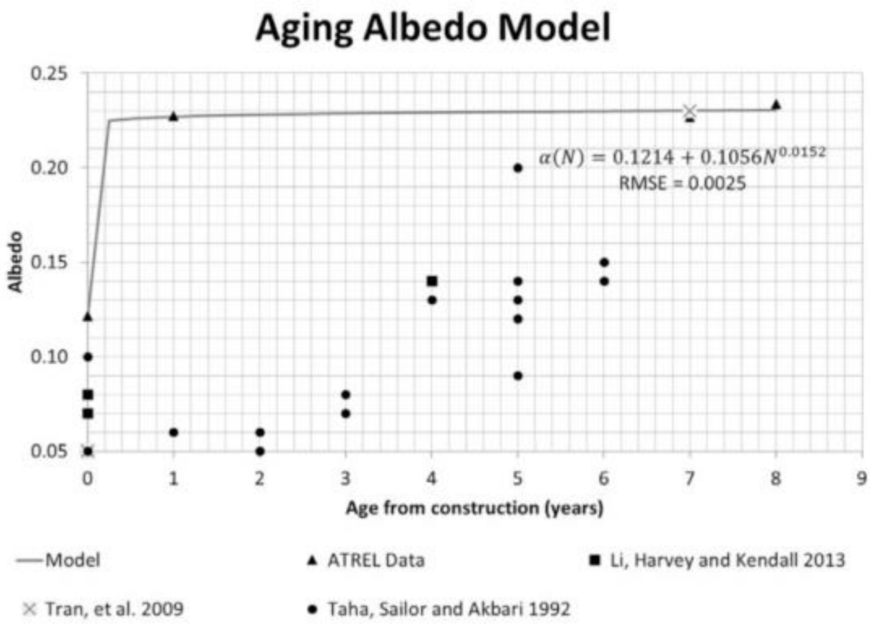

Figure 7 - The aging albedo model, visualizing the albedo of an asphalt pavement against its age from construction (Sen & Roesler, 2016).

4.1.2. The Role of Aggregates on Asphalt Albedo

In asphalt mixtures, the bitumen are covering the aggregates until this bitumen film wears off, after which, the aggregates become exposed instead. Because of the aggregates being exposed to sunlight rather than the binder and their higher albedo compared to the bitumen, more sunlight will be reflected back into the sky. Other studies give the albedo values of 0.05-0.10 and 0.10-0.15 for new and old asphalt pavement respectively (Qin, 2015a; Santamouris, 2013). The different values in initial and final albedo values can be related to the fact that different bitumen and aggregates are used in these studies. Because of the long exposure of the aggregates to sunlight, finding whiter aggregate alternatives would increase the albedo of the surface asphalt layer for the majority of its life-span.

4.1.3. The Role of Additives on Asphalt Albedo

Additives in the form of pigments and their effects on albedo have been a recent topic in research. Thermochromic pigments are mixed in the bitumen layer and they have a chameleon-like effect on the asphalt albedo. The albedo in summer is decreased, while the albedo in winter is lowered. During the summer a decrease of 6.6 °C in surface temperature is achieved and the rate at which the water freeze point is achieved during winter, has been proven to be decreased (Hu & Yu, 2013). However, as these additives are used in the bitumen layer, the same relative short life-span of the bitumen film would lead to a low potential influence on albedo by these pigments. Even the use of high near-infrared (NIR) reflecting pigments have been used as a surface technique in order to only reflect the non-visible NIR light of the solar spectrum. The results show a total albedo value, i.e. including the reflectance of visible light, of 0.6 (Xie et al., 2019) and 0.44-0.51 (Kinouchi et al., 2004). An 0.81 albedo value for only NIR light reflectance was also found (Wan et al., 2009). Despite these benefits in albedo, the disadvantage is the low life-span of the top layer, due to road usage. Because of this the albedo properties degrade in the long-term and are only a short-term solution, when looking at changing the albedo of additives.

4.1.4. The Final Set of LRA Alternatives

From these three components, the aggregates are the most promising and long-term alternative in creating a high albedo among asphalt mixtures. While interviewing experts, it became obvious that aggregates are the preferred component to be changed. No matter what colour pigments you use in the modified bitumen, the colour will always approximate that of the aggregate and that it is the best long-term alternative (Interviewee 2). From experience, white binders are costly and not easy to work with (Interviewee 3). Hence, in this paper, the focus will be on specific aggregate alternatives.

In the MCA, the alternative LRA aggregates need to be judged either qualitatively or quantitatively. Therefore, data plays an important role in determining the best alternative possible. In order to be confident that this data will be available for the most part, a selection already known to the chain of companies within ReintenInfra is made. This selection consists of the following aggregates and is already, partly, known to the asphalt producer within ReintenInfra, i.e. Asfalt Centrale Twente (ACT):

- Labradoriet (LD)
- Luxovit (LV)
- Reflexing White (RW)
- Bestone (BS)

LD and RW both originate from Norwegian grooves and are classified as anorthosite. They both are retrieved in their natural white colour, whereas LV is pre-processed at high temperatures in order to get its white colour. Therefore, it is also known as a calcified and artificial aggregate. In order to make a recommendation for whether these white-coloured aggregates should be used in asphalt mixtures, a comparison with the conventional darker aggregate is made, i.e. BS.

4.2. LRA Criteria and Corresponding Weights and Scores

In this chapter the different criteria and their scores will be discussed (Section 4.2.1). Also the weights assigned to the MCA criteria will be elaborated (Section 4.2.2). These two sections will form the input for the outcome of the MCA which is to be analysed in Section 4.2.3. All these three sections together will answer the second and third sub research question of this study.

4.2.1. Criteria and Corresponding Scores Per Alternative

The criteria in the MCA, which LRA alternatives must meet, are based on the three pillars of sustainability, i.e. the environmental (Section 4.2.1.1), economic (Section 4.2.1.2) and social pillar

(Section 4.2.1.3), which must be in balance in order for the innovation of LRA to be successfully applied within the supply chain (Dyllick & Hockerts, 2002) of ReintenInfra.

The criteria need to be as SMART as possible, i.e. **S**pecific, **M**easurable, **A**chievable, **R**elevant and **T**ime-oriented (*S.M.A.R.T. Objectives - Wayne LEADS - Wayne State University*, n.d.). The more SMART the criteria are the more accurate the MCA can be. Hence, this is an important framework to take into account.

If possible, the scores of the alternatives are based upon characteristics of the aggregates themselves. If this is not possible, the scores are determined by comparing the possibility for the total LRA mixtures to have the criteria property. A qualitative score using the following scale is used:

- 1: Poor
- 2: Insufficient
- 3: Mediocre
- 4: Sufficient
- 5: Excellent

These scores will be based on quantitative values found in either literature or the expert interviews, whenever possible. If a quantitative basis for the final scores is not established, the expert scores are used, as they were interviewed to score the alternative based on the criteria using the scale above. A summary of each interview is given in Appendix C. Table 2 provides an overview of the different interviewees and the appendix in which the interview summary can be found.

Table 2 – Overview textual interview reference and appendix reference.

Textual interview reference	Appendix reference
Interviewee 1	Appendix C.1
Interviewee 2	Appendix C.2
Interviewee 3	Appendix C.3
Interviewee 4	Appendix C.4
Interviewee 5	Appendix C.5
Interviewee 6	Appendix C.6
Interviewee 7	Appendix C.7

4.2.1.1. Environmental Criteria

Reducing the intensity of environmental impacts are important, as the Dutch authorities aim for a CO_2 neutral energy system by the year of 2050 (*Rijksoverheid Stimuleert Duurzame Energie | Duurzame Energie | Rijksoverheid.Nl*, n.d.). The environmental criteria in this study are defined as the criteria that contribute towards combatting various aspects of climate change and the urban heat island.

4.2.1.1.1. UHI reducing capacity during warmer periods

The effects of the UHI are preferably mitigated during the warmer periods throughout the year. Current research suggest that pavements are one of the causes for the UHI effect (Akbari & Kolokotsa, 2016; Gago et al., 2013; Mohajerani et al., 2017; Qin, 2015a; Santamouris, 2013, 2015). Further research suggests that increasing the albedo of cities can reduce the UHI effect (Yang et al., 2015). More specifically, increasing the albedo of pavement, i.e. with the use of LRA, may reduce the UHI effect (Mohajerani et al., 2017; Naus et al., 2016) if applied correctly (Santamouris, 2013). According to an empirical study, an albedo increase of 0.1 decreases the surface temperature of pavements by 4°C (Pomerantz & Pon, 2000).

Although, another experimental study concludes that the material properties influencing the albedo of materials are the color and roughness (Doulos et al., 2004), the communal material property reducing the UHI effect, with regards to the LRA innovation, is that of albedo. Hence, the UHI reducing capacity will be estimated based on the albedo property of the aggregate alternatives. The higher the albedo, the better it scores on this criteria.

Both experts interviewed on this criterion give somewhat the same scores (interviewees 6 and 7). However, interviewee 6, gives both a quantification and more specific score per alternative. Interviewee 2 also mentions LV being the whitest aggregate, which does not contradict the findings that albedo is influenced by the colour of a material (Doulos et al., 2004). Hence, it can be said that experts in general, agree with literature, which implies that albedo of pavements does correspond with lower surface temperatures. Based on the quantification of interviewee 6 the final scores of this criterion are shown in Table 3.

Table 3 – MCA scores based on the UHI reducing capacity during warmer periods per aggregate alternative.

	BS	LD	LV	RW
Qualitative score (Interviewee 7)	3	5	5	5
Qualitative score (Interviewee 6)	3	4	5	4
Quantitative score interviewee 6	30-35	55	70-75	60
Final qualitative score	3	4	5	4

4.2.1.1.2. UHI maintaining capacity during colder periods

In general, mitigation strategies tend to focus on just the mitigation of the UHI effect during the summer (Debbage & Shepherd, 2015). While the UHI effect in summer is considered as negative, the UHI in the winter can lead up to reduced heating loads in terms of energy and thus can be considered as favourable. For instance, during the winter, the heating load of buildings in the central part of Athens was found to be reduced by 30% due to the UHI effect (Santamouris et al., 2001).

More specific research indicates that the sole focus on summer also applies for the research around the mitigation technique of LRA (Yang et al., 2015). Another study states that the criterion of being able to change the albedo of LRA under seasonal circumstances should be taken into account (Qin, 2015a). A LRA alternative which is able to have a low albedo during colder periods is preferred.

The literature does suggest thermochromic coatings on pavements (Hu & Yu, 2013), but in terms of aggregates literature fails to mention what aggregate characteristics lead to a lower albedo in these colder periods. Hence, this gap in research needs to be alleviated with the use of expert judgement.

Despite the fact that interviewees 3, 6 and 7 all mention that the natural aggregates turn dark when under wet conditions, which is in accordance with the literature just mentioned, they do not find it an important criterion. Nonetheless, the importance of each criteria is determined using the surveys distributed among municipality employees, and should not be determined by the experts. Hence, only the scores of the experts are taken into account. Assuming that during colder periods, more precipitation occurs, it can be said that LD (natural) and RW (natural) turn darker, while LV (artificial) stays white. The BS alternative is already relatively dark and therefore scores high on this criterion. Although, both interviewees, used for scoring, advocate for aggregates that stay white to have a higher score because it would achieve more energy-savings for road illumination, the criterion of maintaining the UHI during colder periods is unscathed. They both gave the same qualitive scores based on energy-savings of road illumination, which resulted in the opposite scores (see Table 4) for the criterion discussed in this section, i.e. UHI maintaining capacity during colder periods.

Table 4 - MCA scores based on the UHI maintaining capacity during colder periods per aggregate alternative.

	BS	LD	LV	RW
Qualitative score Interviewee 7	2	3	5	3
Qualitative score Interviewee 6	2	3	5	3
Final qualitative score (Inverse scores of the experts)	4	3	1	3

4.2.1.1.3. Sustainability

The sustainability of a material, i.e. aggregate in this study, is defined as the environmental effects, e.g. CO_2 emissions, that the utilization of such a material would imply. The sustainability of construction materials can be assessed using tools such as DuBoCalc or EcoChain. These tools can calculate the environmental effects of the material to be used throughout its life. These effects will then turn into an Environmental Cost Indicator (*abbreviation*: ECI) . With this indicator, a ''shadow''-price is created and assigned to the materials (in euros/ton) (Rijkswaterstaat, n.d.; the Bruyn et al., 2018). The lower the ECI, the more sustainable the material is . However, what this source fails to mention, are all the different factors taken into account when determining the ECI of a specific material such as aggregates. A better understanding of the process needs to be researched using expert judgement.

Speaking to an ACT employee (Interviewee 4) with knowledge on the EcoChain tool, the Bestone ECI gives a value of 2.30 euros/ton. For the three LRA alternatives the specific ECI is unknown. Instead, a general product map is used, which excludes environmental costs induced by transport, and gives a value of 2.16 euros/ton. Furthermore, the interviewee adds that these values are solely based on production emissions, excluding any indirect positive environmental effect of the aggregates on the project context. Hence, this criterion can be treated as separate.

Transport does play a decisive role and could increase the ECI of the LRA alternatives well-above the BS alternative (Interviewee 4). Besides the transport factor, the LV alternative also requires processing at high temperatures in order for it to achieve a whiter colour (Interviewee 2). This increases the ECI which makes the LV alternative less environmental friendly than the other alternatives based on production energy consumption. Based on these findings from the expert interviews, the scores are determined per alternative (see Table 5).

Table 5 - MCA scores based on the sustainability criterion per aggregate alternative.

	BS	LD	LV	RW
Quantitative scores in euros/ton (Interviewee 4)	2.30	2.16	2.16	2.16
Qualitative score including transport (Interviewee 4)	4	2	2	2
Final score including transport and energy usage due to pre-processing	4	2	1	2

4.2.1.1.4. Durability

The durability is defined as the life-span of the asphalt mixture and is indicated by the functional life-span and albedo life-span.

4.2.1.1.4.1. Functional life-span

The functional life-span of the asphalt layer is defined as the total life-span of the surface asphalt layer. Increasing the albedo of pavements by 0.1 decreases the surface temperature by 4 °C (Pomerantz & Pon, 2000). A strong relation has been found between temperature and the rate at which a failure mechanism of asphalt occurs, e.g. rutting or shoving (Pomerantz et al., 2000). The results showed that the testing repetitions of experimental traffic representation required 10 times the amount before reaching the failure criterion for rutting when the temperature of the samples was decreased from 53 to 42 °C. For the shoving failure a decrease in temperature from 60 to 40 °C showed a 100 fold increase of repetitions needed in order to reach the failure criterion. This gives an indication that reducing the UHI intensity might increase the asphalt life-span as well.

Despite, the expert judgement, which implies that the life-span of asphalt mixtures might be related to the PSV (Polished Stone Value) (Interviewees 5 and 6) and LA (Los Angeles) coefficient (Interviewee 5), the above mentioned literature does make a strong point that the albedo of the aggregates could play a dominant role in increasing the life-span of the asphalt top layer. Hence, based on the albedo quantification of the aggregate alternatives provided by interviewee 6, the scores are determined (see Table 6).

Table 6 - MCA scores based on the functional life-span per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Qualitative score (Interviewee 6)	3	4	5	4
Quantitative score (Interviewee 6)	30-35	55	70-75	60
Final qualitative score	3	4	5	4

4.2.1.1.4.2. Albedo life-span

The second factor influencing the durability of an asphalt mixture is whether or not a high albedo can be maintained throughout the life-span of the asphalt mixture, i.e. the albedo life-span. More specifically, the albedo life-span indicates whether or not the albedo of the aggregates decreases as the asphalt layer is exposed to traffic and other factors, such as dirt. Interviewee 1 says that it is important that the albedo property of a LRA mixture is to be maintained as long as possible. Otherwise the potential of LRA diminishes significantly. No literature surrounding this criterion has been found. Hence, expert interviews were held to gather more information about this criterion. After bringing this criterion to their mind, interviewees 2 and 7 both agree and mention that a slight endarkening shift may occur for the alternatives in general, due to dirt. Interviewee 7 even goes on and says that this reduction is higher for the LRA alternatives than for the conventional alternative. However, no difference between the whiter aggregates was found according to this interviewee. The qualitative scores can be found in Table 7.

Table 7 – MCA scores based on the albedo life-span per aggregate alternatives.

	BS	**LD**	**LV**	**RW**
Qualitative score (Interviewee 7)	4	3	3	3
Final qualitative score	4	3	3	3

4.2.1.1.5. Re-usable capacity in top layers

In terms of re-usability of asphalt mixtures and thus, aggregates, the following restrictive guidelines for surface layers of AC and SMA mixtures and the use of asphalt granulate are given (CROW, 2015):

- For AC surface layers, the mass percentage of asphalt granulate may only contain up to 30% of a new asphalt mixture.
- For SMA surface layers, the mass percentage of asphalt granulate is restricted to 0% of a new asphalt mixture.

There has been research going on to advocate for another category of aggregates that should not fall within these limitation categories and therefore, can result in a higher percentage of aggregates being re-used in asphalt mixtures (Jacobs et al., 2016). The idea is that if the quality of the aggregate is very constant throughout its life-cycle, no limitations to re-usability percentages should be assigned.

Despite the demand for a higher re-usability percentage by some contractors, the different aggregate characteristics related to the re-usability capacity in top layers is not given in literature. Hence, expert judgement is used instead.

According to the interviewees the aggregate characteristics in Table 8 are related to the re-usability capacity in surface layers. For surface layers the requirements for aggregate type 3 conform (CROW, 2015) are used according to interviewee 5. Based on these requirements and quantitative data, the qualitative scores of experts can be adjusted to remove any bias.

For the BS alternative, both the PSV and LA coefficient meet the requirements and consequently, is given a score of 5. Also, both experts speak highly of this alternative which justifies this score. RW comes in second with the score of 4, despite nearly missing the requirements. The reason for a sufficient score is that both experts score speak moderately-highly of this alternative. LV scores dramatically on the LA coefficient and LD scores dramatically on the PSV. They do score (near) sufficient for the other respective characteristic, which prevents the score from being a 1 and instead the score of 2 is given for both these alternatives.

Table 8 - MCA scores based on the re-usable capacity per aggregate alternative.

	Requirement aggregate type 3[1]	**BS**[2]	**LD**[3]	**LV**[4]	**RW**[5]
Declared PSV (Polished Stone Value) (Interviewees 5 and 6)	$\geq PSV_{58}$	PSV_{60}	PSV_{50}	PSV_{55}	PSV_{56}
LA (Los Angeles) coefficient (Interviewee 6)	$\leq LA_{15}$	LA_{15}	LA_{14}	LA_{50}	LA_{16}
Qualitative scores (Interviewee 5)	-	4	4	3	4
Qualitative scores (Interviewee 6)	-	5	1	4	5
Final scores	-	5	2	2	4

[1] Requirements used from (CROW, 2015).
[2] Values found in technical reports (*Toeslagmateriaal - Bestone 2/5*, 2017; *Toeslagmateriaal - Bestone 4/8*, 2017; *Toeslagmateriaal - Bestone 8/11*, 2017).
[3] Values found in technical reports (*Gesteinskörnungen Nach TL Gestein-StB (EN 13043)*, 2010).
[4] Values found in technical reports (*Nr. GB 2-5*, 2015; *Nr. GB 5-8*, 2015).
[5] Values found in technical reports (*Prestatieverklaring Nr: RW2 - Versie 4.0*, 2019).

4.2.1.1.6. Energy-saving Potential with respect to Public Lighting

One of the benefits of LRA is that a possible reduction in energy-usage of road illumination can be achieved (Naus et al., 2016; Santamouris, 2013). More specifically, an energy demand reduction of up to 40% is possible (Ter Huerne et al., 2014). An example of LRA is Luminumpave which can reduce the energy demand of lighting by 40-50% without endangering the traffic situation (*Luminumpave | Dura Vermeer*, 2015). Another study estimates a 20% reduction of strength in street lighting when the reflectivity of visible light is increased with 10-30% (Pomerantz et al., 2000). The latter study shows the albedo to be the decisive characteristic. However, other and more recent papers mention that in order to achieve the same amount of illumination the diffusiveness of the LRA needs to be considered (Naus et al., 2016; Ter Huerne et al., 2014). In order to find the relation between aggregate characteristics and road illumination energy-savings, literature alone, does not provide a clear answer.

Expert judgement indicates that the whiteness (luminance factor) and diffusiveness of the aggregates play a role in the amount of possible energy-savings in public lighting (Interviewees 6 and 7). This confirms the lighting properties found in literature (Naus et al., 2016; Ter Huerne et al., 2014). Based on the quantified luminance factor provided by interviewee 6 and the qualitative diffusiveness of interviewee 7, the final scores in Table 9 are determined. In terms of diffusiveness BS has high mirror factor, but it is not too dark. Hence, BS has the score of 2. LV has the highest luminance factor and is also quite diffusive, resulting in a score of 5. The LD and RW alternative have the same diffusiveness, but a lower luminance factor in comparison with the LV alternative. Consequently, a score of 4 is assigned to these two aggregates. Despite, the unanimous decision of giving LD a 3 instead of a 4, it would not be justified as both these alternatives (LD and RW) have the same luminance factor (Interviewee 6) and the same diffusiveness (Interviewee 7).

