MASTER

Creating a Social Cost-Benefit Analysis Decision Support System to optimize the replacement of public lighting

An investigation into replacing not yet depreciated public lighting with intelligent Light Emitting Diode lighting to help reach energy goals

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Creating a Social Cost-Benefit Analysis Decision Support System to optimize the replacement of public lighting

An investigation into replacing not yet depreciated public lighting with intelligent Light Emitting Diode lighting to help reach energy goals

Construction Management and Engineering thesis[1] [2] *(40 ECTS)*

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[1]The master's thesis has been carried out in accordance with the rules of the TU/e Code of Scientific Integrity.
[2]All information included within this document is public information.

Contents

Summary

Dutch municipalities experience boundaries concerning the implementation of (new power-saving) public lighting. Due to these boundaries, energy goals concerning public lighting will likely not be reached. The boundaries that can be falsified with literature are a lack of funds, the innovation not being worthwhile, and potential civil backlash. The remaining boundaries to implementation that can be resolved using research are a lack of time and not yet depreciated assets. The remaining boundary, split budgetary streams, cannot be falsified with literature since it is a governmental choice.

To help municipalities in alleviating the remaining boundaries, that can be resolved using research, it is proposed that a (time-saving and transparent) Decision Support System (DSS) is made regarding the implementation of Light Emitting Diodes (LEDs) with or without intelligent control in replacing depreciated and not yet depreciated public lighting. To maximize the time savings, a Dutch governmental format Social Cost-Benefit Analysis (SCBA) will be followed. Since it is required that a DSS is made to counter the lack of time boundary encountered by municipalities, the research question should not be answerable without a DSS. This leads to the following research question:

Under which circumstances can (intelligent) LED public lighting replace (not yet) depreciated public lighting according to a Dutch governmental format SCBA?

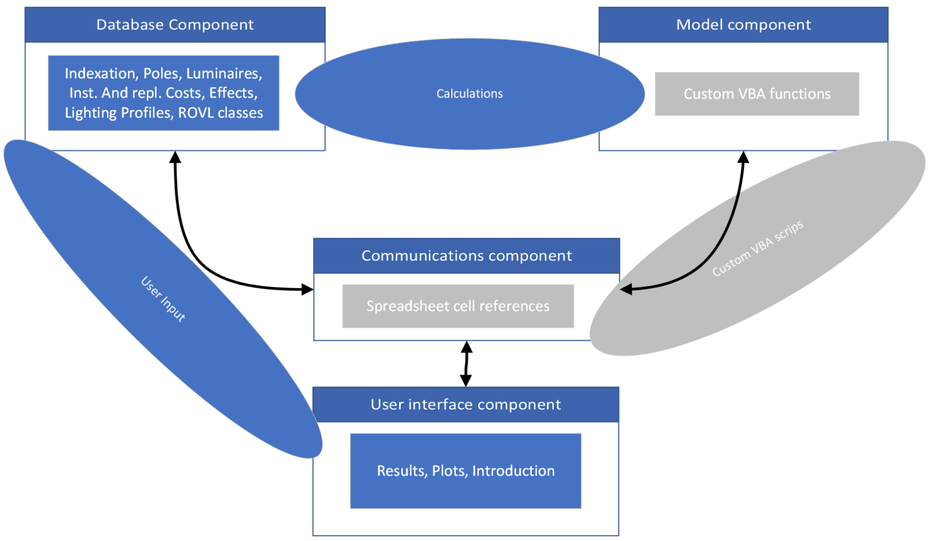


Figure 1: DSS stucture

Novel work is provided by answering this research question since no DSS using SCBA methods in the context of public lighting currently exists that can answer this question. A DSS using SCBA as its decision analysis model for public lighting has not been created in the past due to a lack of interest, a lack of publishable scientific data that can be gathered using them, and because the organizations implementing public lighting are of such a small scale, that from a cost perspective, performing a SCBA (and implementing it into a DSS) is perceived not to make sense. This leaves the companies manufacturing public lighting, students, and publicly funded research agencies such as TNO or the Institute for Highway Safety to perform said research. Companies manufacturing public lighting have a clear conflict of interest and would not publish results that state that public lighting should be reduced. Students can perform such research but, likely, the results are not published publicly and/or cannot be found. Publicly funded research agencies have not gotten around to creating a SCBA DSS for this purpose.

The DSS created in this master's thesis[1] is implemented in a spreadsheet program, the components are divided among several sheets within a workbook file. In Figure 1, an overview of the sheets and their respective functions in the DSS can be seen. The SCBA is conducted in the model component. The DSS has the goal to optimize the Net Present Value (NPV)(, energy usage, or NPV with X% of energy savings) for a certain area. The NPV is used as optimization goal since SCBA requires it and since minimizing cost is the policy goals of municipalities. The NPV is the current value of a future expense/revenue. The DSS optimizes what poles, fixtures, and lights to use, when to install them, and what the maintenance intervals should be to reach the goal. These optimized results form the intervention scenarios. The scenario without intervention is the current policy within an area.