Table 9 - MCA scores based on the public lighting energy-savings criterion per aggregate alternative.

	BS	LD	LV	RW
Quantitative score luminance factor (Interviewee 6)	0.34	0.45	0.55	0.45
Qualitative score diffusiveness (Interviewee 7)	Low	Medium	High	Medium
Qualitative score (Interviewee 6)	2	3	5	4
Qualitative score (Interviewee 7)	2	3	4	4
Final qualitative score	2	4	5	4

4.2.1.2. Economic Criteria

The economic aspect of sustainable innovations is important as non-economically feasible innovations become less attractive for the producer. The reason being that the innovation does not provide for an economic healthy environment for the company. The economic criteria in this study are defined as criteria that influence the amount of project opportunities, created by the innovation of LRA, for TWW and ReintenInfra as a whole. Because of the local supply chain dependency (Pomerantz & Pon, 2000), the economic criteria are scored based on expert judgement instead of general literature.

4.2.1.2.1. Total Costs

The total costs to be used in the MCA include material costs and production costs. Staff expenses are negligible according interviewee 5. Furthermore a qualitative score is given, as the costs are considered as confidential data.

Based on the information retrieved from interviewee 5, the qualitative scores are given in Table 10. The BS alternative is simply available for a very cheap price and is given the score of 5. Despite the fact that all aggregate sizes for the LD alternative must be bought together, it is still very cheap and a qualitative score of 4 is given. Both LV and RW are considered as mediocre by the interviewee, but the high production costs of LV make this alternative fall under the category of insufficient, i.e. 2, instead of 3 (RW).

Table 10 – MCA scores based on total costs per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Qualitative score (Interviewee 5)	5	4	2	3
Final qualitative score	5	4	2	3

4.2.1.2.2. Practicality

The practicality is important as it gives an indication towards, the amount of experience there is within the supply chain regarding the use of a certain aggregate alternative. This criterion is divided into the technological know-how, implementation know-how and resource availability.

4.2.1.2.2.1. Technological Know-how

The knowledge retrieved in the laboratory is referred to as the technological know-how. Interviewee 5 gives a sufficient score, i.e. 4, to each of the alternatives with regards to this criterion, as data surrounding these alternatives is well-known for all the alternatives. Table 11 shows the determined scores for each alternative.

Table 11 – MCA scores based on the technological know-how per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Qualitative score (Interviewee 5)	4	4	4	4
Final qualitative score	4	4	4	4

4.2.1.2.2.2. Implementation Know-how

The knowledge and experience among asphalt workers is defined as the implementation know-how. Just like the technological know-how, the implementation know-how regarding all alternatives is considered as sufficient according to interviewee 5. In Table 12, the final scores are given based on this expert interview.

Table 12 - MCA scores based on the implementation know-how per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Qualitative score (Interviewee 5)	4	4	4	4
Final qualitative score	4	4	4	4

4.2.1.2.2.3. Resource Availability

The resource availability is defined as the availability of the aggregate alternative. According to interviewee 5, the general demand towards whiter aggregates has increased over the past few years, which also means that it is more difficult to retrieve batches of these LRA alternatives. However, this still implies a score of 4 for the LRA aggregate alternatives. BS gets a score of 5, as it is easy to get access to this aggregate. The final scores are given in Table 13.

Table 13 – MCA scores based on the resource availability per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Qualitative score (Interviewee 5)	5	4	4	4
Final qualitative score	5	4	4	4

4.2.1.2.3. Applicability in Top Layers

According to interviewee 2, the applicability of an aggregate in a top layer is determined by whether or not it meets the requirements of aggregate type 3 (CROW, 2015). Interviewee 6 mentions that a mix of different aggregates can be used to combine the best characteristics from each aggregate into a single asphalt mixture.

The comparison between requirements and declared values of aggregate data reports is shown in Table 14. Requirements that are different per aggregate type are solely included in this table. The scores are determined based on, to what extent the requirements are fulfilled. Note that a single requirement not met, does not necessarily imply an insufficient score. As interviewee 3 suggests, the combination of different aggregates is possible to compensate for potential weaknesses of the LRA aggregate.

From the data it becomes known that BS meets all the requirements and thus receives a score of 5. All the alternatives meet the percentage of broken surface requirement, which implies that the comparison needs to be made, based on the other requirements, i.e. PSV and LA coefficient. LD scores particularly low on the PSV requirement, while meeting all the other requirements, which results in a score of 3. LV scores a bit low on the PSV value while completely missing the LA requirement, resulting in a 2. RW comes just a bit short for both the PSV and LA coefficient, which is still better than LD, but worse than BS, so a score of 4 is assigned to RW.

Table 14 – MCA scores based on the applicability in top layers per aggregate alternative.

Aggregate characteristic	**Requirement aggregate type 3**[6]	**BS**[7]	**LD**[8]	**LV**[9]	**RW**[10]
Declared PSV (Polished Stone Value)	$\geq PSV_{58}$	PSV_{60}	PSV_{50}	PSV_{55}	PSV_{56}
LA (Los Angeles) coefficient	$\leq LA_{15}$	LA_{15}	LA_{14}	LA_{50}	LA_{16}
Percentage broken surface	$=C_{100/0}$	$C_{100/0}$	$C_{100/0}$	$C_{100/0}$	$C_{100/0}$
Final scores	-	5	3	2	4

4.2.1.3. Social Criteria

As any new product on the market experiences some form of consumer resistance (Cornescu & Adam, 2013), the social aspect of sustainability needs to be taken into account. The social criteria in this study are defined as criteria that keep society content with the implementation of LRA.

4.2.1.3.1. Safety

Providing a safe road surface is the first social criterion to consider. In order to partly quantify safety, it is split up into the following four sub criteria.

4.2.1.3.1.1. Anti-Glare Performance

As a relatively old study has found no glare inducing capacity of LRA alternatives on drivers (Pomerantz et al., 2000), more recent research suggests that the higher albedo of LRA alternatives, may actually result in glare for drivers (Naus et al., 2016; Qin, 2015a; Yang et al., 2015). Reflective coefficients of

[6] Requirements used from (CROW, 2015).
[7] Values found in technical reports (*Toeslagmateriaal - Bestone 2/5*, 2017; *Toeslagmateriaal - Bestone 4/8*, 2017; *Toeslagmateriaal - Bestone 8/11*, 2017).
[8] Values found in technical reports (*Gesteinskörnungen Nach TL Gestein-StB (EN 13043)*, 2010).
[9] Values found in technical reports (*Nr. GB 2-5*, 2015; *Nr. GB 5-8*, 2015).
[10] Values found in technical reports (*Prestatieverklaring Nr: RW2 - Versie 4.0*, 2019).

LRA are given in research (Naus et al., 2016; Ter Huerne et al., 2014). However, which one of these coefficients is the cause for glare is not discussed in these papers and hints at a gap in research knowledge.

Interviewee 7 mentions that the whiteness and diffusiveness of materials play a role in causing a glare effect. Interviewee 6 says the PSV and cubical shape of the aggregates partly determine the diffusiveness and thus, anti-glare performance of the total asphalt mixture. He also adds the fact that a whiter aggregate will be more likely to cause glare than a darker aggregate. Hence, the general trend among interviewees shows that diffusiveness and whiteness give an indication for the anti-glare performance, which fills the gap in literature surrounding the anti-glare criterion.

Table 15 shows the different scores per interviewee and the final scores. According to interviewee 7, the mirror factor is the highest for BS, medium for LD and RW and the lowest for LV. A high mirror factor corresponds with a low diffusion of light and thus more glare is caused. A low mirror factor indicates that the light is reflected into multiple directions rather than have a focused light reflection towards the eyesight of the drivers. Combining the diffusive property with the luminance factor (whiteness), gives a compensating effect for each alternative and gives it a sufficient mark. BS has a high mirror factor, but compensates for it by having a dark colour. LD and RW both have medium whiteness and a medium mirror factor. LV has a low mirror factor, but a high luminance factor.

Table 15 – MCA scores based on the anti-glare performance per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Quantitative score luminance factor (Interviewee 6)	0.34	0.45	0.55	0.45
Qualitative score diffusiveness (Interviewee 7)	Low	Medium	High	Medium
Final qualitative score	4	4	4	4

4.2.1.3.1.2. Road Visibility Boosting Performance during the Night

Additional visibility of the road can increase both the social and traffic safety (Naus et al., 2016; Ter Huerne et al., 2014). Where earlier literature give the albedo as an indication for creating better visibility (Pomerantz et al., 2000), more recent studies focus on the diffusiveness of LRA alternatives as the better indicator for visibility of the road (Naus et al., 2016; Ter Huerne et al., 2014). This conflict in literature, should be resolved using expert judgement.

Interviewee 7 says that both the luminance factor (whiteness) and diffusiveness of the aggregates determine the road visibility during the night. The higher the luminance factor and diffusiveness of the aggregate, the better road visibility will be. These two factors given by this expert, resolve the previously given conflict in literature. Table 16 provides the qualitative scores of both interviewees and also the final scores. BS has both the lowest luminance factor and diffusiveness, resulting in a 2. The reason it is not a 1, is because the luminance factor can even be lower. LV has the highest luminance factor and diffusiveness, resulting in a 5. LD and RW both have a lower luminance factor and diffusiveness than LV, resulting in a 4.

Table 16 – MCA scores based on the road visibility boosting performance during the night per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Quantitative score luminance factor (Interviewee 6)	0.34	0.45	0.55	0.45
Qualitative score diffusiveness (Interviewee 7)	Low	Medium	High	Medium
Qualitative score (Interviewee 7)	2	4	4	4
Qualitative score (Interviewee 6)	2	4	5	4
Final qualitative score	2	4	5	4

4.2.1.3.1.3. Maintaining a High Contrast Between Road Surface and Road Markings

Maintaining a sufficient contrast between road markings is important to take into account when changing the colour appearance of the top layer. Although, there is a lack of research on this topic, guidelines with respect to the colour of road markings and their corresponding luminance factor (β) are available (Kiwa Nederland, 2009). The luminance factor is also known as the ''whiteness'' of materials (Naus et al., 2016). By having a larger difference between the luminance factor of the road surface and the road markings, the contrast will be greater and thus, clearer road markings are present on the road. Based on the guidelines and literature, the most logical unit for this criterion is the difference in luminance factors between road surface and road markings (Δβ).

Both interviewees 6 and 7 mention that the Δβ does get lower as, the asphalt becomes more white. The interviewees also mention that there are possible solutions to maintain a high Δβ and thus, give all the alternatives a score of 4. However, by implying that a solution is needed, the contrast with the lower Δβ does deserve to have a lower score then, as more work is needed towards maintaining the contrast between road marking and road surface. The luminance factor of white road marking paint is 0.80 (Kiwa Nederland, 2009). Subtracting the luminance factor of the road painting with the aggregate luminance factor gives the Δβ. The different scores are given in Table 17.

Table 17 – MCA scores based on contrasts between road markings and road surface per aggregate alternative.

	BS	LD	LV	RW
Quantitative score luminance factor (Interviewee 6)	0.34	0.45	0.55	0.45
Quantitative score Δβ	0.46	0.35	0.25	0.35
Final qualitative score	4	2	1	2

4.2.1.3.1.4. Anti-skid Performance

As with any form of an LRA alternative, the anti-skid performance is an important criterion to take into consideration and maintain. For instance, near-infrared coatings have been tested on their anti-skid performance (Xie et al., 2019; Zheng et al., 2015). Also, it has been studied that the anti-skid performance of chip seals are found to be sufficient (Pomerantz et al., 2003). In the first two studies the BPN is used as an indicator for the anti-skid performance of the coatings.

However, interviewee 5 says the PSV can be used to indicate the anti-skid performance. Based on data reports of the aggregates the PSV becomes known and these quantities can be compared to the qualitative score of the expert (see Table 18). The scores of the expert corresponds with the quantitative data found in reports, thus justifying it.

Table 18 – MCA scores based on the anti-skid performance per aggregate alternative.

	Requirement aggregate type 3[11]	**BS**[12]	**LD**[13]	**LV**[14]	**RW**[15]
Declared PSV (Polished Stone Value)	≥PSV_{58}	PSV_{60}	PSV_{50}	PSV_{55}	PSV_{56}
Qualitative score (Interviewee 5)	-	5	3	4	4
Final scores	-	5	3	4	4

4.2.1.3.2. Noise Reducing Capacity

Characteristics that reduce noise pollution are dependent on two parameters. The first parameter being the void content. Research indicates that a higher void content of asphalt relates to more noise reduction (Merska et al., 2016). The second parameter is that of macro-texture depth. A higher texture groove depth relates to higher noise levels (Merska et al., 2016; Wei et al., 2018). The problem occurring with noise reducing asphalt top layers is that the acoustical properties tend to diminish with age. For instance, the noise reducing capacity of KonwéStil mixtures decreased with an average of 0.5 dB(A) per year, resulting in the noise reduction levels from 4.3 to 0.7 in an 8 year time period for a 50 km/h road (Dekkers et al., 2012). Despite this, interviewee 5 considers noise reduction to be a bonus and worth taking into account.

With regards to aggregate characteristics, the question that know remains is whether asphalt applications with the aggregate alternatives in this thesis are able to achieve high void contents and low macro-texture. Expert judgement should be advised.

Interviewee 6 says that the noise reducing capacity is dependent on the total asphalt mixture. He adds to this that with all the alternatives, a sufficient noise reducing capacity can be achieved, i.e. a score of 4. The final scores are given in Table 19.

Table 19 – MCA scores based on the noise reducing capacity per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Qualitative score (Interviewee 6)	4	4	4	4
Final qualitative score	4	4	4	4

4.2.1.3.3. Environmentally Boosting Performance

Literature on the LRA innovation mention that a potential hindering factor is that the innovation does not fit into its environment, and thus, causes aesthetics problems (Mohajerani et al., 2017; Qin, 2015a). Other research indicates the environmentally appearance boosting capacity of LRA (Naus et al., 2016; Ter Huerne et al., 2014). These conflicts in literature give reason for additional research.

Interviewees 1 and 3 both advocate for a lighter coloured road surface, as it would create a more pleasant environment. Hence, it is viewed as a positive to have LRA as a surface layer. Interviewee 6 says that a higher luminance factor and diffusiveness enlighten the surrounding area more. Thus, increasing the environmentally boosting performance of the aggregates and LRA mixture. The scores

[11] Requirements used from (CROW, 2015).

[12] Values found in technical reports (*Toeslagmateriaal - Bestone 2/5*, 2017; *Toeslagmateriaal - Bestone 4/8*, 2017; *Toeslagmateriaal - Bestone 8/11*, 2017).

[13] Values found in technical reports (*Gesteinskörnungen Nach TL Gestein-StB (EN 13043)*, 2010).

[14] Values found in technical reports (*Nr. GB 2-5*, 2015; *Nr. GB 5-8*, 2015).

[15] Values found in technical reports (*Prestatieverklaring Nr: RW2 - Versie 4.0*, 2019).

are given in Table 20. Interviewee 7 does not differentiate the LRA alternatives, while interviewee 6 gives a more specific answer, which also corresponds with both of the factors mentioned above. Hence, for the LRA alternatives, the score of interviewee 6 is utilized. Both interviewees give the BS alternative a score of 1. This seems unjustified as there are other aggregates on the market with an even lower luminance factor. Hence, a score of 2 is assigned to the BS alternative.

Table 20 – MCA scores based on the environmentally boosting performance per aggregate alternative.

	BS	**LD**	**LV**	**RW**
Quantitative score luminance factor (Interviewee 6)	0.34	0.45	0.55	0.45
Qualitative score diffusiveness (Interviewee 7)	Low	Medium	High	Medium
Qualitative score (Interviewee 6)	1	4	5	4
Qualitative score (Interviewee 7)	1	5	5	5
Final qualitative score	2	4	5	4

4.2.2. Criteria Weights

Now that the criteria are known, weights can be assigned to the different criteria. The main criteria, i.e. the three pillars of sustainability, have to be assigned an equal weights, as in order for the sustainable innovation to be successfully implemented, a balance in the three pillars is needed (Dyllick & Hockerts, 2002).

The sub and sub-sub criteria weights, cannot be found through literature. Talking to interviewees 1 and 3, the stakeholder that determines the criteria the most is the client. In this case the client is the municipality. Their reasoning is that if the municipality is not in accordance with the plans made by the contractor, the implementation of LRA is likely not going to happen at all.

The interest of the municipality is taken into account, by conducting a survey per pillar of sustainability (see Appendix D), such that a pairwise comparison can be made per criteria using the Analytical Hierarchy Process (AHP) (Saaty, 2008). The questions had the format of two statements representing the two criteria and the relative importance between the criteria was given as the answer. The survey was send to a total of 9 municipal employees of which 4 responded back. Hence, each survey has a sample size of 4 except for the sustainable pillar, as one respondent did not fill out the questionnaire completely.

The average weights between the municipal employees are determined and are shown in Section 4.2.3 (Table 21) together with the scores per criteria found in Section 4.2.1. How these weights are calculated is explained in Appendix A.1.

4.2.3. MCA Outcome

The determination of the criteria, scores per alternative and weights of each criteria can together be used to calculate the outcome of the best alternative based on each pillar and all the pillars of sustainability combined. How these scores are calculated is elaborated in Appendix A.2. The results of the MCA are shown in Table 21.

From the MCA it becomes clear, that the conventional aggregate, i.e. BS, has the best overall score. It is by far the best alternative from an economic perspective. From a social perspective, it is also scores better than the LRA alternatives, however not as much from an economic point of view. Environmentally, the LV and RW alternative score slightly better than the BS alternative, but due to the same weights of the main criteria, the overall score favours BS much more. Based on the MCA, it will be more difficult for the LRA alternatives to compete with the conventional aggregates from a supply chain perspective.

Overall, when comparing the LRA aggregates with each other, the LD and RW score higher than LV. Although RW scores slightly better than LD, not much difference, between the overall scores of LD and RW was noticeable. Hence, based on the MCA, a conclusion differentiating between these two LRA alternatives is cannot be made.

LD is the most economically viable LRA alternative, but in terms of re-usable capacity and applicability in top layers, it scores particularly low. LV has the highest albedo, whiteness and diffusiveness, which makes it the best alternative for public lighting energy-savings, road visibility during the dark and environmentally boosting performance. However, LV is also considered to have the same weaknesses as LD. RW is considered the most all-round aggregate, as it comes closest to achieving the requirements of aggregate type 3, i.e. aggregates used for surface layers, while also scoring sufficient on most criteria. Based on the interests of both the municipality and TWW, an aggregate mixture or choice between aggregates can be made using these pros and cons.

The experts used in the MCA for scoring the different alternatives, might be biased towards a certain alternative, as they are currently implementing one of the alternative. This is the case for two out of the three experts used for scoring the alternatives. One has experience with the LD alternative, while the other has experience with the LV alternative. Although, the experts all have knowledge on the RW aggregate, they do not own any products using this LRA alternative. Thus, when scoring RW, the experts were less biased than when scoring LD and LV.

In order to remove any biased expertise opinions about the aggregates and their scores, the characteristics playing a key factor were asked to them before asking for the scores. If the quantification of characteristic properties of the aggregates did not correspond with the score of the experts, the scores were considered as biased and altered accordingly. This way, the scores are altered according to quantification based on technical reports and thus, can be justified. Scores may also be altered if another expert gave quantification of the properties in a separate interview. For instance, this has been done for criteria measured by the whiteness and diffusiveness properties, e.g. anti-glare performance. Every criterion contained a table with the final score per aggregate regarding the criterion. This table contains the both the (biased) expert scores and the non-biased scores in order to provide an overview of all the changes in scores made regarding a specific criterion. The final scores given per criteria in Section 4.2.1 already contain this bias removal.

Table 21 - Final MCA with the green rows presenting the final scores per pillar of sustainability and the combined scores of these three pillars.