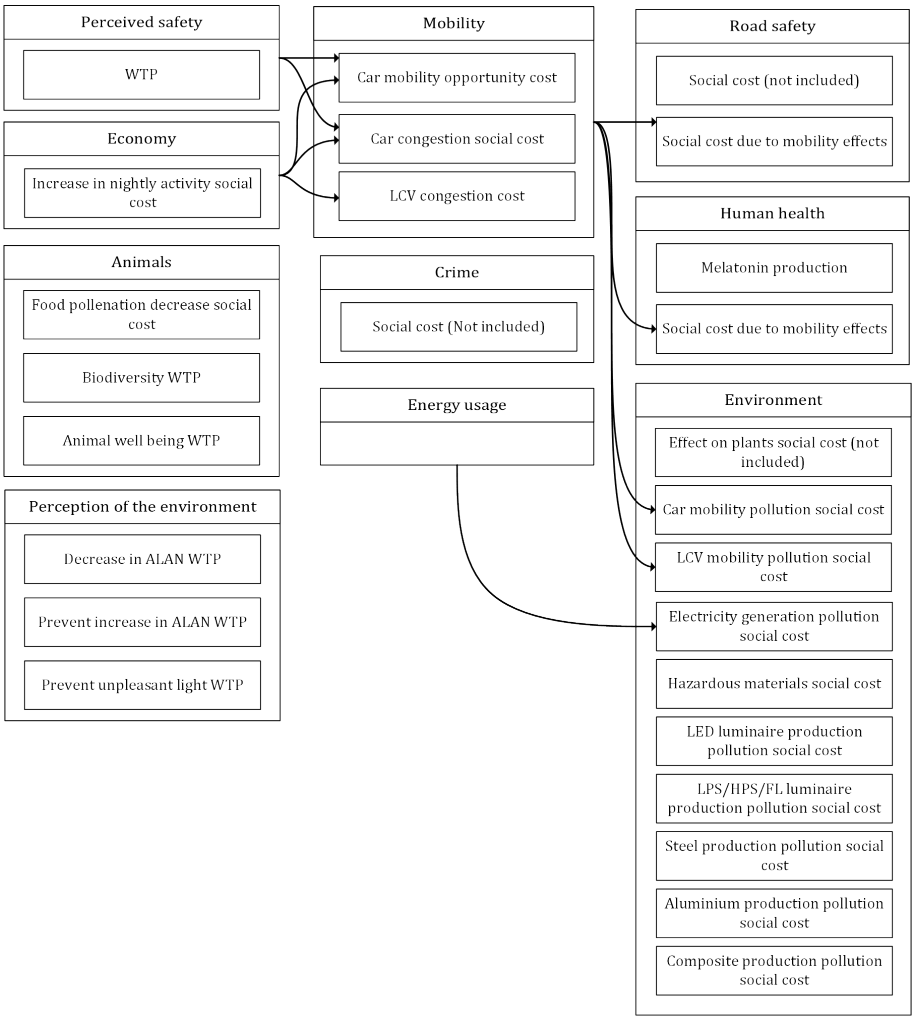


Figure 2: The included effects and relations between the effects in the DSS

[1]The DSS can be downloaded from: *https://1drv.ms/x/s!AnVbYLjK815OoSCTA51sOo5GlCrR?e=YaNo7N*

The included costs and effects in the DSS (contained in the database component) will now be further discussed. In Figure 2, the found effects and relations between the different included effects can be seen. As can be seen, there are direct and indirect effects. The included costs in the DSS (not in Figure 2) are the costs of electricity, poles, fixtures, light sources, placement, and maintenance. The maintenance cost include costs due to failures. The rate of failure is determined using separate Weibull functions for the components based on failure data from the municipality of Nuenen.

The DSS can be used for a a wide range of circumstances (from the research question). However, these circumstances cannot all be included in a report, the DSS was, therefore, tested for a select set of circumstances in a case study. In the case study, three areas in the municipality of Nuenen with different types of not yet depreciated lighting systems (High Pressure Sodium (HPS), Low Pressure Sodium (LPS), and LED) are included. The DSS is run with a selection of settings. The first setting is to run the DSS for global costs and benefits and global lighting policy (EGG). The second setting is to run the DSS for global costs and benefits with a local lighting policy (bound to the area) (EGL). Third, the boundaries of the DSS costs and benefits will be set to local (municipal boundaries) (ELL). Fourth, all effects will be disabled, thus creating a Cost-Based Analysis (CBA) for municipal cost boundaries (CLL).

An overview of the results needed to answer the main research question can be seen in Table 1 and 2. In Table 1, it can be seen which lighting type has the highest NPV according to the different DSS settings. Additionally, the lighting technology with the lowest power consumption is given. In Table 2, the replacement dates of the existing fixtures with the highest NPVs are given. When interpreting these results it should be noted that there are severe limitations. This means that, in the future when these are resolved, the results will likely change.

Table 1: Fixtures with the highest NPV

Setting\Area	**LED**	**HPS**	**FL**
EGG	LPS	LPS	LPS
EGL	LPS	LPS	LPS
ELL	LED static	LED Static	LED Static
CLL	LED Static	LED Static	LED Static
Lowest energy	LED Intelligent	LED Static	LED Intelligent

Table 2: Fixture replacement years with the highest NPV

Setting\Area	**LED**	**HPS**	**FL**
EGG	2039	2035	2035
EGL	2039	2035	2035
ELL	2039	2031	2033
CLL	2039	2031	2033
Base	2036	2033	2033

Using the combined results, conclusions are formed to give the best possible answer to the main research question. In conclusion, intelligent lighting is likely not worth its cost premium. When taking global effects into account, lighting systems can likely not be replaced for more efficient LED lighting solutions according to the currently implemented DSS due to higher environmental social costs. If only local effects are taken into account then replacing the current (less efficient) lighting system for a more efficient one, before the current system is depreciated, can result in a higher NPV if the efficiency difference and light requirements are large enough.

As already mentioned, limitations affect these conclusions. These limitations are that some effects are not properly quantified, that some effects are currently unknown, that most lighting specifications are not used in calculating the impact of the effects, that only one technology switch is implemented, that, currently, no accurate risk estimation exists, and that the end date is fixed across all cases.

Therefore, the provided answers to the research question are not definitive. To give an answer with certainty more research is needed and the results of said research need to be implemented into a DSS. However, a recommendation to the implementers of public lighting can be given based on the knowledge gained by the novel work in this thesis.

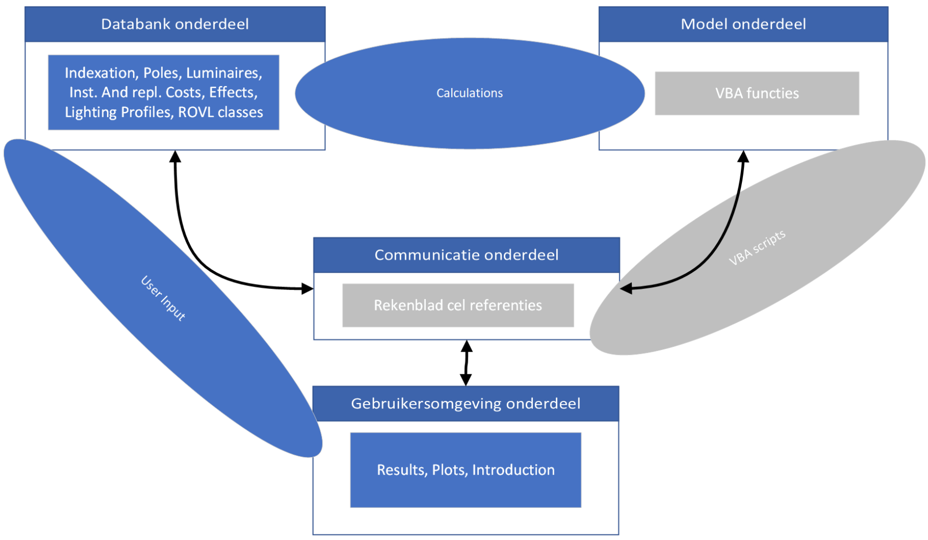
The main recommendation is that, based on the large (estimated) effects found for public lighting, it is best not to use cost-based decision-making. Instead, the social costs and benefits should be taken into account. The result of this recommendation is to use intelligent dimming if it reduces the amount of Artificial Light At Night (ALAN). This is the case since intelligent dimming has little to no negative impacts while ALAN has (severe) negative impacts. When this recommendation is followed, the spending will likely increase, but the welfare of society as a whole will likely still increase due to an order of magnitude difference in the spending increase and the monetized effects decrease. Additionally, if the lighting is applied in an urban area, the lighting has a positive effect on many people. While the overall effect is not per definition positive, it is more likely that lighting overall has a positive effect if more people can benefit. Compare this to lighting in a rural area where lighting, most likely, affects fewer people and more animals (negatively). In these rural areas, lighting (even intelligent) should, therefore, be given extra thought.