Type of criteria	Criteria (Section 4.2.1)	Weights	Alternatives qualitive scores			
			BS	LD	LV	RW
Main criteria	Environmental criteria	0,33	3,26	3,2	3,27	3,33
Sub criteria	UHI reducing capacity warm periods	0,14	3	4	5	4
Sub criteria	UHI maintaining capacity cold periods	0,1	4	3	1	3
Sub criteria	Sustainability	0,23	4	2	1	2
Sub criteria	Durability	0,15	3,74	3,26	3,53	3,26
Sub-sub criteria	Functional life-span	0,26	3	4	5	4
Sub-sub criteria	Albedo life-span	0,74	4	3	3	3
Sub criteria	Re-usable capacity top layers	0,07	5	2	2	4
Sub criteria	Energy-saving potential public lighting	0,31	2	4	5	4
Main criteria	Economic criteria	0,33	4,62	3,84	2,94	3,62
Sub criteria	Total costs	0,38	5	4	2	3
Sub criteria	Practicality	0,47	4,2	4	4	4
Sub-sub criteria	Technological know-how	0,34	4	4	4	4
Sub-sub criteria	Implementation know-how	0,46	4	4	4	4
Sub-sub criteria	Resource availability	0,2	5	4	4	4
Sub criteria	Applicability in top layers	0,16	5	3	2	4
Main criteria	Social criteria	0,33	3,76	3,29	3,37	3,44
Sub criteria	Safety	0,7	4,06	2,98	2,89	3,21
Sub-sub criteria	Anti-glare performance	0,29	4	4	4	4
Sub-sub criteria	Road visibility boosting performance during the night	0,08	2	4	5	4
Sub-sub criteria	Maintaining a high contrast between road surface and -markings	0,4	4	2	1	2
Sub-sub criteria	Anti-skid performance	0,23	5	3	4	4
Sub criteria	Noise reducing capacity	0,16	4	4	4	4
Sub criteria	Environmentally boosting performance	0,14	2	4	5	4
		Overall score	3,88	3,44	3,19	3,47

4.3. Urban Characteristics Influencing Potential of LRA

Besides just having positive effects, e.g. energy-reduction (Naus et al., 2016; Santamouris, 2013; Ter Huerne et al., 2014) or increasing the life-span of LRA relative to conventional asphalt pavements (Pomerantz et al., 2000), the LRA mitigation technique also has negative effects which should be attended to (Yang et al., 2015). By taking into account the urban characteristics of a city, both the positive and negative effects can be strengthened and weakened respectively. The urban characteristics discussed in this section differ per city and need local research (Qin, 2015a; Santamouris, 2013).

These urban characteristics consists of the UHI intensity (Section 4.3.1), public lighting reduction (Section 4.3.2), urban geometry (Section 4.3.3), vulnerable heat stress groups buildings (Section 4.3.4), traffic intensity (Section 4.3.5) and construction year of the top layer (Section 4.3.6). Each urban factor is explained and the implementation potential in the context of Oldenzaal will be given in the form of either a map, statistic or both. Also, all the different streets will be assigned a score per urban characteristic. Finally, all the scores can be combined to determine the final score per asphalt street. The data treatment and processing in order to get to output maps is elaborated in Appendix B. From these maps, the different statistics mentioned throughout the following sections are found. It is important to note that the maps and statistics will be based on asphalt roads that can be used by vehicles and asphalt parking lots, excluding any pedestrian and cycling paths. All the model assumptions are also explained in Appendix B.

4.3.1. UHI Intensity

The UHI intensity at a specific location, partly determines whether or not that location is more or less suitable for the implementation of LRA. The reason being that the more the problem is present, i.e. the UHI intensity, the more a potential solution, e.g. LRA, could be useful (Akbari & Kolokotsa, 2016; Gago et al., 2013; Mohajerani et al., 2017; Qin, 2015a; Santamouris, 2013, 2015). Interviewee 6 also confirms this perspective of implementation potential. The UHI intensity depends on urban characteristics, which differ per city (Qin, 2015a; Santamouris, 2013).

4.3.1.1. Factors Influencing the UHI Intensity

The UHI intensity of Oldenzaal is modelled for 2017 (Remme, 2017) and is shown in Figure 8. It determines the average annual air temperature increase for Oldenzaal due to the UHI effect per cell with size 10 by 10 meters. Whether or not the model takes into account the various urban characteristics influencing the UHI intensity is discussed below. Although, this outcome also takes into account the UHI intensity during the winter, it is still considered as a reliable indication towards the intensity during the summer, which is used in the model proposed in this study.

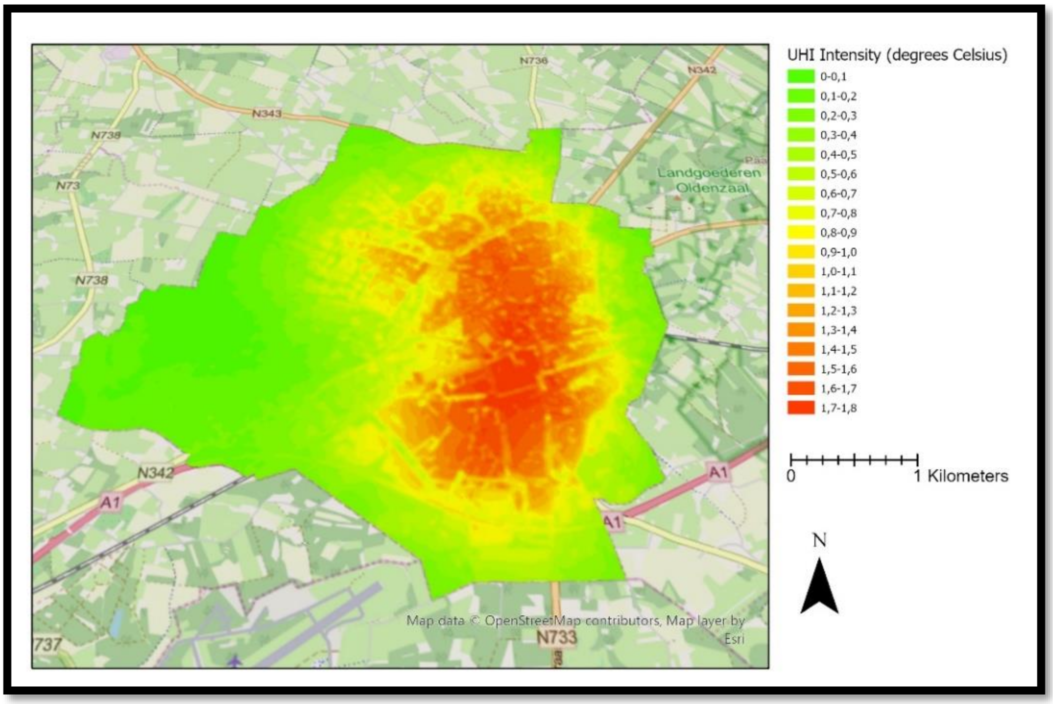

Figure 8 – UHI intensity in Oldenzaal with a level of detail of 10 by 10 meter cells.

4.3.1.1.1. Greenery

Green areas are well-known for their UHI mitigating effect (Gago et al., 2013; Mohajerani et al., 2017; Santamouris, 2013). More specifically, in a review on the past three decades of UHI research, greenery in the form of vegetation, green roofs and green façades have been mentioned to reduce the UHI effect (Akbari & Kolokotsa, 2016). The UHI model for the Netherlands and thus Oldenzaal, also takes into account vegetation by categorizing them between trees, shrubs and bushes, and grass and low vegetation, which have heights of: greater than 2.5, between 1 and 2.5 and less than 1 meters (Remme, 2017).

4.3.1.1.2. Water

Water related mitigation measures, e.g. evaporative pavements (Akbari & Kolokotsa, 2016; Mohajerani et al., 2017; Qin, 2015a; Santamouris, 2013, 2015), can be viewed as an indication that water bodies relate to a lower UHI effect. Although, the UHI intensity model for Oldenzaal does not take into account evaporative pavements, it does take into account water bodies on land and their reducing effect on the UHI intensity, i.e. a 30% reduction (Remme, 2017).

4.3.1.1.3. Pavements and other Urban Fabrics

Research shows that materials can play a role in both increasing or decreasing the UHI intensity (Doulos et al., 2004). More specifically, studies discuss the role of pavements and their darker colour in increasing the UHI intensity (Gago et al., 2013; Santamouris, 2013). Other studies indirectly indicate that pavements are a contributor towards a high UHI city, as they discuss the potential of cool pavements (Akbari & Kolokotsa, 2016; Gago et al., 2013; Mohajerani et al., 2017; Qin, 2015a; Santamouris, 2015). In the UHI intensity model of Oldenzaal, the pavements are taken into account by adding the variable of soil sealing percentage to the model (Remme, 2017).

4.3.1.1.4. Air flow

Studies reveal that windspeeds between buildings can decrease the UHI intensity (Gago et al., 2013; Mohajerani et al., 2017). Both of these studies reveal that higher windspeeds in between building geometry correlates with lower UHI intensities. The UHI model for Oldenzaal takes the windspeed into account at a 10 meter height (Remme, 2017). Wind speeds are linked to different land cover types which have different roughness for length of momentum values.

4.3.1.1.5. Anthropogenic Heat

Another study addresses the impact that inhabitants contribute to the increased UHI intensity in the form of anthropogenic heat (Santamouris, 2015). Although, the model does not necessarily measure the anthropogenic heat directly, the amount of inhabitants around a 10 km range surrounding a 10 by 10 meter cell are taken into account when determining the UHI intensity (Remme, 2017).

4.3.1.1.6. Local Climate Conditions

Climate conditions, such as temperature, wind and humidity also influence the UHI intensity (Kim et al., 2018). The temperature measured in the UHI intensity model covers the annual average UHI and takes into account both day and night temperatures (Remme, 2017). Wind is already discussed and covered by the model. However, what the model forgets to take into account is the humidity, which is worthy of being a point of discussion.

4.3.1.2. Model Outcomes

Based on the UHI map of Oldenzaal, which covers all but one factor (humidity), the UHI intensity for road network in Oldenzaal in general and per asphalt street will be given. Using the model, a visualisation of the UHI per road is made (Figure 9). The centre-located asphalt roads show an increased UHI intensity and are more suitable for the implementation of asphalt roads.

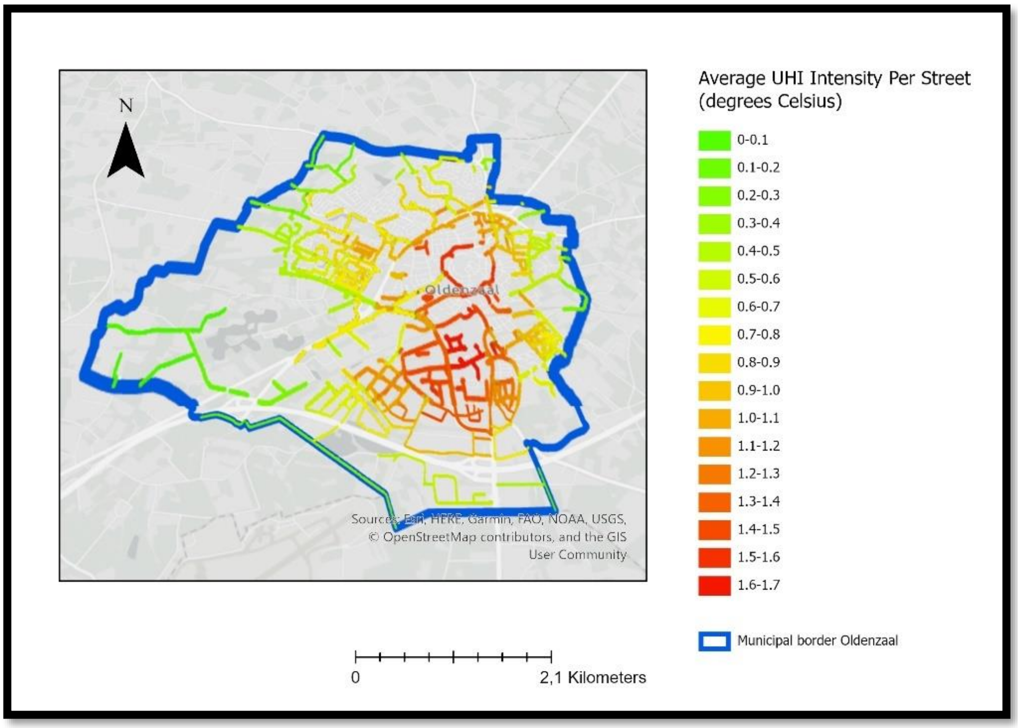

Figure 9 – UHI Intensity visualisation per road expressed in °C.

In order to give a more detailed view of the impact asphalt roads can have on decreasing the UHI intensities, the distribution depicted in Figure 10 is made. The distribution shows that a significant amount of road area is covered by higher UHI intensity categories, which does indicate a potential mitigation of UHI intensity if LRA is to be implemented on a large scale.

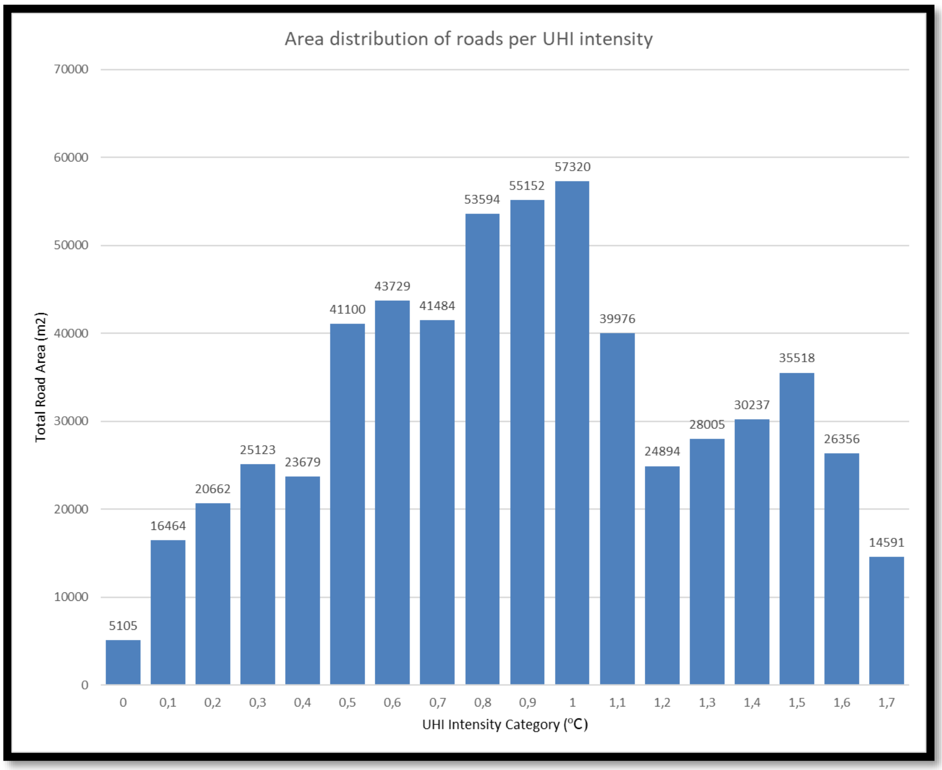

Figure 10 - Distribution of the total road area in m² (y-axis) per UHI intensity category in °C (x-axis).

When comparing the UHI intensity reducing potential within Oldenzaal, it was found that the roads given in Table 22 form the top 5 locations for relative UHI mitigation potential. Note that the scores are determined by comparing the roads with each other. These scores do not necessarily suggest that there is a potential for UHI mitigation when implementing LRA for a high score road. It does suggest that the UHI mitigating potential is higher for a high score road than for a low score road.

Table 22 - Top 5 roads based on relative UHI mitigation potential.

Road	Score (1-10)
Eekboerplein	10
Textielstraat	9.97
Katoenstraat	9.71
P.J. Geldermanstraat	9.60
Eekboerstraat	9.59

4.3.2. Public Lighting Reduction

As literature suggests, the LRA innovation can reduce the energy demand for public lighting (Naus et al., 2016; Santamouris, 2013; Ter Huerne et al., 2014). Interviewees 1, 2 and 3 claim that other LRA cases were initiated because municipalities had an eye on possible energy reduction of the road illumination system. Consequently, the potential for energy reduction is the largest where the energy usage by public lighting is the largest. This depends on the local characteristics of the public lighting distribution and usage in Oldenzaal.

Using geospatial data retrieved from the municipality of Oldenzaal, parameters of the public lighting systems, such as power output, dim regimes and activation times could be deduced. From these parameters, the duration of lighting poles being active and power usage per lighting pole could be deduced an annual basis. From these, the annual energy demand per lighting pole is determined.

Assuming a single street light affects the visibility of a road if it is located within a proximity of 10 meters from the road, all the lighting systems with the purpose of illuminating the asphalt road network can be determined. Model outcomes show a total annual energy demand of approximately 1402 GJ, i.e. 3.89E5 kWh. Assuming an energy reduction of 40% (*Luminumpave | Dura Vermeer*, 2015; Ter Huerne et al., 2014) and an average energy consumption per household of 2960 kWh in Oldenzaal (*StatLine - Energieverbruik Particuliere Woningen; Woningtype En Regio's*, 2020), the potential energy-savings on public lighting equates to 560 GJ, i.e. 1.46E5 kWh. This is the equivalent of 53 household energy consumptions if a large scale implementation of LRA is to take place for all the 222 asphalt roads in Oldenzaal.

The potential of road illumination energy-savings due to LRA will be determined per road. The score will be based upon the sum of annual energy demand of all the lighting posts connected to a road. Illumination sources within a proximity of 10 meters around a road are considered within this sum of annual energy demand. The larger roads are now bound to score higher than smaller roads, as they contain more lighting sources. In order to fairly compare these different surface areas with each other, the sum of total energy demand is divided by the road surface per road (unit: $MJ/m^2/year$), which allows for fair comparison. The visualization of the road illumination energy comparison per road is illustrated in Figure 11.

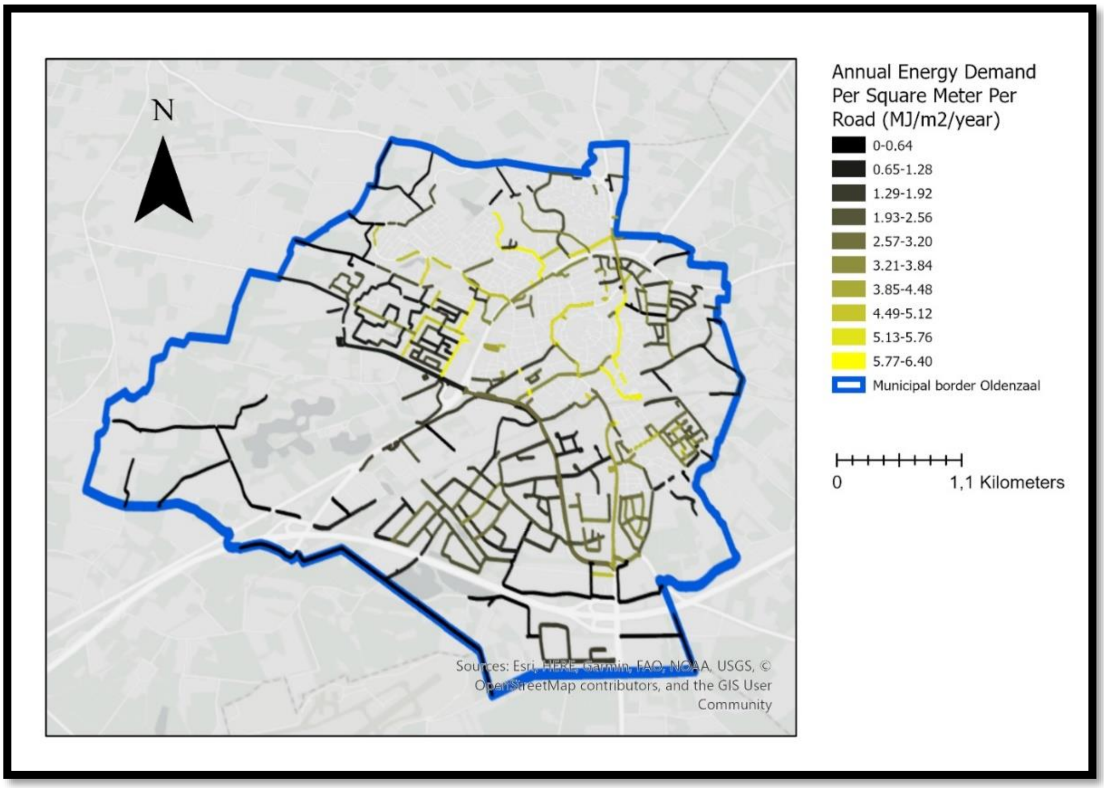

Figure 11 - Visualisation of energy demand per m² per road.

This does lead to outliers when it comes to very small streets, as they are more likely to have relatively more road illumination sources. The outliers are detected using the interquartile range method. The outliers were given the value of the upper bound limit, as these roads cannot be ignored in the analysis. This does lead to twelve roads having a score of 10 instead.

The distribution of road surface area per illumination energy category is given in Figure 12. From this distribution it can be concluded that a larger part of the roads have relatively lower annual energy demands for road illumination purposes.