Samenvatting

Nederlandse gemeenten ervaren beperkingen bij de implementatie van (nieuwe energiebesparende) openbare verlichting. Door deze beperkingen zullen de energiedoelstellingen op het gebied van openbare verlichting waarschijnlijk niet worden gehaald. De ervaren beperkingen die met literatuur kunnen worden gefalsificeerd, zijn een gebrek aan geld, het niet de moeite waard vinden van de innovatie, en mogelijk maatschappelijk verzet. De resterende beperkingen voor de implementatie die met onderzoek kunnen worden gefalsificeerd zijn een gebrek aan tijd en nog niet afgeschreven middelen. De resterende beperking, gesplitste budgettaire stromen, kan niet worden weerlegd met literatuur omdat het een beleidskeuze is.

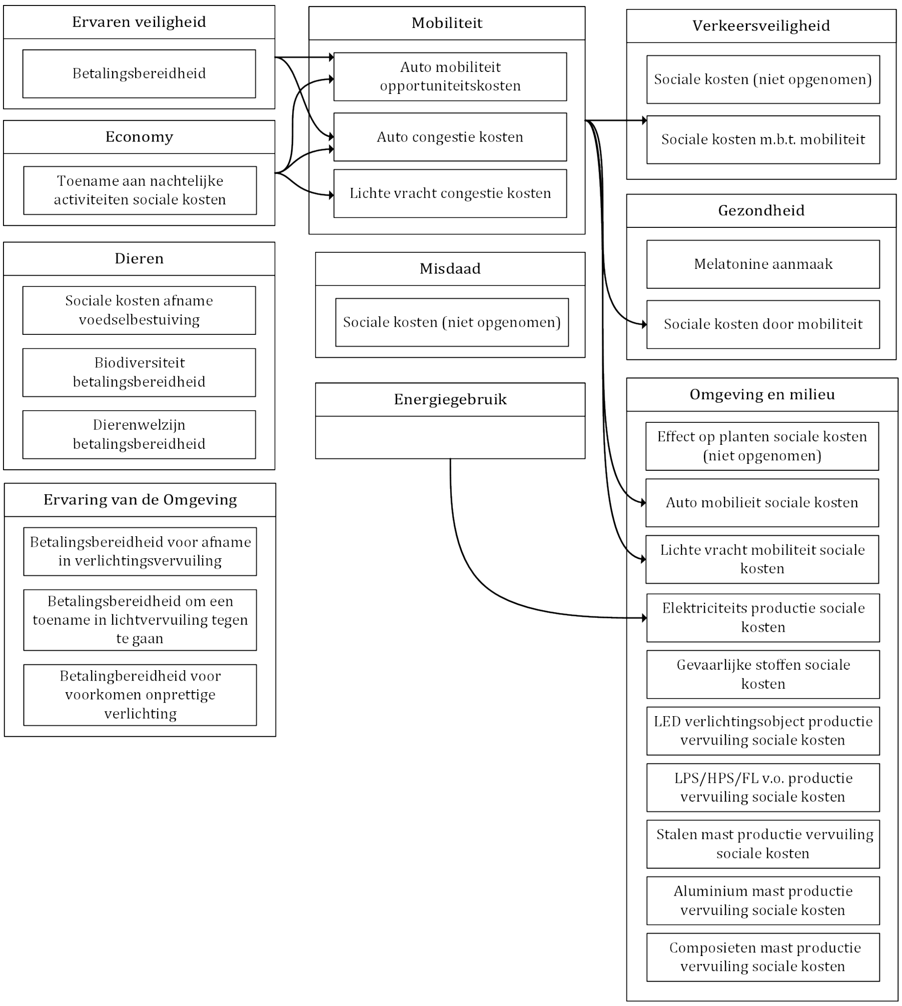
Om gemeenten te helpen bij het weghalen van de resterende beperkingen die met onderzoek kunnen worden gefalsificeerd, wordt voorgesteld om een (tijdbesparende en transparante) beslissingsondersteunend systeem (DSS) te maken met betrekking tot de implementatie van Light Emitting Diodes (LED's) met of zonder intelligente besturing bij het vervangen van afgeschreven en nog niet afgeschreven openbare verlichting. Om de tijdwinst te maximaliseren, zal een Maatschappelijke Kosten-Batenanalyse (MKBA) worden gebruikt (wordt meer gebuikt door de Nederlandse overheid) als de beslissingsmethode in de DSS. Aangezien er vereist wordt dat er een DSS wordt gemaakt om het gebrek aan tijd waarmee gemeenten worden geconfronteerd, tegen te gaan, zou de onderzoeksvraag niet beantwoord moeten kunnen worden zonder een DSS. Dit leidt tot de volgende onderzoeksvraag:

Onder welke omstandigheden kan (intelligente) LED openbare verlichting (nog niet) afgeschreven openbare verlichting vervangen volgens een MKBA?



Figuur 3: DSS stuctuur

Innovatief werk wordt geleverd door het beantwoorden van deze onderzoeksvraag, aangezien er momenteel geen DSS met MKBA-methoden in de context van openbare verlichting bestaat die deze vraag kan beantwoorden. Een MKBA geïmplementeerd in een DSS voor openbare verlichting is in het verleden niet tot stand gekomen vanwege een gebrek aan intresse, een gebrek aan publiceerbare wetenschappelijke gegevens die daarmee kunnen worden verzameld, en omdat de organisaties die openbare verlichting beheren zo kleinschalig zijn, dat het uitvoeren van een MKBA vanuit een kostenperspectief (en het implementeren ervan in een DSS) niet als zinvol wordt ervaren. Dit laat de bedrijven die openbare verlichting maken, studenten en publiek gefinancierde onderzoeksbureaus zoals TNO of the Institute for Highway Safety over om het onderzoek uit te voeren. De bedrijven die openbare verlichting maken hebben een duidelijk belangenconflict en zou geen resultaten publiceren waarin staat dat de openbare verlichting moet worden verminderd. Studenten kunnen dergelijk onderzoek doen, maar de resultaten worden waarschijnlijk niet openbaar gepubliceerd en/of kunnen niet worden gevonden. Publiek gefinancierde onderzoeksbureaus zijn er (nog) niet aan toe toegekomen om hiervoor een MKBA DSS te maken.