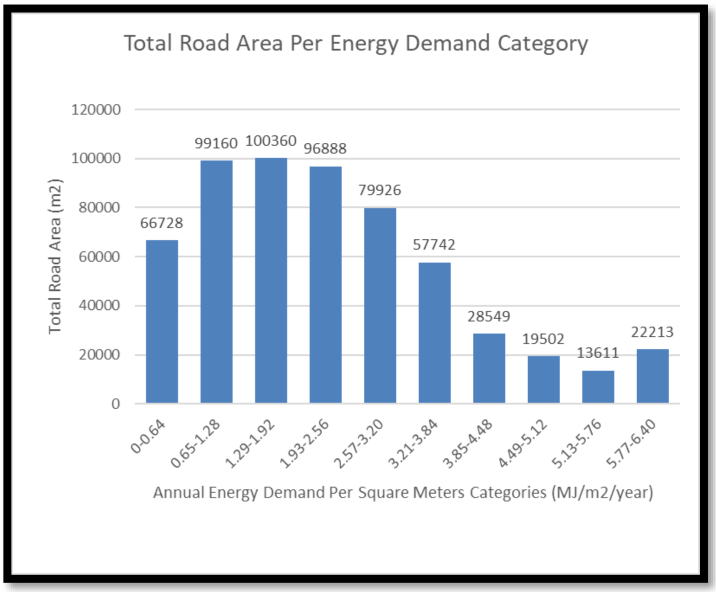

Figure 12 - Distribution of road area in m² (y-axis) per energy demand category in MJ/m²/year (x-axis).

Worth mentioning is that the model does not take into account 3D aspects of public lighting. For instance a tunnel with public lighting running underneath an asphalt road, will make the model also assign the tunnel lighting to the asphalt lighting. This also caused potential outliers in the dataset for larger roads, e.g. Stationsplein.

Furthermore, the model does not specifically show parts of asphalt road that are energy-consuming. It only takes the average for asphalt roads falling under the same road name. If a specific project context is known, the model can be zoomed in on the public lighting layer of Oldenzaal to calculate what the potential energy-savings are for this specific project.

4.3.3. Urban Geometry

Because of the diffusive property of asphalt roads (Naus et al., 2016; Ter Huerne et al., 2014), it is important for the sunlight reflected by LRA, to not be absorbed by adjacent walls of surrounding buildings. It is recommended to only use LRA if the urban canyon aspect ratio is no greater than 1.0 (meaning the height of the canyon divided by the width of the canyon), as it would avoid the additional cooling load and would successfully lower the urban canyon albedo (UCA) as well (Qin, 2015b). Interviewee 3 confirms the preference of implementing LRA in open areas, which corresponds with a low aspect ratio. The same study also analysed the influence of urban canyon orientation on the UCA and additional cooling load of buildings. The conclusion is that no sizeable difference in total albedo values between N-S and E-W oriented canyons was found. Consequently, only the urban canyon aspect ratio is taken into account in the model proposed in this study.

Out of the 222 asphalt roads, 17 roads were proven to have an aspect ratio higher than 1.0 (see Figure 13). For these roads, implementation of LRA is prohibited and thus seen as a constraint. These low amount of prohibited streets are no surprise as the average building height for Oldenzaal is equal to 6.48 meters. The low average building height gives an indication that, the potential LRA locations with regards to urban canyon aspect ratios is favourable in the context of Oldenzaal.

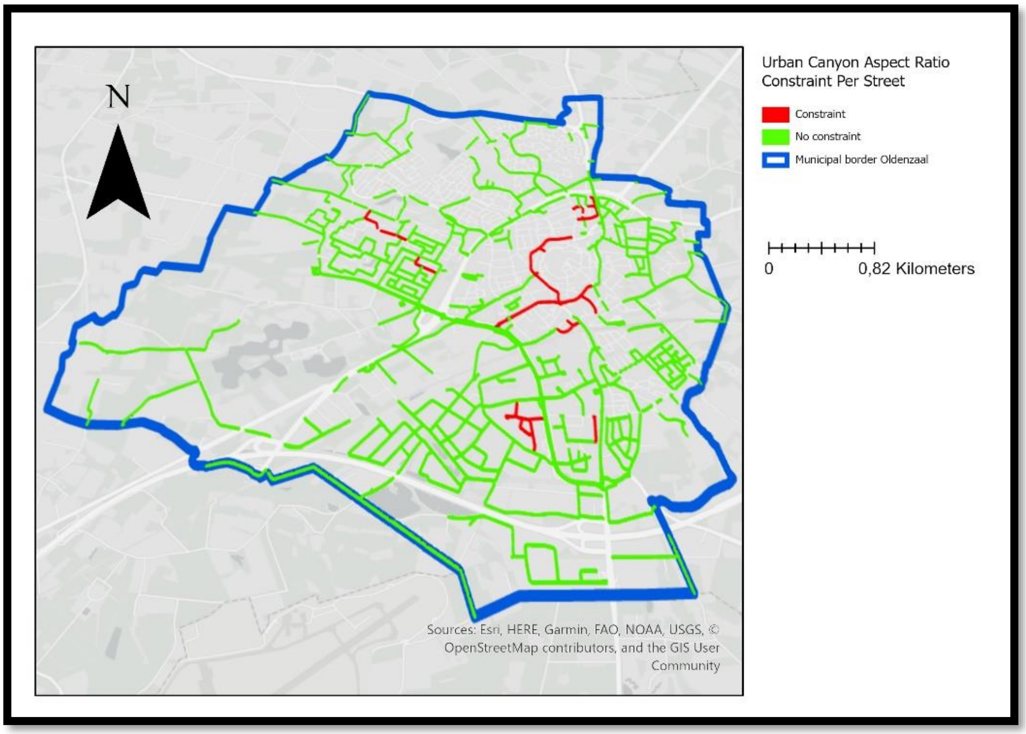

Figure 13 - Urban canyon aspect ratio constraint visualisation per road.

Using a conservative approach with the two parameters, i.e. presence and aspect ratio of the urban canyon, the streets forming a constraint towards LRA implementation were determined. Appendix B.4, gives an elaboration on the data processing for this urban factor. Based on the perimeters of both the streets and the walls facing these streets, the actual presence of the urban canyon is determined. The width of the urban canyon is to be considered two times that of the average distance of buildings within a 15 meter proximity of asphalt roads. Thus, not taking into account the width of the street, which makes it even more conservative. Per street the maximum building height of the buildings is taken within the 15 meter proximity. The reason being that the maximum height fits the conservative approach. The width and height of urban canyon are used to calculate the aspect ratio of the urban canyon per street.

The model described above, only determines the constraint per street with regards to an insufficient aspect ratio. The assumptions described in Appendix B.4, are counteracted by the conservative approach taken in determining the aspect ratios. In order to determine whether or not a smaller part of the asphalt road has a sufficient aspect ratio, a zoomed-in visual inspection is necessary, using the model.

4.3.4. Vulnerable Heat Stress Groups

Although, higher albedo of pavements may lead to lower air temperatures, it may also lead to an increase in thermal stress for pedestrians (Erell et al., 2014). The same study adds to this that it may not even be considered as an objection at a larger scale of implementation, but only if it is implemented on a small scale.

Medical studies identify the vulnerable groups to thermal stress, as mostly elderly people (>65 years) (Benmarhnia et al., 2015). So in order to avoid additional thermal stress near this vulnerable group, LRA implementation will be restricted near building types which will most likely contain this group. The building function, within the building data, that corresponds the most with the elderly people, is that of health care buildings.

Out of the 222 asphalt roads, 15 roads are prohibited from the implementation of LRA (see Figure 14). Similarly to the previous urban factor, a conservative approach is applied for the constraint of vulnerable heat stress groups. 37 healthcare buildings were found using the building data, where a proximity of 20 meters is used to attach a constraint to nearby asphalt roads. Even if the smallest part of an asphalt road is within this 20 meter proximity, the road is considered as a constraint and not suitable for the implementation of LRA. The fact that such a small part of the roads is only prohibited, while using a conservative approach, only indicates that the restricting potential of vulnerable heat stress groups is low in the case of Oldenzaal.

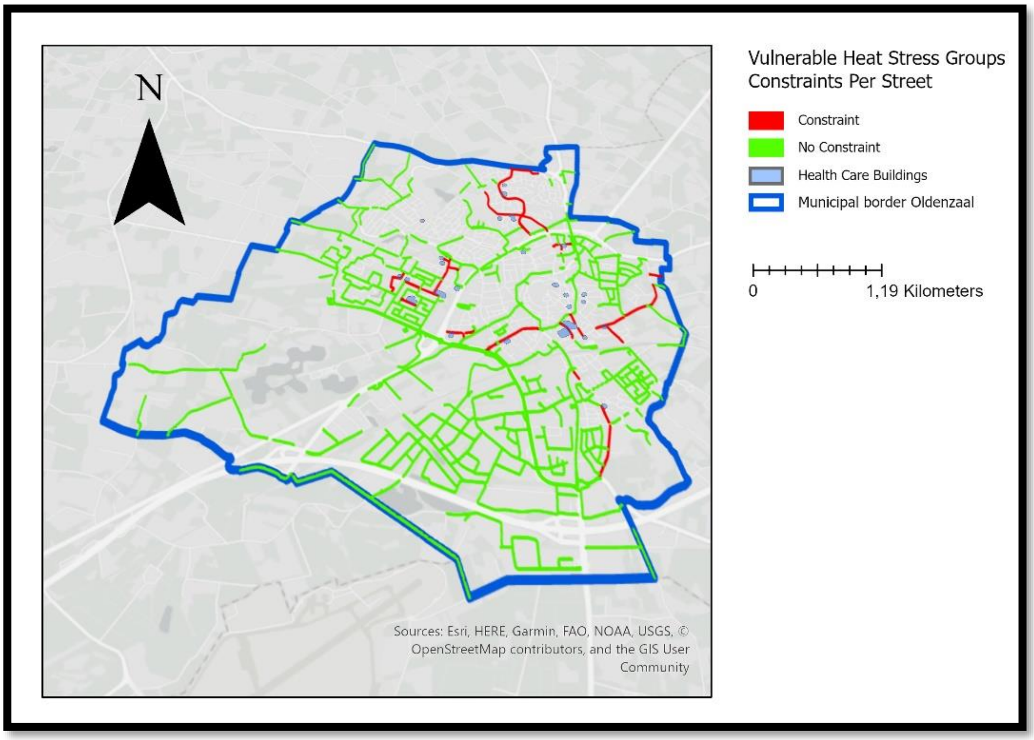

Figure 14 – Vulnerable heat stress group constraints visualization per road.

4.3.5. Traffic Intensity

Traffic intensity can influence the implementation potential of LRA for two reasons. The first reason is that failure mechanisms, such as rutting or shoving, show a correlation with the amount of traffic driving over the asphalt. The higher the traffic intensity the earlier the asphalt shows symptoms of these failure mechanisms (Pomerantz et al., 2000).

The second reason is that with the use of LRA, a safer driving environment will be created (Naus et al., 2016; Ter Huerne et al., 2014). The same opinion is shared by interviewee 3. Another study shows that the night-to-day crash ratio is about 13% (Bullough et al., 2013). Which gives a slight indication that more accidents happen in the dark when there is less illumination and visibility than during the day with better illumination and visibility. So better visibility due to LRA should be especially implemented for roads with higher traffic intensity.

Geo-spatial data concerning traffic intensities is not considered in this report, as it was not available at the time of research. Consequently, future studies should update the model accordingly, such that traffic heavy roads are visualized and considered in Oldenzaal.

4.3.6. Construction Year

The construction year of the top asphalt layer is an indicator for the current state of the layer. Studies argue that resurfacing for some cases may be more beneficial than reconstructing all the asphalt layers (Qin, 2015a; Santamouris, 2013). For instance, if the top layer of the road is 2 years old, it will be a waste of resources to reconstruct the entire road. Hence, the older the top layer is, the more potential it has for the implementation of LRA.

However, the data containing the construction year per asphalt road are both incomplete and are not necessarily recorded for the top layer. Because of both these inaccuracies, the model does not take into account the construction year of the asphalt surface layers. If this data does become available and complete in the future, the model should be updated accordingly.

4.3.7. Final Model Scores

Based on the scores or constraints per urban factor given earlier, the final scores can be determined per street (Figure 15). The final scores are based on the average score of the UHI intensity and energy demand urban factors. If a street is prohibited due to a constraint, a score of 0 is assigned to the road. The two constraints are preventing 29 asphalt roads of the implementation of LRA. Three roads have both these constraints, i.e. Berkstraat, Kruisstraat and Watertorenstraat. It is advisable that LRA should not be implemented for these 29 roads.

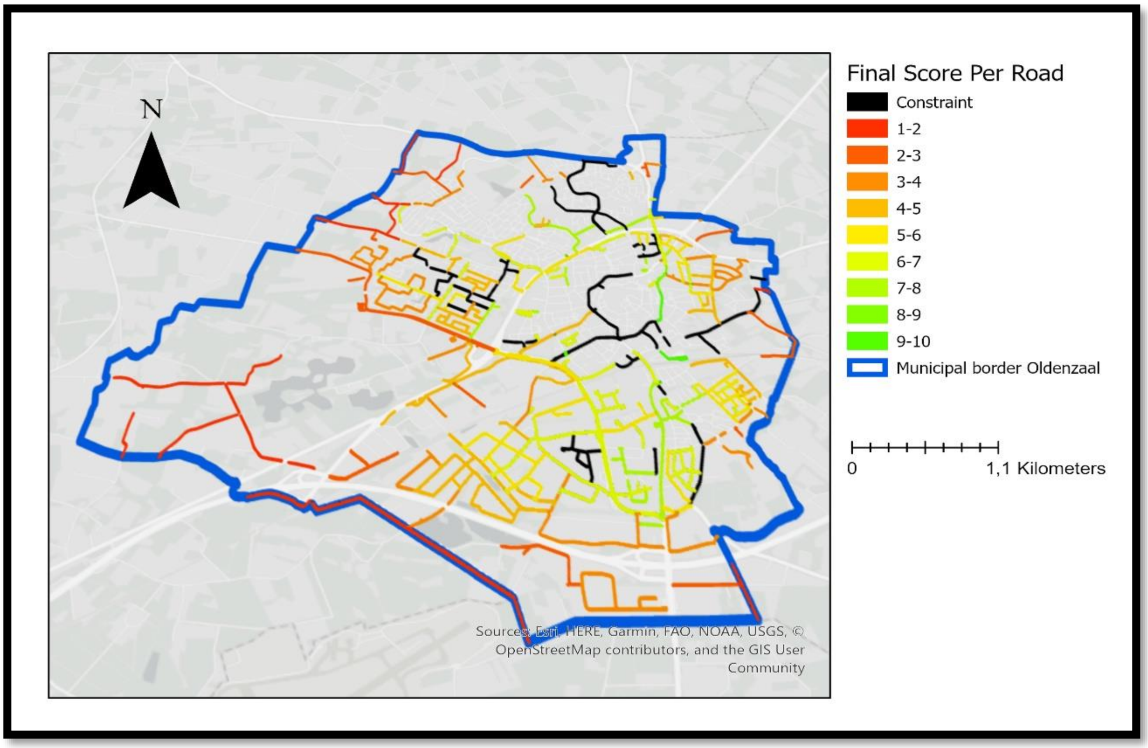

Figure 15 - Visualization of the final scores for LRA implementation (1-10) per road, combining all four urban factors.

The distribution of road surface area per final score is shown in Figure 16. From the distribution it becomes clear that a lot of road surface scores below a score of 8. Approximately 80,000 m^2 of road surface is prohibited from applying a LRA surface layer, due to the constraints of heat stress and urban canyon aspect ratio. The top 5 roads with the highest final scores are given in Table 23.

Table 23 – Top 5 roads based on the final scores of the four urban factors combined.

Road	Final Score (1-10)
Prossinkhof	9.47
Bisschop Balderikstraat	9.47
Stationsplein	9.18
Titus Brandsmastraat	9.05
Bleekstraat	9.03

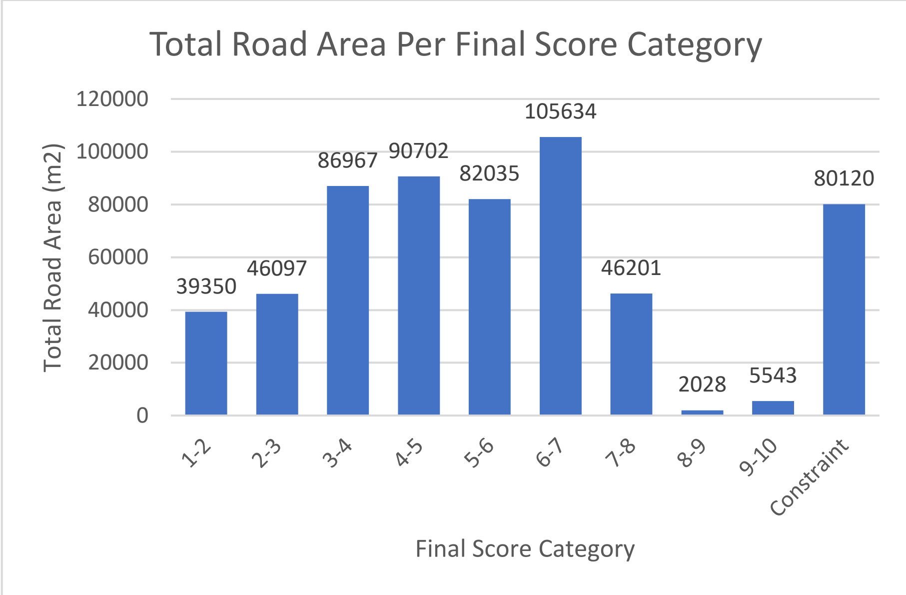

Figure 16 – Distribution of road surface in m² (y-axis) per final score category (x-axis).

4.3.8. Model Validation

As no external data is available to compare model outcomes with, another way of validating the model is needed. The model output is a relative scoring system per road. The output is dependent of the input layers used in the geo-spatial software. These consist of road, UHI, public lighting and building data. The idea is to do a reality check on these input layers. The reality check will be based on similarities between model input and reality. Because no specific values can be deduced from this reality check, the presence of input parameters will be used for the validation process. The validation will be based on one road per final score category, i.e. high, middle, low and constraint. The chosen roads will be based on their the road category and to ease the process of validation, and if possible, smaller road areas will be chosen. After the road selection is made, the site has been checked on the following aspects:

- Asphalt area shape, i.e. does the shape of the asphalt road correspond with that of the model?
- Actual asphalt surface, i.e. is the surface actually made of asphalt, like the model suggests?
- Public lighting presence, i.e. are no lighting sources missing, misplaced or not present in reality compared to the model?
- Building presence, i.e. are the building actually present like the model suggests? In case of the constraint, the presence of a deep canyon, i.e. aspect ratio larger than 1.0, and the presence of healthcare buildings is also checked for.

Note that the UHI is difficult to check in reality, without setting up an observational study. Consequently, this input layer is left out in the validation process due to the time limitation of 10 weeks. The summary of the visual validation, for the input parameters discussed above, is shown in Table 24. The differences are visually shown in Figures 17-24, which show both the model inputs and the real-life situations.

Table 24 - Model validation of input parameters per score category.

Road category	Road used for validation	Road surface area (m^2)	Asphalt area shape	Actual asphalt surface	Public lighting presence (amount of correct objects in model/reality)	Building presence
High final score (7-10)	Bisschop Balderikstraat (9.47)	146	Accurate	Accurate	One source missing (3/4)	One building missing
Middle final score (4-6)	Tijweg (4.42)	602	Accurate	Accurate	Accurate (5/5)	Accurate
Low final score (1-3)	Grensweg (2.41)	671	Accurate	Accurate	Accurate (1/1)	Accurate
Constraint (0)	Watertorenstraat (0)	1360	Accurate	Accurate	One object missing and one object not present in reality (12/14)	Accurate

The Bisschop Balderikstraat is located in a newly built area, which might be the cause for the slight inaccuracy in public lighting and building presence (see Figure 17). The real-life situation of this road is depicted in Figure 18.

Figure 17 – Visual validation differences between model inputs and reality for the Bisschop Balderikstraat.

Figure 18 - Real-life situation of the Bisschop Balderikstraat. Picture taken from point of view 1 in Figure 17.

The Tijweg and Grensweg have been unchanged for a long time and result in accurate input parameters. The input parameters for both these roads are visualised in Figure 19 and 21 respectively. The real-life situations for both these roads are depicted in Figure 20 and 22 respectively.

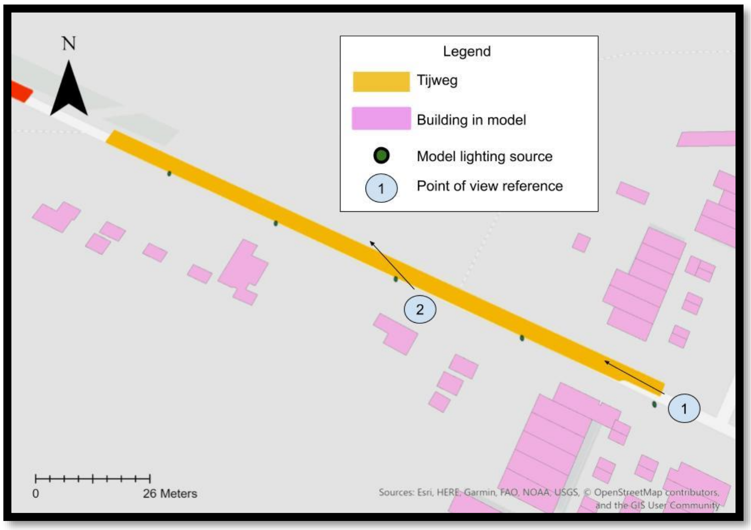

Figure 19 – Accurate model inputs of the Tijweg (no difference with reality).

Figure 20 – Real-life situation of the Tijweg. The picture on the left and right are taken from point of view 1 and 2 in Figure 19 respectively.

Figure 21 – Accurate model inputs of the Grensweg (no difference with reality).

Figure 22 – Real-life situation of the Grensweg. Picture taken from point of view 1 in Figure 21.

The public lighting sources at the Watertorenstraat have a modern design, which indicates that they are newly placed, which might be the cause for the not-fully updated model (see Figure 23). The real-life situation for this road is given in Figure 24.

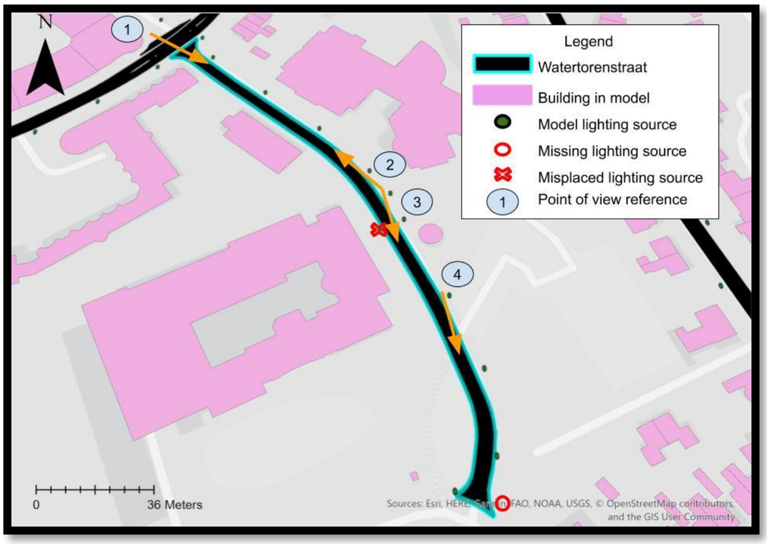

Figure 23 – Visual validation differences between model inputs and reality for the Watertorenstraat.

Figure 24 – Real-life situation of the Watertorenstraat. The picture on the top left, top right, bottom left and bottom right are taken from point of view 1, 2, 3 and 4 in Figure 23 respectively.

The general trend between these four roads is that newly built areas and new public lighting allocation in reality are linked to a slight inaccuracy in model parameters. This should form a critical discussing point when using the model to assign LRA locations to newly built areas. Road shape and actual asphalt layers are accurately described in the model based on the example roads used in the validation process.

4.3.9. General Model Limitations

The model created does give an indication whether or not Oldenzaal in general has potential to profit from benefits of a large scale LRA implementation. However, conclusions regarding the potential of LRA implementation per road, can only be given using a comparison between the different asphalt roads. Consequently, a final score of 10 only gives a rough indication that it is more LRA-suitable than a road with a final score of 6. Moreover, a high score does not necessarily equate to the asphalt road, benefiting from the LRA advantages if being implemented.

The model operates and gives indications and comparisons on the scale level of municipality up to entire roads. If a small part of a road, is to be analysed for potential LRA implementation, a separate visual and zoomed-in inspection is needed for each of the urban factors mentioned above. This could be useful when a project area is assigned to TWW by the municipality and the question arises of what the implementation potential of LRA is for this particular project context.

Furthermore, only four out of the six urban factors found in literature and expert interviews were used, as data limitations surrounding traffic intensity and construction years are present. For the remaining four applied urban factors, assumptions were needed in order for the model to perform the necessary calculations. The assumptions per urban factor are explained throughout Appendix B.

5. Conclusion

The implementation potential of LRA in Oldenzaal can be split up into two parts. One part consists of the sustainable supply chain management potential and the other part of the urban potential.

The potential from a SSCM perspective is that the LRA alternatives are overshadowed by the conventional aggregate, i.e. Bestone (BS). The pillar contributing the most to this dominance, is that of the economic pillar. This does not necessarily mean that LRA is not feasible at all, as the aggregate composition can consist of a mix of conventional and LRA aggregates.

When comparing the three LRA alternatives, the MCA score suggests that Labradoriet (LD) and Reflexing White (RW) are more feasible than Luxovit (LV) from a sustainable supply chain management perspective. Again, the biggest difference in score originates from the difference in economic scores between the LRA alternatives.

More specific pros and cons can also be deduced from the MCA. LD is the most economically viable LRA alternative, but in terms of re-usable capacity and applicability in top layers, it scores particularly low. LV has the highest albedo, whiteness and diffusiveness, which makes it the best alternative for public lighting energy-savings, road visibility during the dark and environmentally boosting performance. However, LV is also considered to have the same weaknesses as LD. RW is considered the most all-round aggregate, as it comes closest to achieving the requirements of aggregate type 3, i.e. aggregates used for surface layers, while also scoring sufficient on most criteria. Based on the interests of both the municipality and TWW, an aggregate mixture or choice between aggregates can be made using these pros and cons.

From an urban perspective, the implementation potential has to be divided into the four urban characteristics discussed in this report. From an UHI mitigating potential, a large proportion of roads is covered by high UHI intensity areas. Thus, meaning that LRA roads can have potential in tackling the problem of UHI.

The possible road illumination reduction is equal to that of approximately 53 average household energy consumptions on an annual basis, if LRA is applied for all 222 asphalt roads in Oldenzaal. Hence, from an energy-saving perspective there is quite the implementation potential in Oldenzaal.

The urban geometry of Oldenzaal is taken into account by the model, by calculating the aspect ratio and the actual urban canyon presence per road. The urban geometry in Oldenzaal is considered as favourable. The model shows that only 17 out of 222 asphalt roads are prohibited for the implementation of LRA. This result is based on a conservative calculation method for the aspect ratio of urban canyons. Thus, in reality, this number of constrained roads might even be lower than suggested by the model. The high potential can be explained by taking into account the low average building height in Oldenzaal, i.e. 6.48 meters.

As LRA might induce additional thermal stress on people nearby roads, the vulnerable heat stress groups, i.e. elderly inhabitants, are to a certain extent taken into account by the model. Roads close to healthcare buildings (37 buildings in total) are prohibited from LRA implementation. These 37 buildings constraint 15 out of 222 asphalt roads in Oldenzaal, using a conservative calculation method.

Combining these urban factors, a relative potential per road is given only indicating which road is more suitable than other roads. This report gives the top 5 roads per urban factor and the combination of these factors. The latter top 5, from high to low, consists of the following roads: Prossinkhof, Bisschop Balderikstraat, Stationsplein, Titus Brandsmastraat and Bleekstraat. Overall, the model does indicate LRA implementation potential from an urban perspective.

Besides the many advantages of LRA, suggested by literature, there are also disadvantages linked to the implementation of LRA (Yang et al., 2015). All the pros and cons have been taken into account by both the MCA and urban model. Most of the pros and cons suggested by literature should be taken into account according to the experts. Thus, confirming literature on this regard. Furthermore, the need for localized research when implementing LRA (Gago et al., 2013; Mohajerani et al., 2017; Qin, 2015a; Santamouris, 2013, 2015; Yang et al., 2015) has been confirmed, as not all disadvantages have proven to play a role for the case of Oldenzaal. For instance, the urban geometry aspect ratio, is rather favourable for Oldenzaal, as there are no tall skylines. For a capital city, such as Amsterdam, the aspect ratios might be significantly higher than for Oldenzaal and thus prohibiting more roads from LRA implementation. All in all, the literature discussed in this research, has been largely confirmed by the experts and models.

6. Discussion

The results of the MCA give the indication that the conventional aggregate, i.e. Bestone, is a much more viable option than the other LRA alternatives. Despite this, the MCA does not necessarily suggests that a combination of these conventional and LRA aggregates is prohibited. On the contrary, a mixture of aggregates in order to take advantage of the positive property of each of the alternatives may result in a more all-round LRA mixture. Consequently, future studies should focus on finding an optimal LRA mixture to reduce the gap in viability between conventional and LRA aggregates, while benefiting from LRA advantages.

Moreover, the MCA is partly based on the opinion of experts. Meaning that biased scores for the different alternatives could play a considerable role in influencing the final MCA scores and thus, causing inaccuracy. The inaccuracy caused by biased experts may have been mitigated, as the interviewees were asked which quantifications of aggregate characteristics would indicate the non-biased score. Only after these characteristics became known, the interviewees were asked to give their scores. This way bias could be identified if quantification (by either literature or other experts) has been performed, as expert scores and literature quantification could be compared. Although, bias has been removed by comparing experts knowledge with literature and other experts, criteria scores should still be interpreted with caution. This comparison between experts with literature and other experts also helps to justify and compensate for the small sample size of expert interviews.

Despite the small sample size of survey respondents, i.e. four, it still is proportional to the population of nine municipal employees. Reminders were sent to all the participants by the contact person within the municipality, but it was still not possible to get a reaction from the remaining five participants. Due to the COVID-pandemic, the survey participants were more difficult to reach for both me and the municipal contact person. Until the measurements against the COVID-situation became milder, the survey participants were approached face-to-face and a response was retrieved. To determine the weights of the main criteria literature was used instead of survey respondents. This allows for a large part of the weights within the MCA to be non-biased. The rest of the criteria weights, were determined by using the survey results.

Although the model for predicting urban implementation potential indicates a high potential, it does not take into account the traffic intensity and construction year of asphalt surface layers. Hence, the model results should be used with caution. Before relying on the results of the model, a visual inspection for both of the remaining urban factors should be analysed. This could lead to a shift in implementation potential of LRA in Oldenzaal. If geo-spatial data regarding these two urban factors becomes available, the model should be updated accordingly.

Furthermore, the model can only be used to give an absolute recommendation on the LRA implementation potential in Oldenzaal, disregarding cycling and pedestrian paths. Relative scores per road are assigned for each of the four urban factors. Combining these factors resulted in a final score per road, indicating relative LRA implementation potential. This does not necessarily imply that a high score results in a LRA road that actually makes use of the different benefits of an LRA surface layer. It simply tells us that a road with a score of 9 will more likely be more suitable for LRA implementation than a road with a score of 7. Also, only the input of the model is partly validated, as this is the only observable part of the model. By observing the input in reality, the comparison between model and reality could be made. The results of the visual validation show that newly built areas tend to have more inaccuracies for the input parameters, as the geo-spatial data is not fully updated for these areas yet. Observational studies should be conducted in the future if the municipality decides to implement LRA roads. By measuring different parameters before and after the implementation of LRA, the model in this study could be fully validated.

The MCA and urban model in this report do not suggest that LRA implementation would necessarily be a successful innovation if applied. It merely informs the contractor, i.e. TWW, about the LRA benefits and disadvantages of the different alternatives proposed in the MCA. For instance, LV has the whitest colour and is the most diffusive LRA aggregate in the MCA, which suggest it has the highest potential for public lighting energy-savings, road visibility in the dark and environmentally boosting performance. Furthermore, LD is the most economically viable LRA alternative. The last LRA alternative (RW), comes the closest to being considered as a type 3 aggregate and therefore, scores better on re-usability capacity and actual applicability in top layers. Finally, RW can be seen as the all-round LRA alternative, while LD and LV have certain extreme disadvantages, i.e. the re-usability capacity and actual applicability in top layers.

For the client, i.e. the municipality, it merely suggest the most suitable LRA locations in Oldenzaal and gives information surrounding the general potential of LRA in Oldenzaal. If the municipality has a specific, project area in mind for LRA, e.g. part of a road, the model may not be sufficient enough in determining the LRA feasibility, as the model only goes as far as the detail of an entire road. If an LRA project is assigned to TWW, the MCA could indicate which LRA alternative is most useful in the context of the project as well.

References

Ahi, P., & Searcy, C. (2013). A comparative literature analysis of definitions of green and sustainable supply chain management. *Journal of Cleaner Production*, *52*, 329–341. https://doi.org/10.1016/j.jclepro.2013.02.018

Akbari, H., & Kolokotsa, D. (2016). Three decades of urban heat islands and mitigation technologies research. *Energy and Buildings*, *133*, 834–842. https://doi.org/10.1016/j.enbuild.2016.09.067

Benmarhnia, T., Deguen, séverine, Kaufman, J., & Smargiassi, A. (2015). Vulnerability to Heat-related Mortality: A Systematic Review, Meta-analysis, and Meta-regression Analysis. *Epidemiology (Cambridge, Mass.)*, *26*. https://doi.org/10.1097/EDE.0000000000000375

Bullough, J. D., Donnell, E. T., & Rea, M. S. (2013). To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. *Accident Analysis & Prevention*, *53*, 65–77. https://doi.org/10.1016/j.aap.2012.12.029

Cornescu, V., & Adam, R. (2013). The Consumer Resistance Behavior towards Innovation. *Procedia Economics and Finance*, *6*, 457–465. https://doi.org/10.1016/S2212-5671(13)00163-9

CROW. (2015). Hoofdstuk 81 Bitumineuze verhardingen. In *Standaard RAW Bepalingen 2015*.

Debbage, N., & Shepherd, J. M. (2015). The urban heat island effect and city contiguity. *Computers, Environment and Urban Systems*, *54*, 181–194. https://doi.org/10.1016/j.compenvurbsys.2015.08.002

Dekkers, R. J., Dijkink, J. H., & Tollenaar, C. C. (2012). *Monitoring dunne geluidreducerende asfalt deklagen*. 10.

Doulos, L., Santamouris, M., & Livada, I. (2004). Passive cooling of outdoor urban spaces. The role of materials. *Solar Energy*, *77*(2), 231–249. WorldCat.org. https://doi.org/10.1016/j.solener.2004.04.005

Dyllick, T., & Hockerts, K. (2002). Beyond the Business Case for Corporate Sustainability. *University of St.Gallen*, *11*. https://doi.org/10.1002/bse.323

Erell, E., Pearlmutter, D., Boneh, D., & Kutiel, P. B. (2014). Effect of high-albedo materials on pedestrian heat stress in urban street canyons. *ICUC8: The 8th International Conference on Urban Climate and the 10th Symposium on the Urban Environment*, *10*, 367–386. https://doi.org/10.1016/j.uclim.2013.10.005

Fuladlu, K., Riza, M., & Ilkan, M. (2018, May 22). *THE EFFECT OF RAPID URBANIZATION ON THE PHYSICAL MODIFICATION OF URBAN AREA*.

Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749–758. WorldCat.org. https://doi.org/10.1016/j.rser.2013.05.057

Gesteinskörnungen nach TL Gestein-StB (EN 13043). (2010). Dr. Moll.

Howard, L. (1818). *The Climate of London: Deduced from Meteorological Observations, Made at Different Places in the Neighbourhood of the Metropolis* (Issue v. 1). W. Phillips, sold also by J. and A. Arch. https://books.google.nl/books?id=7skTAAAAYAAJ

Hu, J., & Yu, B. (2013). Experimental Study of Sustainable Asphalt Binder: Influence of Thermochromic Materials. *Transportation Research Record: Journal of the Transportation Research Board*, *2372*, 108–115. https://doi.org/10.3141/2372-12

Ichinose, T., Matsumoto, F., & Kataoka, K. (2008). Chapter 15—Counteracting Urban Heat Islands in Japan. In P. Droege (Ed.), *Urban Energy Transition* (pp. 365–380). Elsevier. https://doi.org/10.1016/B978-0-08-045341-5.00015-3

Jacobs, M. M. J., Frunt, M. H. T., & Rering, A. (2016). *PA-stone: Op weg naar asfalt met 100% recycling*. 9.

Kim, H., Gu, D., & Kim, H. Y. (2018). Effects of Urban Heat Island mitigation in various climate zones in the United States. *Sustainable Cities and Society*, *41*, 841–852. https://doi.org/10.1016/j.scs.2018.06.021

Kinouchi, T., Yoshinaka, T., Fukae, N., & Kanda, M. (2004). 4.7 DEVELOPMENT OF COOL PAVEMENT WITH DARK COLORED HIGH ALBEDO COATING. *5th Conference for the Urban Environment*, *50*.

Kiwa Nederland. (2009). *Nationale Beoordelingsrichtlijn voor het KOMO productcertificaat voor Wegmarkeringsmaterialen*.

KNMI: Tijden van zonopkomst en -ondergang 2020. (2019, September 24). https://cdn.knmi.nl/system/ckeditor_assets/attachments/102/tijden_van_zonopkomst_en_-ondergang_2020.pdf

Luminumpave | Dura Vermeer. (2015, June 25). https://www.duravermeer.nl/product/luminumpave

Merska, O., Mieczkowski, P., & Żymełka, D. (2016). Low-noise Thin Surface Course – Evaluation of the Effectiveness of Noise Reduction. *Transport Research Arena TRA2016*, *14*, 2688–2697. https://doi.org/10.1016/j.trpro.2016.05.445

Mohajerani, A., Bakaric, J., & Jeffrey-Bailey, T. (2017). The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*, *197*, 522–538. WorldCat.org.

Naus, R., Zijlstra, P., Hetebrij, D., & Dijkema, R. (2016). *Helderheid in wegdekreflectie*. 10.

NEN-EN 13108-1. (2016). *Bituminous mixtures—Material specifications—Part 1: Asphalt Concrete*. European Committee for Standardization.

NEN-EN 13108-5. (2016). *Bituminous Mixtures—Material specifications—Part 5: Stone Mastic Asphalt*. European Committee for Standardization.

NEN-EN 13108-8. (2005). *Bituminous mixtures—Material Specifications—Part 8: Reclaimed Asphalt*. European Committee for Standardization.

Nr. GB 2-5. (2015). Silmer.

Nr. GB 5-8. (2015). Silmer.

Pomerantz, M., Akbari, H., Chang, S.-C., Levinson, R., & Pon, B. (2003). *Examples of cooler reflective streets for urban heat-island mitigation: Portland cement concrete and chip seals* (LBNL--49283, 816205; p. LBNL--49283, 816205). https://doi.org/10.2172/816205

Pomerantz, M, & Pon, B. (2000). *The Effect of Pavements' Temperatures on Air Temperatures in Large Cities*. 24.

Pomerantz, Melvin, Akbari, H., & Harvey, J. T. (2000). *Cooler Reflective Pavements Give Benefits Beyond Energy Savings: Durability and Illumination*. 12.

Prestatieverklaring Nr: RW2—Versie 4.0. (2019). Gudvangen Stein AS.

Qin, Y. (2015a). A review on the development of cool pavements to mitigate urban heat island effect. *Renewable and Sustainable Energy Reviews*, *52*, 445–459. WorldCat.org. https://doi.org/10.1016/j.rser.2015.07.177

Qin, Y. (2015b). Urban canyon albedo and its implication on the use of reflective cool pavements. *Energy & Buildings*, *96*, 86–94. WorldCat.org. https://doi.org/10.1016/j.enbuild.2015.03.005

Remme, R. (2017). *Cooling by vegetation and water in urban areas*. RIVM. https://acceptatie.atlasleefomgeving.nl/sites/default/files/2019-04/Technical%20Documentation%20Cooling%20in%20urban%20areas%281%29.pdf

Rijksoverheid stimuleert duurzame energie | Duurzame energie | Rijksoverheid.nl. (n.d.). Retrieved 30 March 2020, from https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/meer-duurzame-energie-in-de-toekomst

Rijkswaterstaat. (n.d.). *DuboCalc* [Webpagina]. Retrieved 22 May 2020, from https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/inkoopbeleid/duurzaam-inkopen/dubocalc/index.aspx

Rossi, F., Pisello, A. L., Nicolini, A., Filipponi, M., & Palombo, M. (2014). Analysis of retro-reflective surfaces for urban heat island mitigation: A new analytical model. *Applied Energy*, *114*, 621–631. https://doi.org/10.1016/j.apenergy.2013.10.038

Saaty, T. (2008). Decision making with the Analytic Hierarchy Process. *Int. J. Services Sciences Int. J. Services Sciences*, *1*, 83–98. https://doi.org/10.1504/IJSSCI.2008.017590

Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. *Renewable & Sustainable Energy Reviews*, *26*, 224–240. WorldCat.org.