Figuur 4: De in de DSS opgenomen effecten en relaties tussen deze effecten

De DSS die in deze master afstudeerscriptie is gemaakt[2], is geïmplementeerd in een spreadsheetprogramma, de componenten zijn verdeeld over verschillende bladen in een werkmapbestand. In Figuur 3 is een overzicht van de werkbladen en hun respectievelijke functies in de DSS te zien. De MKBA wordt uitgevoerd in het modelonderdeel. De DSS heeft als doel de Netto Contante Waarde (NCW)(, energieverbruik of NCW met X% energiebesparing) voor een bepaald gebied te optimaliseren. De NCW wordt gebruikt als optimalisatiedoel omdat MKBA dit vereist en aangezien het minimaliseren van kosten de beleidsdoelen van gemeenten zijn. De NCW is de huidige waarde van een toekomstige uitgave/opbrengst. De

[2]De DSS kan worden gedownload op: *https://1drv.ms/x/s!AnVbYLjK815OoSCTA51sOo5GlCrR?e=YaNo7N*

DSS optimaliseert welke masten, armaturen en lampen moeten worden gebruikt, wanneer ze moeten worden geïnstalleerd en wat de onderhoudsintervallen moeten zijn om het doel te bereiken. Deze geoptimaliseerde resultaten vormen de interventiescenario's. Het scenario zonder ingrijpen is het huidige beleid binnen een gebied.

De opgenomen kosten en effecten in de DSS (opgenomen in het databank onderdeel) zullen nu verder worden besproken. In Figuur 4 zijn de gevonden effecten en relaties tussen de verschillende opgenomen effecten te zien. Zoals te zien is, zijn er directe en indirecte effecten. De opgenomen kosten in de DSS (niet te zien in Figuur 4) zijn de kosten van de elektra, masten, armaturen, lichtbronnen, plaatsing en het onderhoud. De onderhoudskosten zijn inclusief kosten als gevolg van storingen. De storingsintervallen wordt bepaald met aparte Weibull-functies voor de componenten op basis van storingsgegevens van de gemeente Nuenen.

Omdat niet alle mogelijke omstandigheden (uit de onderzoeksvraag) in een verslag kunnen worden opgenomen, is de DSS getest op een aantal omstandigheden in casus. In de casus zijn drie gebieden in de gemeente Nuenen opgenomen met verschillende typen nog niet afgeschreven verlichtingssystemen (hoge druk natrium (HPS), lage druk natrium (LPS) en LED). De DSS wordt uitgevoerd met een aantal instellingen. De eerste instelling is het uitvoeren van de DSS voor wereldwijde kosten en baten en wereldwijd verlichtingsbeleid (EGG). De tweede instelling is het uitvoeren van de DSS voor wereldwijde kosten en baten met een lokaal verlichtingsbeleid (gebonden aan het gebied) (EGL). Ten derde worden de grenzen van de kosten en baten van DSS gesteld op lokale (gemeentelijke grenzen) (ELL). Ten vierde worden alle effecten uitgeschakeld, waardoor een kostenanalyse ontstaat (voor gemeentelijke kostengrenzen) (CLL).

Een overzicht van de resultaten die nodig zijn om de onderzoeksvraag te beantwoorden is te zien in Tabel 3 en 4. In Tabel 3 is te zien welk verlichtingstype de hoogste NCW heeft volgens de verschillende instellingen. Daarnaast wordt de lichttechniek met het laagste stroomverbruik gegeven. In Tabel 4 staan de vervangingsdata van de bestaande armaturen met de hoogste NCW's. Bij het interpreteren van deze resultaten moet er rekening mee worden gehouden dat er ernstige beperkingen in de DSS zitten. Dit betekent dat in de toekomst, wanneer deze zijn verholpen, de resultaten waarschijnlijk zullen veranderen.

Tabel 3: Armaturen met de hoogste NCW

Instelling\Gebied	**LED**	**HPS**	**FL**
EGG	LPS	LPS	LPS
EGL	LPS	LPS	LPS
ELL	LED Statisch	LED Statisch	LED Statisch
CLL	LED Statisch	LED Statisch	LED Statisch
Laagste energieverbruik	LED Intelligent	LED Statisch	LED Intelligent

Tabel 4: Vervangings jaren voor de armaturen met de hoogste NCW

Instelling\Gebied	**LED**	**HPS**	**FL**
EGG	2039	2035	2035
EGL	2039	2035	2035
ELL	2039	2031	2033
CLL	2039	2031	2033
Basis	2036	2033	2033

Aan de hand van de samengevoegde resultaten worden conclusies getrokken om een zo goed mogelijk antwoord te kunnen geven op de onderzoeksvraag. Concluderend, intelligente verlichting is de extra kosten waarschijnlijk niet waard. Wanneer rekening wordt gehouden met wereldwijde effecten, kunnen verlichtingssystemen waarschijnlijk niet worden vervangen door efficiëntere LED-verlichtingsoplossingen, vanwege hogere milieukosten, volgens de momenteel geïmplementeerde DSS. Als alleen rekening wordt gehouden met lokale effecten, kan het vervangen van het huidige (minder efficiënte) verlichtingssysteem door efficiëntere systemen, voordat het huidige systeem wordt afgeschreven, resulteren in een hogere NCW als het efficiëntieverschil en de lichtbehoefte groot genoeg zijn.

Zoals reeds vermeld zijn beperkingen van invloed op deze conclusies. Deze beperkingen zijn dat sommige effecten niet goed zijn gekwantificeerd, dat sommige effecten momenteel niet bekend zijn, dat verlichtingsspecificaties niet worden gebruikt bij het berekenen van de impact van de effecten, dat er slechts één technologie-switch is geïmplementeerd, dat er momenteel geen nauwkeurige risico-inschatting bestaat, en dat de einddatum voor alle gevallen vastligt.

Daarom zijn de gegeven antwoorden op de onderzoeksvraag niet definitief. Om met zekerheid een antwoord te kunnen geven is meer onderzoek nodig en dienen de resultaten van dat onderzoek te worden geïmplementeerd in een MKBA. Wel kan op basis van de opgedane en nog niet eerder gecombineerde kennis een advies worden gegeven aan de uitvoerders van openbare verlichting.

De belangrijkste aanbeveling is, dat op basis van de (geschatte) effecten die voor openbare verlichting zijn gevonden, het beter is om kostengebaseerde besluitvorming niet te gebruiken. In plaats daarvan moet rekening worden gehouden met de maatschappelijke kosten en baten. Het resultaat van dit advies is om intelligent te dimmen als het de hoeveelheid kunstlicht 's nachts (ALAN) vermindert. Dit is het geval aangezien intelligent dimmen weinig tot geen negatieve effecten heeft, terwijl ALAN (ernstige) negatieve effecten heeft. Wanneer dit gebeurt, zullen de bestedingen waarschijnlijk toenemen, maar het welzijn van de samenleving als geheel zal waarschijnlijk toenemen als gevolg van een orde grootteverschil in de stijgende bestedingen en de afnemende gemonetariseerde effecten. Als de verlichting in een stedelijk gebied wordt toegepast, heeft de verlichting op veel mensen een positief effect. Hoewel het algehele effect niet per definitie positief is, is het waarschijnlijker dat verlichting in het algemeen een positief effect heeft als meer mensen hiervan kunnen profiteren. Vergelijk dit met verlichting in een landelijk gebied waar verlichting hoogstwaarschijnlijk minder mensen en meer dieren (negatief) treft. In deze landelijke gebieden moet daarom extra nagedacht worden over verlichting (zelfs intelligente verlichting).

Abstract

In this thesis, a Decision Support System[3] (DSS) is developed to investigate under which circumstances (intelligent) Light Emitting Diode (LED) public lighting can replace (not yet) depreciated public lighting according to a Dutch governmental format Social Cost-Benefit Analysis (SCBA). Included in the DSS are relevant costs and monetizable effects for public lighting. It answers the question of under which circumstances (intelligent) Light Emitting Diode (LED) public lighting can replace (not yet) depreciated public lighting, by maximizing lighting systems Net Present Value (NPV) under various circumstances and, therefore, recommend the type of lighting systems (poles, fixture, light source, dimming type), maintenance schedules, and placement dates to use. The NPV is the current value of a future expense/revenue. The alternative with the highest NPV is the best alternative according to a SCBA.

The DSS was tested for a set of circumstances in a case study. In the case study, three areas in the municipality of Nuenen with different types of not yet depreciated lighting systems (High Pressure Sodium (HPS), Low Pressure Sodium (LPS), and LED) were tested. For none of the areas included did intelligent LED public lighting have the highest NPV. The fact that intelligent LED lighting is not the best lighting option is probably the case because most effects in the SCBA are not dependent on lighting and intelligent dimming does likely affects the associated effects positively.

To resolve the issue of the exclusion of light dependence for these effects, additional research into (quantifying and monetizing) the effects of public lighting is needed. This research should also cover the effects of different spectra and intensities of light. Furthermore, for creating a reliable SCBA risk analysis, it is of importance to also investigate the probability densities of these effects and their sensitivity to macroeconomic developments. Meanwhile, it is recommended for road authorities to place intelligent LED lighting if this reduces the amount of light emitted since for intelligent dimming no negative effects were found and the cost increase is two orders of magnitude smaller than the monetized negative effects for Artificial Light At Night (ALAN).

Keywords:
Public lighting, Intelligent lighting, Social Cost-Benefit Analysis, Decision Support System, Maatschappelijke Kosten-Batenanalyse

[3]The DSS can be downloaded from: *https://1drv.ms/x/s!AnVbYLjK815OoSCTA51sOo5GlCrR?e=YaNo7N*

List of abbreviations

ALAN	Artificial Light At Night
CAPEX	Capital expenses
CBA	Cost-Based Analysis
CEA	Cost-Effectiveness Analysis
CLL	CBA for local costs and benefits and local lighting policy
DSS	Decision Support System
EGG	Effect (and cost) based analysis for global costs and benefits and global lighting policy
EGL	Effect (and cost) based analysis for global costs and benefits and local lighting policy
ELL	Effect (and cost) based analysis for local costs and benefits and local lighting policy
FL	Fluorescent
HPS	High Pressure Sodium
LED	Light Emitting Diode
LPS	Low Pressure Sodium
MCA	Multiple-Criteria Analysis
MH	Metal Hydrite
MKBA	Maatschappelijke Kosten-Batenanalyse
NCW	Netto Contante Waarde
NPV	Net Present Value
OPEX	Operational expenses
SCBA	Social Cost-Benefit Analysis
VBA	Visual Basic for Applications

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Chapter 1

Introduction

Public lighting has existed since the Roman age (Luckiesh, 1920). The first known recorded instance is from the 4th century in the city of Antioch (Luckiesh, 1920). Despite this old age, the development of public lighting has continued throughout the ages and is still ongoing. The first major revolution was the invention of the 'van der Heyden' oil lamp in the late 17th century due to reduced cost and increased light production (Lintsen, 1993). Another major revolution was the invention of the electric arc lamp two centuries later and the incandescent lamp slightly thereafter (Korporaal, 2006), (Reedijk, 1993). The latter two were major revolutions since the (electric) light sources did not need individual lighting by a person (Korporaal, 2006), (Luckiesh, 1920). Since then, these early electric lamps have been replaced with more efficient and longer lifespan gas discharge lamps and fluorescent lamps (Korporaal, 2006), (Reedijk, 1993). These technologies are still used today in combination with Light Emitting Diodes (LEDs) (Reedijk, 1993), (HeiSolar, n.d.).

Currently, public lighting may be on the verge of yet another revolution. This could be the case since according to the Energieakkoord, the total reduction in energy usage of public lighting should be 20% by 2020 compared to 2013 in the Netherlands (van den Elshout, 2018), (Gemeente Ridderkerk, 2018). However, in 2018 only 4.7% was reached (van den Elshout, 2018). While this data is slightly out of date, one can imagine that the goal was not reached, and to achieve the 2030 goal of 50% (energy reduction compared to 2013) large-scale intervention is needed. This in turn means that another large-scale technology shift may be needed. The technologies that are destined for this power-saving revolution are intelligent public lighting and LEDs (Signify, 2018).

1.1 Research problem

As already mentioned previously in the introduction, the 2020 goals in the Energieakkoord are most likely not reached and large-scale interventions are required to reach the 2030 goal. Signify, formerly Philips Lighting, performed a study in 2018 among Dutch municipalities and found that only 15% to 17% of municipalities were implementing LED (not per definition intelligent) lighting on a large scale (Signify, 2018). This is of special relevance since in 2016 municipalities in the Netherlands controlled 94% of the countries total public lighting (Rijkswaterstaat, 2016).

The study by Signify also reported the reasons for the lack of implementation according to the people responsible for lighting within municipalities. (Signify, 2018). The reasons for a lack of implementation that were stated are:

- 1. A perceived lack of funds (reported by 47% of the respondents);
- 2. Some perceive the innovation not as worthwhile (little cost/energy savings);

- 3. Fear of potential civil backlash to LEDs;
- 4. Separate budget streams for maintenance and placement;
- 5. A perceived lack of time;
- 6. Not yet depreciated assets.

A perceived lack of funds (1) can be refuted with literature. There are case studies available that point out that the overall cost of operation is reduced. These (cost-reducing) case studies have been performed by researchers (Cacciatore et al., 2017), (RIVM, 2009) as well as by the industry (TVI, n.d.). These case studies might not hold for all circumstances, however.