Santamouris, M. (2015). Regulating the damaged thermostat of the cities—Status, impacts and mitigation challenges. *Energy & Buildings*, *91*, 43–56. WorldCat.org. https://doi.org/10.1016/j.enbuild.2015.01.027

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., & Assimakopoulos, D. N. (2001). On the impact of urban climate on the energy consumption of buildings. *Urban Environment*, *70*(3), 201–216. https://doi.org/10.1016/S0038-092X(00)00095-5

Sen, S., & Roesler, J. (2016). Aging albedo model for asphalt pavement surfaces. *Journal of Cleaner Production*, *117*, 169–175. https://doi.org/10.1016/j.jclepro.2016.01.019

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Sustainability and Supply Chain Management*, *16*(15), 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020

S.M.A.R.T. Objectives—Wayne LEADS - Wayne State University. (n.d.). Retrieved 22 May 2020, from https://hr.wayne.edu/leads/phase1/smart-objectives

StatLine—Energieverbruik particuliere woningen; woningtype en regio's. (2020, January 14). https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?fromstatweb

Synnefa, A., Karlessi, T., Gaitani, N., Santamouris, M., Assimakopoulos, D. N., & Papakatsikas, C. (2011). Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. *Building and Environment*, *46*(1), 38–44. https://doi.org/10.1016/j.buildenv.2010.06.014

Ter Huerne, H., Hetebrij, D., & Elfring, J. (2014). *Ontwikkeling van licht reflecterende deklagen door KWS:* 12.

the Bruyn, S., Ahdour, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., & Vergeer, R. (2018). *Environmental Prices Handbook 2017: Methods and numbers for valuation of environmental impacts*. CE Delft.

Toeslagmateriaal—Bestone 2/5. (2017). Graniet Import Benelux BV.

Toeslagmateriaal—Bestone 4/8. (2017). Graniet Import Benelux BV.

Toeslagmateriaal—Bestone 8/11. (2017). Graniet Import Benelux BV.

Wan, W., Wong, N. H., Ping, T., Zhi, A., & Aloysius, W. (2009). *A Study on the Effectiveness of Heat Mitigating Pavement Coatings in Singapore*. *7*.

Wei, D., Li, B., Zhang, Z., Han, F., Zhang, X., Zhang, M., Li, L., & Wang, Q. (2018). Influence of Surface Texture Characteristics on the Noise in Grooving Concrete Pavement. *Applied Sciences*, *8*, 2141. https://doi.org/10.3390/app8112141

Xie, N., Li, H., Abdelhady, A., & Harvey, J. (2019). Laboratorial investigation on optical and thermal properties of cool pavement nano-coatings for urban heat island mitigation. *Building and Environment*, *147*, 231–240. https://doi.org/10.1016/j.buildenv.2018.10.017

Xie, N., Li, H., Zhao, W., Zhang, C., Yang, B., Zhang, H., & Zhang, Y. (2019). Optical and durability performance of near-infrared reflective coatings for cool pavement: Laboratorial investigation. *Building and Environment*, *163*, 106334.

https://doi.org/10.1016/j.buildenv.2019.106334

Yang, J., Wang, Z.-H., & Kaloush, K. E. (2015). Environmental impacts of reflective materials: Is high albedo a 'silver bullet' for mitigating urban heat island? *Renewable and Sustainable Energy Reviews*, *47*, 830–843. WorldCat.org. https://doi.org/10.1016/j.rser.2015.03.092

Zheng, M., Han, L., Wang, F., Mi, H., Li, Y., & He, L. (2015). Comparison and analysis on heat reflective coating for asphalt pavement based on cooling effect and anti-skid performance. *Construction and Building Materials*, *93*, 1197–1205. https://doi.org/10.1016/j.conbuildmat.2015.04.043

Appendices

Appendix A: MCA Calculations

Based on the survey data collection, the weights are determined. How this has been done, is explained in Appendix A.1. Furthermore based on these weights and scores given in Section 4.2.1, the final scores per alternative were determined. The score calculation is determined in Appendix A.2.

Appendix A.1: Weight Calculation

The weights per criteria was determined using the AHP method (Saaty, 2008). The method determines the relative importance based on pairwise comparisons. Using a mathematical matrices operations, the weights were determined using the following steps.

1. The answers of the survey respondents were translated to the relative importance scale (Saaty, 2008) using the conversion Table 25.

Table 25 - Conversion values used to get from the survey data to the relative importance.

Answer reference in the survey	**Corresponding relative importance (Saaty, 2008)**
1	0.11
2	0.14
3	0.2
4	0.33
5	1
6	3
7	5
8	7
9	9

2. The pairwise comparison matrix is determined, where each of the criteria are compared with each other.
3. The pairwise comparison matrix is normalized (comparisons between criteria are represented by a score on a scale of 0 to 1.
4. Step 3 allows for the geometric mean to be calculated (mean per row within the normalized matrix). This geometric mean represents the weight of the criterion the row was linked to.
5. Repeat steps 2-5 for each respondent.
6. Take the average of each respondent per criteria. These averages are the final weights used in the MCA.

Appendix A.2: Score Calculation

Now that the scores and weights are known, the final scores need to be determined for the MCA. First the different criteria levels within the MCA need to be understood. Each pillar of sustainability (main criteria level) is broken down into smaller components. These smaller components consist of sub criteria and if separated further, the sub-sub criteria level is created. The hierarchy order for the different types of criteria consists of the following order.

1. Main criteria.
2. Sub criteria.
3. Sub-sub criteria.

The scores of either the second or third level criteria are known, which can be used to calculate the higher hierarchy criteria levels when combined with the weights.

Appendix B: Geo-Spatial Data Processing

In this section, the flowchart illustrating the geo-spatial calculation approach is given (see Figure 25). Furthermore, the information used in the starting maps is elaborated in Table 26. An elaboration on how each of the final road maps are determined is given per urban factor in Appendices B.1 – B.6. These also contain how the scores are determined.

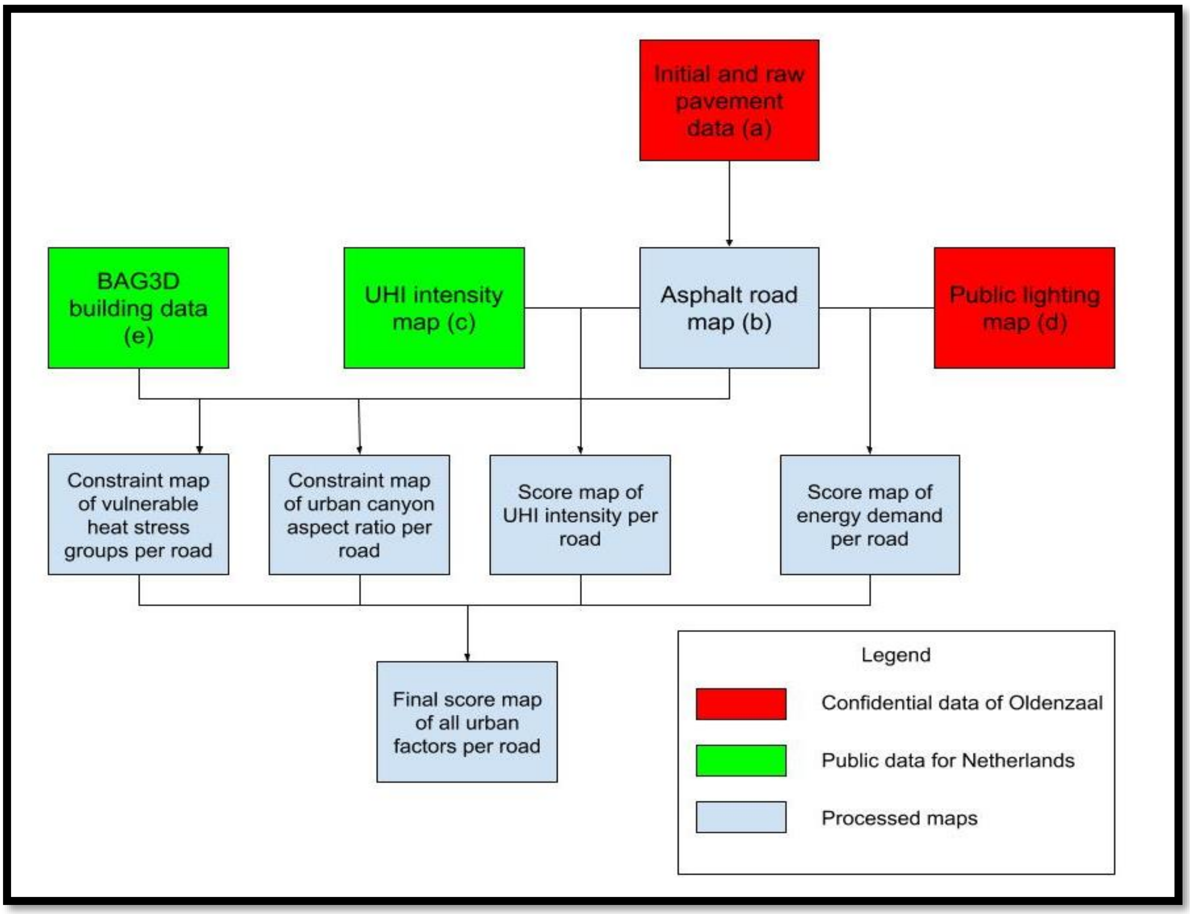

Figure 25 - Flowchart of the starting maps and the process to get to the final score map per road.

Table 26 - Starting maps and their data to be used in the geo-spatial calculations.

Starting map (reference in Figure 25)	Data to be used
Initial road map (a)	• All kinds of pavement types are registered of which the main asphalt roads were used. • Surface material category is known. • Pavements were arbitrarily split up into several polygons, with each having a street name. • Area sizes per polygon are known.
Asphalt road map (b)	• The split up asphalt road polygons are aggregated based on the 222 asphalt street names. • Area sizes per street name are known. • Road perimeters are known.
UHI intensity map (c)	• Annual average air temperature increases relative to rural areas are known per 10 by 10 meter cell. Can be used to indicate UHI intensity.
Public lighting map (d)	• All the recorded public light sources locations. • Type of light source, e.g. road illumination or billboard. • Dim regimes codes. • Maximum power output. • Duration purpose, e.g. night or evening.
BAG3D Building data (e)	• Locations are known. • Building function, e.g. healthcare or educational. • Perimeter values. • Building height (pand hoogte in Dutch).

Appendix B.1: Road Data Processing

In order to get the base asphalt road map (b), the initial raw data (a) has to be filtered and merged together. The steps for doing this are:

1. The raw data consists of pavements with all types of surface layer materials. Only the surface layers classified as asphalt are used in the model.
2. Filter out roads based on the their user function, leaving out the following types of pavements:
    a. Integrated cycling paths next to main roads.
    b. Cycling and pedestrian paths.
    c. Small parking spots fused to the main roads (asphalt parking lots are left untouched and thus, used in the model).
3. The polygons in the data are merged together based on their street name, which can be used to provide recommendations. These merged polygons form the asphalt road map (b) (Figure 25 and Table 26).
4. The merged polygons have an area which is automatically determined by the ArcGIS Pro software. There is no overlap in polygon areas, as each polygon only has one street name. These areas will be used in urban factor data processing.

Appendix B.2: UHI Scores

The UHI scores per road are determined using the following steps:

1. The raw UHI starting map consists of raster data and is applicable for the entire Netherlands. This dataset has been clipped to the context of the municipality of Oldenzaal, because of both the research scope of this project and the lack of computational hardware power.
2. The raster data containing the UHI intensity per 10 by 10 meter cell is translated into a polygon dataset.
3. Now that both the road data and the UHI intensity data are in the form of polygons, they can be combined, to assign UHI intensity values to roads.
4. As step 3 splits the single roads back into several polygons with each polygon having its own area and UHI intensity value, the average UHI intensity per road is calculated by:
    a. Determining the percentage of area per UHI intensity within a single road name category, e.g. Stationsplein.
    b. Multiplying these percentages with their respective UHI intensity, in order to calculate the relative UHI intensity (ΔT_{rel}).
    c. Adding all the ΔT_{rel} within the same road together to determine the average UHI intensity per road (ΔT_{road}).
5. The scores, on a scale from 1 to 10 are determined using the following steps:
    a. The extreme values found in the set of ΔT_{road} values are linked to a scale of 1 to 10. The maximum and minimum values are assigned a score of 10 and 1 respectively.
    b. A linear function in the form of $y = ax + b$ will be used to determine the scores, where:
        i. y is the score from a scale from 1 to 10.
        ii. x is the ΔT_{road} value.
        iii. a is the slope of the function based on the extreme values of both x and y.
        iv. b is the minimum score possible, i.e. 1.
6. Now each street is assigned a score based on their ΔT_{road} value.

Appendix B.3: Public Lighting Energy-Saving Scores

The potential energy reduction for public lighting score is calculated using the following steps:

1. Annual energy demand per lighting source is calculated by:
    a. From the municipality, the different activation and deactivation times were determined. These are based on the sunrise and -set times. Consequently, the average annual sunrise and -set times for 2020 were determined using publicly available data (*KNMI: Tijden van Zonopkomst En -Ondergang 2020*, 2019). The average annual activation times were used to assign the annual activation time in seconds per the different categories of duration purpose, i.e. t_{annual}.
    b. Assigning a factor to the different dim regimes f_{dim}, that a lighting source can have. This factor indicates the percentage of the maximum power output in step 1c actually used per dim regime.
    c. With the known maximum power per lighting source, i.e. P_{max}, the annual energy demand per lighting source E_{annual} (in GJ) can be determined using Eq. 2.

$$E_{annual} = P_{max} \times f_{dim} \times t_{annual} \qquad \text{Eq. 2}$$

2. Lighting sources are filtered out if they are either a ground light source or billboard.
3. Lighting sources are assumed to have a 10 meter proximity. These illumination sources within this 10 meter proximity of an asphalt road will be assigned to the road. Using the following steps, the total energy demand per area unit will be determined per road:
    a. The sum of annual energy demand of all the lighting sources per road is determined.

   b. This sum is dived by the area of the road it is linked to, to get the energy demand per road, i.e. $E_{annual,road}$.
4. The energy scores are determined using the same calculation method as described in step 5 in Appendix B.2, i.e. with the use of a linear function. The only difference is that the 1.5 interquartile range method is applied to detect any outliers. The upper bound limit functions as the extreme value, whilst the lower bound limit is below zero and has no outliers.
5. Now each road is assigned a score based on their $E_{annual,road}$ value.

The assumption is used that illumination sources 10 meters away from asphalt road are considered as road illumination with the exception of sources mentioned in step 2.

Appendix B.4: Urban Canyon Aspect Ratio Scores

The urban canyon aspect ratios constraint scores are determined using the following steps.

1. Buildings within a 15 meter proximity range, were only taken into account when determining the aspect ratio. Because the average building height in Oldenzaal is 6.48 meters, it is not likely that a building at a distance greater than 15 meters is likely going to cause an urban aspect ratio higher than 1.0, as the height will most likely not be higher than 15 meters.
2. The selected buildings were each assigned to a specific road.
3. Per road, the tallest building represented the height of the urban canyon (h) and the average distance from each building to the road was considered as the half width (w_{half}) of the canyon.
4. Eq. 3 indicates the urban canyon aspect ratio (UC_{AR}).

$$UC_{AR} = h/2w_{half} \quad \text{Eq. 3}$$

5. As it is now, Eq. 3 does not take into account the width of the street, because the additional radiation to adjacent building walls, is seen as the limiting factor. The radiation will not start at the middle of the road. Instead it will begin at the nearest point of the asphalt road to the wall, i.e. at w_{half} distance from the building wall. By leaving out the road width in the UC_{AR} calculation, a conservative value representing the AR will be assigned to each road, whilst also taking into account the additional energy load for buildings into the constraint determination.
6. Although, steps 1-5 do determine the AR, it can still occur that no UC is actually present. It might very well be the case that one building with a height of 10 meters is located at a distance of 5 meters from the road, thus resulting in a UC_{AR} of 2.0 according to Eq. 3. To prevent this from happening, the actual UC (UC_{actual}) is calculated using the following steps:
   a. Buildings are considered as squares in the model. Their perimeter is divided by 4, and all the buildings connected to the same road are added together. This value is denoted as UC_B from this point on.
   b. Roads are considered as lines and their perimeters are denoted as UC_R. Some roads have indents and gaps within them, which cause the UC_R to be greater than it in reality is. Therefore, for 26 roads a correcting factor ($f_{perimeter}$) is manually applied, based on the amount and size of the indents and gaps.
   c. Using Eq. 4, the (UC_{actual}) per road is determined.

$$UC_{actual} = \frac{UC_B}{UC_R \times f_{perimeter}} \quad \text{Eq. 4}$$

d. The UC_{actual} value in Eq 4. is used as an indicator for whether or not there is an urban canyon present within a road.

7. Using both the UC_{actual} and UC_{AR} parameters, a constraint can be assigned to a road, if the following conditions are true:

   If $UC_{AR} > 1.0$ and $UC_{actual} > 0.3$, then the road is considered as a constraint.

   The 0.3 value is chosen, as it would serve as a conservative approach towards taking no risk implementing the LRA innovation in a deep canyon.

The most important assumptions in this model calculation are that:

- The buildings are assumed to be squares. If a rectangular building is present and a short side is facing the road, then UC_{actual} will get larger than should be. This is actually no problem as it makes the model more conservative and no additional risk is taken. However, if the larger side of a rectangular building is facing the road, then UC_{actual} would be smaller than it should be. Thus, not staying true to the conservative approach.
- Roads are assumed to be lines, while neglecting twice the width at the ends of an road. This could lead to inaccurate perimeters for smaller streets.

Appendix B.5: Vulnerable Heat Stress Groups Scores

The calculations of the vulnerable heat stress groups constraint scores are determined using the following steps:

1. The building data was filtered to only map healthcare buildings.
2. The healthcare buildings within a 20 meter proximity of asphalt roads, are considered as a constraint.

The 20 meter proximity of buildings is considered as the assumption here. This does may not represent reality here necessarily. The problem here is partly counteracted by taking a conservative approach, meaning any asphalt road falling within the 20 meter proximity will be seen as a constrained road.

Appendix B.6: Final Scores

The final scores are determined using the following conditions:

If both constraints calculated in Appendices B.4 and B.5 are shown to be present, than a 0 value is assigned. If not, the average score between the UHI and public lighting energy value is given. This is done for every road and correspondingly the final scores are determined.

Appendix C: Interviews

During the interviews, notes were made about the answers of the interviewees. As these notes were only understandable to a limited amount of readers, they have been used to summarize the answers given during the interviews. Be aware that the answers do not contain direct quotes from the interviewees. The questions are denoted with a number in front of them and are written in **bold letters.** The answers are written in *italic letters.*

Appendix C.1: Interviewee 1 (TWW)

1. ***How familiar are you with the concept of LRA and do you know any LRA cases in the surrounding area of Oldenzaal?***
   I have heard about the idea of the usage of white aggregates use in asphalt mixtures, but that is about it.

The municipality of Enschede has implemented it in the Roombeek a while back. Where the main middle part of the road is white and the outer parts are darker coloured. There has been no specific reason towards doing this from an environmental stand point though.

The municipality of Losser did implement it with the thought of public lighting savings in their mind.

As far as Oldenzaal goes, nothing has been done yet to this point with regards of LRA.

2. ***Do you see any potential in the implementation of LRA in Oldenzaal***.
There is definitely potential of LRA in Oldenzaal. The only big question mark left is, to what extent is it a potential innovation. Durability is a big factor in the success of LRA and any other innovation for that matter. If the pavement loses its functionality over a couple of years for example, the potential diminishes significantly.

   A good example is noise reducing pavement. It quickly lost its noise reducing effect, after which it is just considered a regular pavement.

3. ***The criteria of LRA are divided into different levels of criteria, i.e. main criteria, sub criteria and sub-sub criteria. The main criteria are divided into the following three perspectives: environment, economic and social. The sub and sub-sub criteria which fall under these perspectives are determined by the definition of these main criteria:***
   a. ***The environment criteria contribute towards combatting various aspects of climate change and the urban heat island.***
   b. ***The economic criteria contribute toward creating project opportunities for TWW and ReintenInfra as a whole.***
   c. ***The social criteria contribute towards keeping society content with the implementation of LRA.***

   The criteria and their definitions were sent to you beforehand. To what extent do you agree or disagree with the definitions of these main criteria?

   I fully agree with this list.

4. ***Do you think any of the criteria are misplaced or missing?***
When determining the extra material costs, it is important to compare the extra costs of for example white aggregates with those of black aggregates. And white bitumen with black bitumen.

   I think the extra labour costs are negligible, however there might be extra staff that is required in the asphalt factories. In terms of implementing the LRA in practice, no additional labour forces are required I reckon.

   The applicability will largely depend on the thickness of the LRA alternative, however before applying a fresh coating, the previous top layer will be removed. Also the maximum aggregate size will play a role, as the thickness of the LRA layer will have to be 2,5 as large as the maximum aggregate size. Hence, the difference between the applicability of a complete new surface layer and just the top layer will not be that significant. It should just fall under one category of applicability.

   In terms of practicality, the supplier availability should be defined as the availability of resources, because maybe the element of the LRA alternative is not even available.

The contrast between road markings and the asphalt layer is a good point, however, most of the roads within a city do not even have road markings, so the importance there might be less significant.

Noise reduction can be perceived as a bonus for the LRA alternative.

5. **One of the sub-criteria is the durability performance of the LRA alternative. According to the definitions of the main criteria, under which of these main criteria, should this sub-criteria fall under and why?**
   Mostly under environment, as the benefits of a more durable product will fall under this perspective.