The same case studies also suggest that the innovations are worthwhile (2) due to the energy and (long-term) cost-saving potential. Again these conclusions might not hold for all circumstances

While public backlash cannot be ruled out (3), the found complaints are mainly because of LED public lighting's cold color profile (Vohra, 2014), (LEDinside, 2017). Negative health and safety effects were also found for cooler color profiles when compared to more traditional warmer public lighting (American Medical Association, 2016), (US department of Energy, 2017). This is mainly due to the reduction of melatonin production and the increased glare of blue light respectively (American Medical Association, 2016), (US department of Energy, 2017). However, this is a non-issue since the lighting profile of traditional lights can be closely matched with LED (RIVM, 2009), (US department of Energy, 2017). It is, therefore, not a problem caused by LEDs but rather the implementation of (LED) public lighting. Potentially occurring public backlash concerning the safety of intelligent lighting is also unjustified since the safety does not have to decrease with intelligent lighting (United States Department Of Transportation, 2014). This occurs because when fewer road users are present less lighting is required (United States Department Of Transportation, 2014). Furthermore, if no traffic is present, lighting can of course be reduced safely.

Split budgetary streams (4) cannot be refuted with literature since it is a governmental choice.

No literature regarding not yet depreciated assets (5) was found. Whilst one can never be certain that it does not exist, an extensive search was conducted through literature databases (the exact method can be seen in Appendix A).

The experienced boundary concerning limited time (6) may always remain valid. However, the validity of this claim can be reduced if a usable Decision Support System (DSS) relating to the retrofitting of public lighting exists. A DSS is a computerized system that collects and analyzes data, then combines it to produce useful information (Segal, 2020). Most organizations or businesses use some sort of DSS to compare the advantages and disadvantages of the different alternatives (Segal, 2020). To check whether or not a DSS for the topic of public lighting retrofitting exists, a similar search was performed as for the former point. No results including depreciation and intelligent lighting were found, the details can be seen in Section 2.1.

As already mentioned, no relevant literature was found that falsifies the claim regarding not yet depreciated assets and that helps with reducing the time required for the implementation. This means that these may indeed be valid counterarguments for LEDs and intelligent public lighting implementation. However, since the argument regarding the replacement of not yet depreciated assets was not found to be investigated (as seen in Section 2.1), it can still be falsified. If this information is included in some sort of DSS then the resulting DSS can answer the question if not yet depreciated assets can be replaced while also reducing the time investment needed from municipalities (or other implementers of public lighting). This DSS can also answer the question of whether or not the innovation is worthwhile for any case. To make sure that the DSS saves as much time as possible during the preparatory phases of a potential project for the Dutch municipalities, a Dutch governmental evaluation technique will be followed within the DSS.

The Planbureau voor de Leefomgeving and the Centraal Planbureau have a manual available on how to make a Dutch governmental format Social Cost-Benefit Analysis (SCBA) (NL: Maatschappelijke Kosten-Batenanalyse (MKBA)) (CPB & PBVL, 2013). SCBA is an evaluation technique that aims to estimate the impact of a project/policy on societal wealth by summing the Net Present Value (NPV) for the costs and monetized effects (MKBA-informatie.nl, n.d.). The NPV is today's value of a future stream of costs/revenues (Fernando, n.d.) (See Subsection 3.2.1 for the required calculations).

For infrastructure projects, the majority of the people questioned in Mouter et al. (2012) find SCBA the best evaluation technique compared to Multiple-Criteria Analysis (MCA) and Cost-Effectiveness Analysis (CEA). Furthermore, it is recommended to use SCBA, when external effects are occurring, due to a policy choice/implementation (Koopmans & Hof, 2014). External effects most certainly occur for public lighting as can be read in Section 5.2. SCBA also has a strong foundation in economic theory and has a nonsubjective approach (Koopmans & Hof, 2014). This allows for better consideration of a project and getting insight into the order of magnitude of different effects in one unit.

Aside from the benefits of SCBA, there are also drawbacks to SCBA. Mouter et al. (2012) questioned practitioners and recipients of Dutch governmental format SCBA analyses about their perception of the advantages and disadvantages of the method. The main perceived disadvantage is that there is an inherent limitation in a SCBA regarding the values and wealth effects which can in practice only be included to a limited extent. Other mentioned disadvantages found by Mouter et al. (2012), are that the results of a SCBA are unsure and, therefore, disputable and that the limitations are often not disclosed properly. Therefore, the SCBA is seen as too powerful by people not aware of the limitations. When people are aware of the limitations they are, however, often distrusting of the results. CPB & PBVL (2013) mention additional limitations and points of critique. The main issue here is the morality of SCBA. For instance, it was argued in Dworkin (1979), that slavery can have a net positive wealth effect according to SCBA. The SCBA utilitarian view on society is, therefore, often critiqued when used in situations relating to safety or moral questions. Furthermore, there is the question of, for instance, a criminal's bounty should count as a benefit. Another issue is that people are generally terrible at assigning value to effects. In reality, they often increase the WTP for a negative effect if the effect occurs (Boardman et al., 2018). Additionally, Boardman et al. (2018) mentions that the quality of a SCBA is highly dependent on the quality of its conduction. However, even properly executed SCBAs can have rated the same projects completely different due to different choices in the quantification and monetization steps. Additionally, the goal of society might not always be to maximize efficiency. A problem with the implementation of SCBAs is that it is common to use a SCBA as verification for an already made decision (Rienstra, 2008). Aside from the fact that optimization is no longer possible, this also means that canceling a project might be necessary (Rienstra, 2008). However, this is often not done (Rienstra, 2008), the exception is if the effects are very negative Mouter (2016). Due to this, the results of a SCBA are often painted as untrustworthy/biased by the people behind a non-profitable project.

These points lead to boundaries in the application and usefulness of neutral and "good" SCBA results (Rienstra, 2008) (Mouter, 2016). To take away these boundaries several recommendations on the conduction of SCBAs can be given. These will be followed to the best possible extend in this thesis. The recommendations are that the calculations and data sources need to be more transparent and shared (Mouter, 2016). Furthermore, SCBAs need to be conducted in early phases of projects and published as soon as possible. This gives additional time for discussion of the results and to use SCBAs for optimization instead of go/no go decisions (Rienstra, 2008) (Mouter, 2016).

There are also practical limitations concerning SCBAs. The main reason not to conduct a SCBA in most cases is when it is perceived as not cost-effective or if the paid-for results will not be useful due to limited quantifiable and monetizable effects (Boardman et al., 2018). However, since this is a thesis, this is not an issue since the cost is relatively low.

Since the recommendations will be followed, the cost is low, and it is the best alternative for infrastructure projects, it is argued that a Dutch governmental format SCBA is the right decision analysis model for analyzing public lighting in the, to be made, DSS. If the SCBA analyses cannot be fully completed at this time, partial results should give novel results and can serve as an incentive for future research (limitations of the implemented DSS can be seen in Section 9.1). For these reasons, SCBA is deemed suitable for this project and is, therefore, used.

On a side note, the SCBA method explained in CPB & PBVL (2013) is interpreted, in this report, as a type of SCBA. While MKBA is a literal translation of SCBA, this is done since there are some differences. In Appendix B, these differences are pointed out. To clarify, in the remainder of the report, when SCBA is mentioned this includes MKBA, but when a Dutch governmental format SCBA is mentioned this is specific to MKBA.

To summarize, the problem is that municipalities experience boundaries concerning the implementation of (new power-saving) public lighting. Due to a lack of structuring of information, these boundaries cannot be overcome. Due to these boundaries, energy goals concerning public lighting will likely not be reached. The valid boundaries to implementation found in this introduction are a lack of time and not yet depreciated assets. To help municipalities in alleviating both these boundaries, it is proposed that a (time-saving and transparent) DSS is made regarding the implementation of LEDs with or without intelligent control in replacing depreciated and not yet depreciated public lighting. To maximize the time savings, a Dutch governmental format SCBA will be followed. Since it is required that a DSS is made to solve the problem encountered by municipalities, the research question should not be answerable without a DSS. This leads to the following (wide) research question:

Under which circumstances can (intelligent) LED public lighting replace (not yet) depreciated public lighting according to a Dutch governmental format SCBA?

1.2 Research design

Since the research question includes the Dutch governmental format SCBA structure, the research design follows the eight steps listed in the manual of CPB & PBVL (2013). The first step listed in the manual is to analyze the problem and make sure that the problem is relevant. As can be read in the previous section, the problem is defined and it is relevant concerning missing the energy goals for public lighting. One might argue about the severity of not reaching the energy goals or the usefulness of public lighting. This will, however, not be investigated beyond what can be seen when interpreting the DSS results (Section 9.2) to not make the research topic even wider. Therefore, the research will start at step 2. However, before this is done, a question needs to be answered that does not relate to the Dutch governmental format SCBA. This is a question concerning the adaptable DSS that needs to be made. This is the following question:

- 1: How should the DSS, in which the different effects, costs, risks, and situations are to be implemented, be made?

If this question is answered, the answers gathered and calculations required in the following steps can be implemented within the boundaries of the DSS and thus result in a DSS that can answer the main research question for different circumstances.

Step 2 is where the scenario without intervention (current situation) is analyzed (CPB & PBVL, 2013). In step 3, the possible alternatives for intervention need to be identified (CPB & PBVL, 2013). However, since the DSS is meant to be applicable in more than one municipality/area, the scenarios should not be limited to one type of public lighting system but should instead be kept variable. This means in practice that a selection of public lighting systems and policies needs to be identified with the option to add more by the user. These public lighting systems should then be applicable in the DSS in any number of combinations and quantities. The identified public lighting systems and situations also define the range of circumstances for which the main research question can be answered within the DSS. Step 2 and 3 can be performed by answering the following questions respectively:

- 2.1: What types of public lighting systems are currently installed?
- 2.2: What are likely policies without intervention (current situations)?
- 3.1: What types of public lighting systems are currently available?
- 3.2: What are likely intervention policies (future situations)?

In step 4 of a Dutch governmental format SCBA, the effects of the alternatives need to be identified, estimated, quantified, and monetized (CPB & PBVL, 2013). To do this, the following research questions have been created.

- 4.1: What are the effects of public lighting?
- 4.2: How can these effects be quantified?
- 4.3: What are the boundaries (areas of effect) for these effects?
- 4.4: How can these effects be monetized?
- 4.5: What are the monetized effects of the current and available lighting systems?

In step 5 the costs of the different public lighting systems need to be identified (CPB & PBVL, 2013). This step can be performed by answering the following research question.

- 5: What are the costs for the current and available public lighting systems?

After this step, a sensitivity and risk analysis need to be performed (step 6) (CPB & PBVL, 2013). To investigate the possible risks, they need to be identified, and a suitable method of analysis needs to be found. To do so, the following research questions need to be answered:

- 6.1: What is a suitable method for assessing risks in SCBA?
- 6.2: What are the risks for the costs and benefits according to the selected method?

The remaining steps are making an overview of the costs and benefits (per situation) (step 7) and presenting the results (step 8) (CPB & PBVL, 2013). No further questions are required to perform these steps since they only present already investigated material according to a prescribed method.

1.3 Collaboration

Since the DSS will be capable of answering the main research question for an almost unlimited number of circumstances all results cannot be included in a report. Therefore example area(s), that defines the circumstances is/are needed to present results in the report. This means that the report will only give a partial answer to the main research question, while the provided DSS can be used to answer the research question for all circumstances. It was chosen to use a real-world area since having a real-world application allows for the gathering of realistic and potentially reusable data. The municipality of Nuenen was chosen and contacted due to their experience with and data concerning intelligent lighting (since 2013) (TVI, n.d.). They have granted access to their data concerning public lighting for this project. The information that is shared includes but is not limited to financial data, energy usage data, and placement data. They are willing to share this information since it is not (privacy) sensitive. In return for their cooperation, the municipality of Nuenen will co-define the cases and get the results of the analyses.

1.4 Methods for sub-questions

The methods used and research types required for answering the individual sub-questions are discussed in this subsection.

1.4.1 Sub-question 1: The DSS

Sub-question 1 states how the different effects, costs, risks, and situations should be implemented and combined in a DSS. This question can be answered by looking at potential programming alternatives, their accessibility, ease of use, and more. The answer to this question should, however, not only take into account the author's skills and possibilities but also the skills and possibilities of a potential user of the software, in this case, a road authority employee. Furthermore, the implementation should be logical, therefore, literature research is conducted on DSS theory. The literature research regarding DSS theory is covered in Section 3.1. The implementation is covered in Section 3.2.

1.4.2 Sub-question 2.1 and 3.1: Lighting systems

For sub-questions 2.1 and 3.1, the installed and available lighting systems should be identified. This will be done by looking at the data provided by the case provider. This includes the data about current installations, but also possible alternatives in tender documents. Alternatively, (or complementary) specification websites can be used. The current and available lighting systems can be seen in Section 4.1.

1.4.3 Sub-question 2.2 and 3.2: Policies

Sub-questions 2.2 and 3.2 consist of defining the scenarios. It will, however, not be set beforehand what type of lighting systems will be used. Instead, the policy goals will be set and the lighting systems will be determined accordingly. This is done to keep the DSS usable for as many road authorities as possible. The scenarios will be a product of optimization based on policy goals. Current policy and policy goals can be identified by/with a road authority or be taken from literature. In this case, they were identified by analyzing multiple municipal policy documents. This can be seen in Subsection 4.3.1. The implementation in the DSS can be seen in Subsection 4.3.2.