6. ***Durability of a product has its benefits and costs. To what extent are these pros and cons distributed between municipality and contractor (ReintenInfra).***
   Most of the benefits will go towards the client, e.g. energy savings and thus lower costs for the client. However, there are also benefits for the contractor, e.g. image of the company becomes better.

   All in all, I think more benefits go towards the client, rather than towards the contractor, i.e. ReintenInfra.

7. ***Another one of these criteria is the re-usability performance of the LRA alternative at the end of its life-cycle. Under which of these main-criteria should this sub-criteria fall under and why?***
   Under environment as less materials from the source are needed.

8. ***To what extent are the pros and cons of re-usability distributed between municipality and contractor (ReintenInfra)***
   The asphalt becomes cheaper as less materials has needed, so the client has to pay less for it. Hence, the client gains more from re-useable asphalt mixtures.

9. ***Should aesthetics of the pavement surface layer be regarded as a criteria and did ReintenInfra have any trouble with this in the past?***
   I don't think aesthetics will play any hindering role among inhabitants. If anything, it will only be more attractive towards citizens. If the colour distribution is uniform and there are no spots of a different colour, aesthetics will not be a problem in my eyes.

10. ***To what extent is an infrastructure project at ReintenInfra B.V. financed by subsidies?***
    Innovations are stimulated by the government, this is done by reserving money in the form of subsidies by the government. What these subsidies contain, I do not know exactly.

11. ***In order to determine the importance of the criteria, a survey is to be conducted among the main stakeholders involved with the LRA innovation. So far the following stakeholders are used and defined in the context of Oldenzaal:***
    a. ***Entrepreneurs: The companies involved in the production process of LRA, i.e. the whole chain of companies within ReintenInfra B.V.***
    b. ***Governmental bodies: Policy makers with regards to climate and infrastructure decisions at the municipality of Oldenzaal.***
    c. ***Society: the end users of the LRA innovation, i.e. the inhabitants of Oldenzaal.***

To what extent do you agree or disagree with this set of main stakeholders, to determine the criteria importance of the LRA innovation and why? Are there any other stakeholders that should have a say in the importance of criteria of LRA?

You could say the research conform LRA is also important and such be mentioned in the entrepreneurs definition as well. So the definition of entrepreneurs should mention these R + D departments as well.

12. ***Which stakeholder(s) should be determining the importance between the main criteria, i.e. environmental, economic and social criteria?***
    The governmental bodies should determine which perspectives are most important as they have the most influence on the implementation of LRA and thus, they decide.

13. **Which stakeholder(s) should be determining the importance of the sub and sub-sub criteria within these main criteria?**
    The importance of environmental criteria should be determined by the contractor, as they decide which aspects will be incorporated more in the design of the alternatives.

    The importance of the economic criteria will be decided by the client, as they decide what their budget is and whether or not the alternative is within their budget. If they do not agree with the financials of the LRA alternative, no projects are likely to happen.

    The importance of social criteria will also be decided by the client as they want to keep society content.

    The reason for not making the society an influential stakeholder in determining the importance of criteria, is because they simply have no influential power on the success of the LRA. If the importance of criteria (in the eyes of inhabitants) are in conflict of those of the client, the client will at the end of the day, decide whether they stick to a project or not.

Appendix C.2: Interviewee 2 (Asfalt Centrale Twente)

1. ***How familiar are you with the concept of LRA?***
   There has been a long history with white reflective asphalt, in particular in Germany, where about 40% of the market has been occupied by Reef Infra, now known as Strukton Civiel.

   Most of these LRA alternatives consists of an asphalt mixture of which 30% of the aggregates are replaced with white labradoriet aggregates from Norway.

   Another aggregate used for mixtures is luxovit, which is replacing 30% of the aggregates in these mixtures. These mixtures however are heated before acquiring their white appearance which takes a toll on the strength of these aggregates.

   The last aggregate that I am focusing on is that of Reflexing White, which is another aggregate from Norway, except a disadvantage of this aggregate is that the density is very high.

2. ***Do you see any potential in the implementation of LRA in Oldenzaal and to what extent?***
   No real potential, except you do see municipalities applying more and more energy-efficient LED lighting for road illumination. Maybe LRA mixtures can play a role in terms of energy-savings of road illumination.

3. ***What are the most noteworthy implementation cases of LRA in the local area?***
There has been a car garage in the municipality of Rijssen-Holten which has been replaced using whiter aggregates for 20% of the total aggregate volume. A more visible and whiter road surface is created.

4. ***What were the incentives for applying the innovation of LRA in these cases?***
The example of Rijssen-Holten gave the effect of making the environment more bright and creating more driving safety because of the enhanced illumination. These were also the incentives behind the idea of LRA in this case.

5. ***Did these cases show any troublesome side-effects to your knowledge? If not what troubles do you foresee yourself from either an environmental, economic or social perspective?***
No troublesome side-effects, the density of the Reflexing White alternative has a high density, but that does not matter, as a bitumen correction is applied to this mixture. This means that for a higher density of aggregates, a lower amount of aggregates is needed, this results in less bitumen needed.

6. ***When developing a LRA mixture, the elements within the mixture need to be changed, what are the preferred elements to be changed and why?***
The aggregates determine the colour of the asphalt mixture. Hence, this is the preferred alternative. Research suggests that mixtures with red pigments and white aggregates tend to shift towards the colour and thus albedo of the aggregates instead of the pigment. What this shows is that for the longer-term durable solution for increasing the albedo of asphalt, the aggregates are the preferred choice for change. This also is the case when looking at the SMA and AC surf mixtures with both a 30% aggregate content in which the SMA mixtures give a whiter appearance. This is due to the percentage of aggregates in both these mixture types, as SMA and AC surf mixtures contain a 75-78% and 55% aggregate content respectively.

7. ***To what extent has ACT been developing a LRA alternative mixture?***
Two SMA alternatives, one being the labradoriet variant and the other the Reflection White variant. Both the aggregates content contained 30% of the corresponding white aggregate.

8. ***What were the problems occurring with these developments?***
In general no problems as the client, which is the municipality, give the requirements of the asphalt mixtures. Sometimes this contains a specific value for the requirement and other times they have flexible requirements to be met. In both cases these are not that hard to meet.

9. ***Within the LRA category there are different directions of LRA alternatives. For instance, there is the option of simply using whiter aggregates and seal coat them onto the surface layer during maintenance. Also, the use of near-infrared reflective pigments is an option to consider. Thermochromic pavement with doped reflective pigments to change the albedo depending on the season is also an option.***

    To what extent has ACT been researching these broader set of LRA alternatives and have you already eliminated any options?

Nothing has been done, as the functional durability of the pigments is very short relative to the solution of replacing the aggregates instead. When using pigments of any colour, eventually the colour of the aggregates will be visible for most of the life-span of the asphalt.

What we found is that Reflexing White is the easiest to get access to. This is also the case for the different aggregate sizes, as you can order them individually. These sizes are 2/5, 5/8 and 8/11 mm. Labradoriet on the other hand are an all-in-one package deal so to say as you have to order all the aggregate sizes. And as ACT only needs the 5/8 ones, this becomes a burden in a sense.

10. **In an initial stage of the innovation process of LRA, what would be more useful for ReintenInfra: Analysing the broader perspective of LRA alternatives, i.e. comparing the sealcoat, NIR and thermochromic, or comparing a specific set of LRA alternatives within one of these broader alternatives.**
As mentioned before the aggregate determines the long-term colour of the asphalt mixture. Hence, different aggregate alternatives should be analysed.

11. ***Several criteria that the LRA must meet, were sent to you beforehand, do you think any of them are misplaced or missing?***
The brightness of the surface layer is very important I think, as this increases the aesthetics of the environment and the driving safety. Also, under wet conditions people think the brightness becomes enhanced, except this is only an optical illusion so to say.

12. ***Do the units of the criteria make sense to you and could they be measured by ACT?***
Nothing comes to mind. The only thing I would add is that the PSV-waarde in the initial state of the asphalt life is low but sufficient, as bitumen still need to be scratched of the surface so to say.

Furthermore there are three aggregate types: 1,2 and 3 of which type 3 is always used in the surface layers.

13. ***Could the light criteria be measured by ACT, such as albedo, visibility and glare or should external companies be advised?***
At ACT we only make sure the requirements of the asphalt mixtures are in line with the Standard RAW Bepalingen 2015. Hence, the light measurements should be measured or indicated by other companies. Also, suppliers do not mention these 'light' criteria as they are not necessary. Maybe they do not even perform these measurements.

14. ***Could the cost of the LRA alternatives be predicted relatively to each other in the unit now mentioned euro/m₂, or is another unit preferred?***
Criteria related to price can be given by ACT if needed. If not, a qualitative score can always be given.

15. ***What about the noise reduction, is it measurable and comparable to other the alternatives.***
Again, external companies are needed for this as sound is not a real requirement. It can be seen as a bonus.

Appendix C.3: Interviewee 3 (PolyCiviel)

1. ***Do you see any potential in the implementation of LRA in the Netherlands?***
   Yes lots of potential, as less public lighting is needed, especially in tunnels where it is dark all the time. Also conventional pavements cause light pollution. Furthermore, by providing a better illumination of infrastructure network, the traffic safety is increased significantly. Finally, heat stress has been linked a lot to the concept of LRA.

2. ***What are the most noteworthy implementation cases in the Netherlands so far?***
   The most cases have been on provincial roads, in most of the provinces. These did show the potential points mentioned in the previous question. Also LRA has been applied for cycling roads with positive results.

3. ***What were the incentives for applying the innovation of LRA in these cases?***
   The incentives consist of the following points:
   - *Traffic safety.*
   - *Less public illumination needed, as more light is reflected back when using LRA.*
   - *Research has shown that people above the 40, have difficulties seeing the roads. LRA reduces these difficulties. Hence, older people require a better illumination of the environment and roads.*
   - *LRA has shown to reduce the UHI effect of cities. Surface temperature reductions of 8-15 degrees Celsius and feeling temperature reductions of 2 degrees Celsius, which is a lot actually.*
   - *Proven that bitumen skeleton of the LRA mixture, has an increased life-time, due to keeping the bitumen cooler.*

4. ***Did these cases show any troublesome side-effects to your knowledge? If not what troubles do you foresee yourself from either an environmental, economic or social perspective?***
   A lot of attention is required in monitoring the effects of the applied LRA.

   Choices in aggregates is important, as natural stones tend to turn grey as it rains, whereas calcified aggregates from Denmark and France are kept white during rainy periods.

   Also for maintenance, the materials need to be prepared at all times. If a crack or tear is created because of a heavy freight truck, this needs to be repaired quickly.

   The art is in finding the right mixture of the LRA alternative.

5. ***The criteria of LRA are divided into different levels of criteria, i.e. main criteria, sub criteria and sub-sub criteria. The main criteria are divided into the following three perspectives: environment, economic and social. The sub and sub-sub criteria which fall under these perspectives are determined by the definition of these main criteria:***
   a. ***The environment criteria contribute towards combatting various aspects of climate change and the urban heat island.***
   b. ***The economic criteria contribute toward creating project opportunities for contractors.***
   c. ***The social criteria contribute towards keeping society content with the implementation of LRA.***

   The criteria and their definitions were sent to you beforehand. To what extent do you agree or disagree with the definitions of these main criteria?

The definitions are clear and well-defined in my eyes.

6. ***Do you think any of the criteria are misplaced or missing?***
   All of them seem placed correctly, except for one. The UHI maintaining capacity would have the negative effect of losing energy-saving properties for public lighting.

   There are no further criteria missing.

7. ***Do the units of the criteria make sense to you and are the experimental frameworks available for measuring these criteria?***
   For the night visibility, the PSV also influences the mirror factor and thus diffusiveness of the asphalt layer.

   For the noise reduction, it should just be measured in dB(A).

8. ***One of the sub-criteria is the durability performance of the LRA alternative. According to the definitions of the main criteria, under which of these main criteria, should this sub-criteria fall under and why?***
   If you define it as life expectancy of the LRA alternative, then it should definitely be among the other environmental criteria. You could define it as both an economic, and societal criteria if you use the argument of less traffic accidents, so less tax among the communal wallet of the people. However, in this case I would put in the environmental perspective.

9. ***Durability of a product has its benefits and costs. To what extent are these pros and cons distributed between municipality and contractor.***
   Most of the benefits are towards the long-term advantages the government gains, there annual costs per year for infrastructure is reduced as the asphalt mixture life-span is increased. Also less waste is created.

   Sure the contractor has its benefits from durability, such as a good image towards other municipalities. But most of the advantages are for the client, i.e. the municipality.

10. ***Another one of these criteria is the re-usability performance of the LRA alternative at the end of its life-cycle. Under which of these main-criteria should this sub-criteria fall under and why?***
    It would fall under the category of environment, as the municipality has more need for the advantages of this criteria. Sure it gives a good image for TWW, but the advantages for the environment within the municipality is greater than those of the contractor.

11. ***To what extent are the pros and cons of re-usability distributed between municipality and contractor***.
    The benefits for the municipality are less costs as the asphalt mixture becomes cheaper to produce. Also the waste generation becomes less, which are both a benefit towards the municipality.

    The contractor has the benefits of a good image and less supply needed, so reduced costs, but these cost reductions will be more beneficial for the municipality. Hence, the client, i.e. the municipality has more advantages from this criteria.

12. ***Should aesthetics of the pavement surface layer be regarded as a criteria and why?***
Most definitely, as the people want a more bright and lively environment. One example I like to give is the that of snow, as the white environment is more attractive towards inhabitants. So a brighter alternative should be considered.

13. ***In order to determine the importance of the criteria, a survey is to be conducted among the main stakeholders involved with the LRA innovation. So far the following stakeholders are used:***
    a. ***Entrepreneurs: The companies involved in the production process of LRA, i.e. the contractors.***
    b. ***Governmental bodies: Policy makers with regards to climate and infrastructure decisions at the local municipality***
    c. ***Society: the end users of the LRA innovation, i.e. the inhabitants of the local city.***

    To what extent do you agree or disagree with this set of main stakeholders, to determine the criteria importance of the LRA innovation and why? Are there any other stakeholders missing which should have a say in the importance of criteria for LRA.

I think your set of stakeholders are clear and complete.

14. ***Which stakeholder(s) should be determining the importance between the main criteria, i.e. environmental, economic and social criteria?***
Both the municipality and the inhabitants should be used to determine the weights between these main criteria. As they both want the best for their city and should have a say in what they think is the most important aspect.

15. ***Which stakeholder(s) should be determining the importance of the sub and sub-sub criteria within each of these main criteria?***
The municipality should decide on what environmental criteria are more important, as they have environmental guidelines, they want to achieve.

Both the municipality and the contractors should be involved in determining the importance of the economic values of one another. As they both talk with each other on the budget the government has on one side, and keeping the alternative within the budget by taking this into account within the design.

Both the municipality and the end-users should determine the importance of the social criteria, as they both want the best for society. The municipality wants to keep the inhabitants content and the inhabitants know what they will and will not like about LRA alternatives.

16. ***When developing a LRA, the asphalt mixture needs to be changed, what are the preferred components to be changed and why?***
The choice of aggregates is the best way to change the colour of the asphalt. As I have a bad experience with changing the binder material, i.e. bitumen. It is important that the aggregates can bind with the bitumen and have the same texture as before. Hence, the most likely element to change is the aggregates within the LRA mixture.

17. ***What is the most promising alternative of LRA in the Netherlands in your eyes, if there is any and what are its pros and cons?***
    We are currently researching a mixture with adaptive characteristics with regards to CO_2. However, this is confidential and cannot discuss it with you unfortunately.

18. ***What urban characteristics would you deem as the most influential towards the implementation of LRA in mitigating the UHI?***
    Big open areas are suitable places for LRA. Cycling and pedestrian lanes are suitable as they directly reduce thermal stress on inhabitants.

    Greenery and water already reduce UHI, so use it where UHI is still high for highest potential.

    Solar farms and panels only worsen the effect of the UHI.

Appendix C.4: Interviewee 4 (Asfalt Centrale Twente)

1. **What does the ECI indicate?**
   The ECI translates the different environmental effect into a cost of euros/ton. There are 11 categories of environmental effect determined in research by TU Delft.

2. **Which tool is used to calculate ECI values within ACT?**
   The tool known as EcoChain is used. This tool is particularly used by production firms, where raw materials, gas, water and electricity are used as an input. Processes are linked to the inputs and emissions can be calculated for the production company.

   ACT calculates ECI of aggregates based on production and processing from the start point, i.e. retrieving of the aggregate until arrival at ACT.

3. **What are the factors taken into account by EcoChain in order for it to calculate the ECI of materials?**
   Retrieving of the materials, transport and production are taken into account. Processing and implementation of the asphalt mixtures not taken into account.

4. **How does the tool used, take into account the future re-use of aggregates in top layers again?**
   Future re-use is not taken into account. However, reclaimed asphalt materials used for the production of current asphalt mixture are taken into account, by assigning an ECI value close to 0 euros/ton.

5. **Wordt levensduur van het materiaal in beschouwing genomen?**
   If a project context is given, the ECI can change accordingly. However, without a project context the life-span of the asphalt mixture cannot be taken into account.

6. **A side-effect of whiter aggregates is the cooling capability of the asphalt mixture, which could lead to reduced energy-savings for public lighting. To what extent are side-effects, such as these, taken into account?**
   Effects such as these, cannot be taken into account. In a project context, this could be calculated, but when looking at the aggregates alone, this cannot be considered.

7. **To what extent does transport play a role in determining the ECI values of the aggregates?**
This depends on the location, but large differences in transport energy costs can occur and play a decisive role in determining the ECI value of an aggregate. A product with lots of reclaimed materials will have a lower ECI as these materials require no additional transport.

   BS, LD and RW are retrieved from Norway, while LV is retrieved from Denmark.

8. **How accurate is the general product cart for the LRA aggregates?**
Obviously not that specific. An analysis has been made based on other grooves and their branche averages. After that the amount of diesel required per ton of aggregate is determined and an ECI could be calculated.

9. **Would the ECI value of the different LRA aggregates be higher than that of the BS alternative if transport is to be taken into account?**
Aggregates have to travel by both ocean ship (0.0023 euros/tonkilometer) and inland ship (0.0056 euros/tonkilometer). Hard to say, but is possible for sure to exceed the ECI of BS.

10. **Are there other factors not taken into account in the determination of ECI values of BS and the LRA aggregates?**
I cannot control that right now, but these ECI values are calculated by both an LCA expert and an independent expert. Hence, playing with the outcome is not possible. It is safe to say that these are reliable ECI values, as the LCA method used, has been a very persistent one.

11. **How accurate are the current ECI values?**
For the BS alternative, accurate. The other aggregates miss the transport aspect of the ECI value.

12. **On a scale from 1 until 5 with the following scale definition:**

- **1: Poor**
- **2: Insufficient**
- **3: Mediocre**
- **4: Sufficient**
- **5: Excellent**

How would you score the two different ECI values including transport for the white aggregates?
Bestone would score a 4, as it is sufficient (ECI being 2.30 euros/ton) but it can still be improved. The white aggregates would probably score a 2 when including transport. The ECI of the whiter aggregates are 2.16 euros/ton excluding transport.

Appendix C.5: Interviewee 5 (Asfalt Centrale Twente)

1. **Which of the conventional aggregates, can be best used for comparison with the whiter aggregates? Is there an aggregate which is most used within ACT?**
The most used conventional aggregate in ACT is Bestone, which is well-suited a type 3 aggregate according to the Standaard RAW Bepalingen 2015.

2. **During colder periods, more precipitation occurs. Is it possible that some aggregates turn grey when exposed to precipitation and what are the characteristics related to this?**

Almost negligible if looked at precipitation solely. However, dirt does become a problem with the different alternatives, this is also partly due to precipitation. No characteristics are specifically related to this.

3. **How do the aggregates compare to each other in terms of becoming darker due to precipitation?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	3	1	3
Quantitative score	-	-	-	-

4. **What aggregate characteristics may best be used to indicate the lifespan of the alternative?**
Resistance towards fragmentation (LA), polishing (PSV).

5. **How do the aggregates compare to each other in terms of their life-span?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	3	4
Quantitative score	-	-	-	-

6. **What aggregate characteristics are related to the aggregate gradually losing its white colour?**
No characteristic is linkable to this criteria, as they keep their colour, despite the traffic on top of them. The scores differ though.

7. **How do the aggregates compare to each other in terms of gradually losing their white colour?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	3	3
Quantitative score	-	-	-	-

8. **What are the aggregate characteristics related to re-usability of aggregates in top layers at the end-of-life stage of asphalt?**
LA, PSV and abrasion do play a role in this, however they are being left out. In principal we try to re-use as much of the aggregates as possible in surface layers. If this is not possible, they will be reused in the non-surface layers.

9. **How do the aggregates compare to each other in terms of re-usability in surface layers?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	3	4
Quantitative score	-	-	-	-

10. **Are there any pre-processing costs related to ACT, such as pre-heating of the LF alternative for example?**
Only the high temperatures related to the pre-processing of LV are known.

11. **How do the aggregate alternatives compare to the material costs, i.e. purchase from the supplier?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	4	2	3
Quantitative score	-	-	-	-

The LD alternative, requires an all-in-one package of all the fractions, this makes it three times as expensive as the others. However, the costs are so low that it would still be so much more cheaper than the other white aggregates. The LF alternative, requires heating at high temperatures resulting higher costs.

12. **Are additional staff expenses present when working with these whiter aggregates?**
These are negligible, as no extra persons are needed in neither the laboratory nor the asphalt plows.
13. **How do the aggregates compare to the technological know-how in the laboratory? Are you up-to-date with all the properties of whiter aggregates just like conventional aggregates? Are light properties available within ACT or from an external company?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	4	4
Quantitative score	-	-	-	-

We simply know all the necessary data for all the alternatives. Excluding the light properties of course, as this is not within our expertise.

14. **How do the aggregates compare to each other in terms of the implementation know-how of asphalt plows. Is there any knowledge missing that makes it harder for the asphalt plows to work with the whiter mixes or is it no different than the conventional mixes? Do you foresee any troubles in the implementation of LRA alternatives.**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	4	4

Quantitative score	-	-	-	-

Every variable influencing the implementation know-how is the same. Both the temperature and the composition of the asphalt consisting of these alternatives is the same. Only the colour differs, but this is not an influencing variable for the asphalt plow.

15. **To what extent are the needed aggregate sizes available for each aggregate alternative?**
In terms of fraction sizes RW the most difficult. The 8/11 fraction of RW in particular is difficult to get hands on. In general the scores of Q18 apply, which shows that LF is the least available. In general the whiter aggregates have an increased demand as of late, decreasing the resource availability

16. **How do the aggregates compare to their resource availability?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	4	3	4
Quantitative score	-	-	-	-

17. **How do the aggregates compare to their applicability in top layers? Do they have the characteristics to be able to be used for different asphalt mixtures for urban use, e.g. SMA and AC?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	4	4	4
Quantitative score	-	-	-	-

Convential is a little bit more superior in this regard. However, between the different whiter alternatives, the scores do not differ.

18. **What are the characteristics related to the anti-skid performance of aggregates?**
PSV is the main characteristic in this regard.

19. **How do the aggregates compare to each other in terms of anti-skid performance?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	3	4	4
Quantitative score	-	-	-	-

Appendix C.6: Interviewee 6 (PolyCiviel)

1. **How do the aggregates compare to each other with respect to having a high albedo, and thus reflecting light rather than absorbing it?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	3	4	5	4

Quantitative score	30-35	55	70-75	60

2. **During colder periods, more precipitation occurs. Is it possible that some aggregates turn grey when exposed to precipitation and what are the characteristics related to this?**

   The decisive factor in influencing the albedo and thus, colour of the aggregate is whether the aggregate is a natural or artificial aggregate. Natural aggregates show the lower albedo under wet and cold conditions. This should not be a criterion however, as an LRA mixture should focus on enlightening the environment and providing better visibility.

3. **How do the aggregates compare to each other in terms of becoming darker due to precipitation?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	3	5	3
Quantitative score	-	-	-	-

   Maintaining white colours during winter is also better for visibility and energy-saving reasons.

4. **What aggregate characteristics may best be used to indicate the lifespan of the alternative?**
   The main characteristics are the PSV and regenerating performance of the aggregates.

5. **How do the aggregates compare to each other in terms of their life-span?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	3	5	4
Quantitative score	-	-	-	-

   As LF has breaks down in finer particles, throughout its life, which creates a rougher surface and increases the PSV value of the aggregate again. I like to call this the regenerating capability of LF. The other aggregates are ranked based on their PSV values.

6. **What aggregate characteristics are related to the aggregate gradually losing its white colour?**
   The petrochemical composition of the aggregates plays a role in this.

7. **How do the aggregates compare to each other in terms of gradually losing their white colour?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	3	4	5	4
Quantitative score	-	-	-	-

LF maintains a white colour despite the traffic load and weather circumstances. This leads to a higher score for this alternative.

8. **What aggregate characteristics are related to achieving energy-savings with regards to public lighting?**
   The colour and diffusiveness of the aggregate play a role in this.

9. **How do the aggregates compare to each other in term of leading to a reduction in energy-demand for road illumination?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	3	5	4
Quantitative score	-	-	-	-

The colour of LF always is white, despite traffic load and weather circumstances. Whereas RW is a natural aggregate which turns darker in colour if exposed to precipitation. LD is less white than both LF and RW and also is a natural aggregate. Bestone is significantly darker and thus cannot reflect much light back to the environment, which requires more energy from the road lighting. LF also has the advantage of creating a better texture in order to diffuse more light back into the environment.

10. **What are the aggregate characteristics related to re-usability of aggregates in the surface layer?**
    PSV values play a main role in reusability of the aggregates in the surface layer.

11. **How do the aggregates compare to each other in terms of re-usability?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	1	4	5
Quantitative score	-	-	-	-

LD has the lowest PSV value which is not able to be used in the top layer again. Whereas LF has a sufficient PSV value. Both RW and BS have good PSV values.

12. **How do the aggregates compare to their applicability in top layers? Do they have the characteristics to be able to be used for different asphalt mixtures for urban use, e.g. SMA and AC?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	1	4	5
Quantitative score	-	-	-	-

LD not suitable for top layer because of the low PSV. Combining the different aggregates may combine better properties of these alternatives. Mixing RW and LF for both the PSV and light properties respectively is wise thing to do.

13. **What are the aggregate characteristics relating to glare of the asphalt?**
PSV values and grading shape determine the anti-glare performance. Higher PSV value results in better glare.

14. **How do the aggregates compare to each other in terms of preventing glare?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	5	4	5	4
Quantitative score	-	-	-	-

The higher score of LF is because of the diffuse reflection of sunlight, resulting less glare. Bestone has such a high absorption of light that it has a significantly high anti-glare performance.

15. **What are the aggregate characteristics relating to the visibility of the road in the dark?**
The Retro-reflective coefficient caused by light of the headlights of cars (Rl).

16. **How do the aggregates compare to each other in terms of providing a more visible road in the dark?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	4	5	4
Quantitative score	-	-	-	-

17. **What are the aggregate characteristics in determining whether the contrast between road markings and the road itself is clearly visible?**

The contrast is always achievable and sufficient, but in terms of maintenance, the whiter aggregates require road markings to be more maintained as the their colours shift more towards each other.

18. **How do the aggregates compare to each other when looking at providing a good contrast between road and road markings?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	4	4
Quantitative score	-	-	-	-

In terms of achievability of road contrasts they all score the same.

19. **What are the aggregate characteristics in determining the noise reducing capabilities of an asphalt mixture?**
It depends more on the void content of the asphalt mixtures they are in, rather than texture depth.

20. **How do the aggregates compare to each other in terms of noise reducing capabilities?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	4	4
Quantitative score	-	-	-	-

The void content is always achievable, but requires the know-how. So the scores are all sufficient.

21. **What are the aggregate characteristics in determining the extent to which the environment is given an aesthetic boost?**
Depends on all of the light properties, i.e. Q0, Qd, S1, Rl and Beta.

22. **How do the aggregates compare to each other in terms of providing a more aesthetic environment?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	1	4	5	4
Quantitative score	-	-	-	-

LF is always white as it is an artificial aggregate and in general whiter than LD and RW. Bestone is significantly darker and does not enlighten the environment.

23. **Is a quantification of the different possible per aggregate alternative?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Luminance coefficient Qd (mcd.m-2.lx-1)	-	-	-	-
Mean luminance coefficient Qo (cd.m-2.lx-1)	-	-	-	-
Retro-reflective coefficient RL (mcd.m-2.lx-1)	-	-	-	-
Mirror factor S1 (-)	-	-	-	-
Luminance factor (-)	0.34	0.45	0.55	0.45

The luminance factor is given for the aggregates. The remaining blank light properties are more related to asphalt mixtures rather than aggregates. Hence, an indication cannot be given for these properties.

Appendix C.7: Interviewee 7 (Light Surface Control)

1. **How do the aggregates compare to each other with respect to having a high albedo, and thus reflecting sunlight rather than absorbing it?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	4	4	4
Quantitative score	-	-	-	-

2. **During colder periods, more precipitation occurs. Is it possible that some aggregates turn grey when exposed to precipitation and what are the characteristics related to this?**
Wet circumstances turn natural aggregates more dark of colour. Artificial aggregates stay white and are not affected by precipitation.

3. **How do the aggregates compare to each other in terms of becoming darker due to precipitation?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	3	5	3
Quantitative score	-	-	-	-

Must be seen as a positive if aggregate stays white, as more reduction in public lighting energy-savings.

4. **What aggregate characteristics are related to the aggregate gradually losing its white colour?**
The aggregate do get dirty over time, but rainfall cleans the asphalt again.

5. **How do the aggregates compare to each other in terms of gradually losing its white colour?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	3	3	3
Quantitative score	-	-	-	-

They all decrease in whiteness, but the whiter aggregates even more so than the BS alternative. No difference in luminance factor reduction for the three whiter aggregate alternatives.

6. **What aggregate characteristics are related to producing the same road illumination as before, but with less energy needed?**

Both whiteness and diffusiveness play a role. Diffusiveness corelates with the mirror factor and texture. The lower the mirror factor the higher the diffusiveness, which illuminates the road even more if light is shined upon it. The more white the asphalt surface layer, the more bright it will be and thus less light is needed.

7. **How do the aggregates compare to each other in term of leading to a reduction in energy-demand for road illumination?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	3	4	4
Quantitative score	-	-	-	-

All mixtures possible but based on the diffusiveness and whiteness of the aggregates LV and RW are better. LD still has whiter colour, so illuminates easier.

8. **What are the aggregate characteristics relating to glare of the asphalt?**

The mirror factor and thus, diffusiveness play a role. A high mirror factor results in more glare. In the evening the whiteness also plays a role. The higher the whiteness the more blinding it can be due to glare.

9. **How do the aggregates compare to each other in terms of preventing glare?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	4	4	4
Quantitative score	-	-	-	-

Bestone has a higher mirror factor, resulting in more glare.

10. **What are the aggregate characteristics relating to the visibility of the road in the dark?** *Again the diffusiveness and whiteness play a role here.*
11. **How do the aggregates compare to each other in terms of providing a more visible road in the dark?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	2	4	4	4
Quantitative score	-	-	-	-

12. **What are the aggregate characteristics in determining whether the contrast between road markings and the road itself is clearly visible?** *During the day this might be a problem. Difference in whiteness (luminance factor) is to be analysed here.*

13. **How do the aggregates compare to each other when looking at providing a good contrast between road and road markings?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	4	4	4	4
Quantitative score	-	-	-	-

A sufficient road marking contrast can be achieved for all the aggregates. Solutions could be dark bitumen edge surrounding the white road markings, to accentuate the markings more.

14. **What are the aggregate characteristics in determining the extent to which the environment is given an aesthetic boost?**

    Like the other questions, the whiteness and diffusiveness of the are to play a role in determining the environmentally boosting performance of the aggregates.

15. **How do the aggregates compare to each other in terms of providing a more aesthetic environment?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Qualitive score	1	5	5	5
Quantitative score	-	-	-	-

16. **Is a quantification of the different possible per aggregate alternative?**

	Bestone	Labradoriet	Luxovit	Reflexing White
Luminance coefficient Qd (mcd.m-2.lx-1)	-	-	-	-
Mean luminance coefficient Qo (cd.m-2.lx-1)	-	-	-	-
Retro-reflective coefficient RL (mcd.m-2.lx-1)	-	-	-	-
Mirror factor S1 (-)	High	Medium	Low	Medium
Luminance factor (-)	-	-	-	-

The mirror factor is qualitatively known for the different aggregates. A high mirror factor implies a low diffusiveness of the aggregates. The other way around, a low mirror factor implies a diffusive aggregate.

The other factors I do not know at the moment.

Appendix D: Surveys

The following three surveys were held among four municipal policy makers. They are written and conducted in Dutch. Every survey begins with the introduction of the topic and goal of the survey. Also the format of questions and answers is explained, so as much confusion as possible is avoided. Besides the content specific questions, the respondents were also asked for their function within the municipality and how much experience they have with this function (expressed in years).

Appendix D.1: Environmental Survey

Vraag 1:

Stelling A: LRA dient zijn milieuvriendelijke eigenschappen (bv. het verminderen van hittestress) zolang mogelijk te behouden. Stelling B: De totale levensduur van asfalt dient zo lang mogelijk te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 2:

Stelling A: LRA zelf en zijn milieuvriendelijke eigenschappen (bv. het verminderen van hittestress) dienen zo lang mogelijk mee te gaan. Stelling B: Hitte afkomstig van asfalt moet worden verminderd. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 3:

Stelling A: LRA zelf en zijn milieuvriendelijke eigenschappen (bv. het verminderen van hittestress) dienen zo lang mogelijk mee te gaan. Stelling B: Warmte afkomstig van de zon moet gedurende koudere periodes zoveel mogelijk worden behouden in het wegdek. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 4:

Stelling A: LRA zelf en zijn milieuvriendelijke eigenschappen (bv. het verminderen van hittestress) dienen zo lang mogelijk mee te gaan. Stelling B: Er moet energie bespaart worden op de kunstmatige verlichting van straten in het donker (bv. door lantaarnpalen). In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 5:

Stelling A: LRA zelf en zijn milieuvriendelijke eigenschappen (bv. het verminderen van hittestress) dienen zo lang mogelijk mee te gaan. Stelling B: Oud LRA dient in de toekomst zo veel mogelijk herbruikbaar te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 6:

Stelling A: Hitte afkomstig van asfalt moet worden verminderd. Stelling B: Warmte afkomstig van de zon moet gedurende koudere periodes zoveel mogelijk worden behouden in het wegdek. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 7:

Stelling A: Hitte afkomstig van asfalt moet worden verminderd. Stelling B: Er moet energie bespaart worden op de kunstmatige verlichting van straten in het donker (bv. door lantaarnpalen). In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 8:

Stelling A: Hitte afkomstig van asfalt moet worden verminderd. Stelling B: Oud LRA dient in de toekomst zo veel mogelijk herbruikbaar te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 9:

Stelling A: Warmte afkomstig van de zon moet gedurende koudere periodes zoveel mogelijk worden behouden in het wegdek. Stelling B: Er moet energie bespaart worden op de kunstmatige verlichting van straten in het donker (bv. door lantaarnpalen). In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 10:

Stelling A: Warmte afkomstig van de zon moet gedurende koudere periodes zoveel mogelijk worden behouden in het wegdek. Stelling B: Oud LRA dient in de toekomst zo veel mogelijk herbruikbaar te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 11:

Stelling A: Er moet energie bespaart worden op de kunstmatige verlichting van straten in het donker (bv. door lantaarnpalen). Stelling B: Oud LRA dient in de toekomst zo veel mogelijk herbruikbaar te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 12:

Stelling A: LRA zelf en zijn milieuvriendelijke eigenschappen (bv. het verminderen van hittestress) dienen zo lang mogelijk mee te gaan. Stelling B: Negatieve milieueffecten door productie, vervoer en bewerking van grondstoffen (bv. broeikasgas productie) moet zo gering mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 13:

Stelling A: Hitte afkomstig van asfalt moet worden verminderd. Stelling B: Negatieve milieueffecten door productie, vervoer en bewerking van grondstoffen (bv. broeikasgas productie) moet zo gering mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 14:

Stelling A: Warmte afkomstig van de zon moet gedurende koudere periodes zoveel mogelijk worden behouden in het wegdek. Stelling B: Negatieve milieueffecten door productie, vervoer en bewerking van grondstoffen (bv. broeikasgas productie) moet zo gering mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 15:

Stelling A: Oud LRA dient in de toekomst zo veel mogelijk herbruikbaar te zijn. Stelling B: Negatieve milieueffecten door productie, vervoer en bewerking van grondstoffen (bv. broeikasgas productie) moet zo gering mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 16:

Stelling A: Er moet energie bespaart worden op de kunstmatige verlichting van straten in het donker (bv. door lantaarnpalen). Stelling B: Negatieve milieueffecten door productie, vervoer en bewerking van grondstoffen (bv. broeikasgas productie) moet zo gering mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Appendix D.2: Economic Criteria Survey

Vraag 1:

Stelling A: De kennis in de laboratoria moet aanwezig zijn om tot een LRA mengsel te komen die aan alle eisen voldoet. Stelling B: De asfaltploegen moeten de kennis hebben om de LRA mengsel te kunnen verwerken tot deklaag. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 2:

Stelling A: De kennis in de laboratoria moet aanwezig zijn om tot een LRA mengsel te komen die aan alle eisen voldoet. Stelling B: De beschikbaarheid van leveranciers en de bijbehorende materialen van het LRA dient zo hoog mogelijk te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	

Opmerkingen (optioneel):

Vraag 3:

Stelling A: De asfaltploegen moeten de kennis hebben om de LRA mengsel te kunnen verwerken tot deklaag. Stelling B: De beschikbaarheid van leveranciers en de bijbehorende materialen van het LRA dient zo hoog mogelijk te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 4:

Stelling A: De praktische kennis en beschikbaarheid van LRA materialen moeten zo goed mogelijk zijn. Stelling B: De totale toegevoegde productie-, materiaal- en personeelskosten van LRA dienen zo min mogelijk te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	

9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 5:

Stelling A: De praktische kennis en beschikbaarheid van LRA materialen moeten zo goed mogelijk zijn. Stelling B: Het aantal toepassingsmogelijkheden voor LRA moet zo groot mogelijk zijn om zo meer projectmogelijkheden te creëren. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 6:

Stelling A: De totale toegevoegde productie-, materiaal- en personeelskosten van LRA dienen zo min mogelijk te zijn. Stelling B: Het aantal toepassingsmogelijkheden voor LRA moet zo groot mogelijk zijn om zo meer projectmogelijkheden te creëren. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	

7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Appendix D.3: Social Criteria Survey

Vraag 1:

Stelling A: Er dient zo min mogelijk schittering (verblinding) op te treden door LRA. Stelling B: De extra zichtbaarheid in het donker, gecreëerd door LRA, dient zo hoog mogelijk te zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 2:

Stelling A: Er dient zo min mogelijk schittering (verblinding) op te treden door LRA. Stelling B: Duidelijke verschillen tussen wegdek en wegdekmarkeringen dienen behouden te worden bij een LRA deklaag. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	

6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 3:

Stelling A: Er dient zo min mogelijk schittering (verblinding) op te treden door LRA. Stelling B: De stroefheid van het LRA wegdek (om slippen tegen te gaan) moet zo gunstig mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 4:

Stelling A: De extra zichtbaarheid in het donker, gecreëerd door LRA, dient zo hoog mogelijk te zijn. Stelling B: Duidelijke verschillen tussen wegdek en wegdekmarkeringen dienen behouden te worden bij een LRA deklaag. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	

6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 5:

Stelling A: De extra zichtbaarheid in het donker, gecreëerd door LRA, dient zo hoog mogelijk te zijn. Stelling B: De stroefheid van het LRA wegdek (om slippen tegen te gaan) moet zo gunstig mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 6:

Stelling A: Duidelijke verschillen tussen wegdek en wegdekmarkeringen dienen behouden te worden bij een LRA deklaag. Stelling B: De stroefheid van het LRA wegdek (om slippen tegen te gaan) moet zo gunstig mogelijk zijn. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	

5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 7:

Stelling A: Veiligheid in zichtbaarheid en stroefheid van het LRA wegdek moet zo hoog mogelijk zijn
Stelling B: Het geluid reducerend vermogen van LRA moet zo hoog en lang mogelijk behouden blijven.

In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?

Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 8:

Stelling A: Veiligheid in zichtbaarheid en stroefheid van het LRA wegdek moet zo hoog mogelijk zijn
Stelling B: De verbeterde verlichting van de omgeving gedurende dag en nacht door LRA draagt bij aan een fijnere leefomgeving voor omwonenden.

In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?

Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	

4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	

Vraag 9:

Stelling A: Het geluid reducerend vermogen van LRA moet zo hoog en lang mogelijk behouden blijven. Stelling B: De verbeterde verlichting van de omgeving gedurende dag en nacht door LRA draagt bij aan een fijnere leefomgeving voor omwonenden. In hoeverre is stelling A belangrijker of minder belangrijk dan stelling B?	
Antwoord mogelijkheden	Antwoord (slechts één antwoord mogelijk)
1: Stelling A is totaal niet belangrijk t.o.v. stelling B	
2: Stelling A is veel minder belangrijk dan stelling B	
3: Stelling A is minder belangrijk dan stelling B	
4: Stelling A is iets minder belangrijk dan Stelling B	
5: Stelling A is even belangrijk als stelling B	
6: Stelling A is iets belangrijker dan stelling B	
7: Stelling A is belangrijker dan stelling B	
8: Stelling A is veel belangrijker dan stelling B	
9: Stelling B is totaal niet belangrijk t.o.v. stelling A	
Opmerkingen (optioneel):	