1.4.4 Sub-question 4.1 - 4.5: Effects

Sub-questions 4.1 will require a literature review since it requires determining the effects of public lighting. Sub-questions 4.2-4.5 the quantification and monetization of the found effects. While this requires additional literature, quantification and monetization also require assumptions. Therefore, quantification and monetization are covered separately from identifying the effects. The effects are identified in Section 5.1 (sub-questions 4.1). The quantification and monetization (sub-question 4.2-4.5) are covered in Section 5.2. The quantification and monetization will be implemented within the developed application/model and be variable based on the specifications of the systems. If it is done this way, the results will remain variable and the DSS will thus remain universally applicable and able to answer the research question.

1.4.5 Sub-question 5: Costs (of lighting systems)

Sub-questions 5 will be answered by identifying the cost of individual lighting systems. This will again be done by looking at the data provided by the municipality (and third-party sellers). This will include maintenance and financial data about current installations, but also possible alternatives in tender documents. Then based on these costs, the cost of the different policies can be calculated in the DSS. This is covered in Section 4.2 of the thesis.

1.4.6 Sub-question 6: Risks

For sub-question 6.1 (regarding risks) CPB & PBVL (2013) and Boardman et al. (2018) give a couple of alternatives. These will be elaborated upon in the literature review (Section 6.1). Sub-question 6.2 can then be answered by implementing the chosen method in the developed DSS (Section 6.2).

1.5 Relevance of the thesis

In this section, it is discussed why this thesis is relevant from a societal and a scientific perspective.

1.5.1 Societal relevance

The DSS that will be made can provide municipalities and other road authorities insight into what type of lighting to place according to an (S)CBA analysis. This is of societal relevance since it makes maximizing the wealth public lighting provides possible. This is, however, only possible accurately if all costs and effects can be identified, quantified, and monetized correctly. If this is not possible for this thesis, the work is still of societal relevance since it could lead to valuable insights or promote further research so that, in time, an accurate DSS using (S)CBA as its decision analysis model can be realized.

1.5.2 Scientific relevance

The work conducted in this thesis is of scientific relevance since a previously not investigated topic will be researched (not yet depreciated public lighting), and a new DSS system will be realized. Furthermore, as can be read in Section 2.1, it is the first time it is attempted to create and implement a DSS using SCBA as its decision analysis model for public lighting. Even if this thesis does not fully succeed in identifying, quantifying, and monetizing the relevant costs and effects it might still provide relevant insights based on what is implemented. These insights might also encourage further research.

1.6 Reading guide

The structure of this report is non-typical for a scientific report because a Dutch governmental format SCBA was chosen as the method, and this method has a prescribed format. This prescribed format is mostly respected (except for the fact that cost is covered before the effects and scenarios). That this structure is followed has the effect that far from all of the literature research performed for this thesis is covered in the literature review. This is preferred since this way all relevant information regarding answering a sub-question is contained within the relevant chapter and not all the literature would be included in the literature review anyway due to the combination of literature and assumptions required for quantifying and monetizing the effects (sub-question 4.2-4.5).

First, a literature review is presented. In this review, previous DSS and (S)CBA works in the context of public lighting will be covered. Second, the framework of the DSS is explained. This will be done by answering sub-question 1 as posed in this introduction. Third, the current situation will be covered including costs and policies. Thereby sub-questions 2.1-3.1 and 5 are answered. Fourth, the effects are covered. To do so, it will be investigated what effects to include (sub-question 4.1) before sub-questions 4.2-4.5 are answered (resulting in monetized effects). Fifth, it is discussed how to perform a risk analysis in a SCBA and how this is done in this thesis. Sixth, the developed, (general) DSS will be tested using a couple of cases (areas in Nuenen). The last two chapters are the conclusions and the discussion respectively. In the conclusion, the main research question is answered. In the discussion, the limitations of the thesis are discussed along with the recommendations for future research and road authorities.

Chapter 2

Literature review

In this chapter, prior work regarding Decision Support Systems (DSSs) and social cost-benefit analyses (SCBAs) for public lighting are investigated. This research is performed to make sure that the thesis builds upon existing work instead of redoing it and providing insight into the existing work. Second, since no existing SCBA DSS work exists, the reason for this will be investigated to try to understand why this work does not exist. Third, a summary of the two sections will be provided.

2.1 Prior work

Novel work is provided by this thesis if no existing work can be found that is useful as a DSS, can be used to answer the main research question, and is constructed according to the SCBA methodology. To check this, query searching for relevant scientific works will be done. Afterward, a search not limited to scientific publications will also be conducted. How both are done can be seen in Appendix A.

The relevant materials found regarding DSSs and SCBAs for public lighting will now be reviewed. This is done per paper/work instead of the conventional subject-based method since this way insight can be provided in the completeness of any one work as a SCBA DSS. In this structure, for every found piece of literature, the main conclusions are given, along with what the focus of these conclusions is, in what ways they followed the SCBA methodology, and what recommendations these works provide for future research. The literature found will also be checked for citations to additional relevant DSS or SCBA works within the context of public lighting. If any are found, these works will also be reviewed here.

Mahmoud (2018) investigates the replacement of High Pressure Sodium (HPS) light sources with Light Emitting Diodes (LED) using a "Typical Economic Model". This model takes the direct monetary benefits and costs into account from the perceptive of the utility company owning the light sources. Therefore, it includes factors such as the initial costs, power consumption, and maintenance. It does, however, not take the intelligent control, failures, or the remaining value of the old lights into account. The conclusion of this paper is to replace HPS lights + fixtures with LED lights + fixtures. Those are however not valid SCBA results since the study only takes the company cost and benefits into account. No DSS is given. No recommendations are given. No relevant SCBA/DSS citations regarding public lighting were given.

Perkins et al. (2015) covers a SCBA that is conducted on the reduction of public lighting (intensity). It deals with the effects of public lighting regarding personal security, road safety, crime, fear of crime, sleep quality, and ability to see the night sky. It does, however, not deal with the replacement of assets, only with the effects of existing assets and the effects of dimming or switching off these public lighting assets. This study found little evidence of harmful effects of switch-off, part-night lighting, dimming, or changes to white light/LEDs on levels of road traffic collisions or crime. However, some crime data were heterogeneous, this could indicate that the relationship is spurious and thus not identified correctly. More research is therefore needed regarding the lighting effects on crime. Furthermore, additional research is recommended regarding health impacts, since no results were found. Also, reduced mobility and fear of crime were not included in the SCBA. Furthermore, no additional relevant SCBA/DSS citations regarding public lighting were given and no DSS is provided.

U.S. Office of Energy Efficiency & Renewable Energy (2017) provides a DSS for the replacement of public lighting. No conclusions are drawn since no representative data is provided. It is, however, a good resource for knowing what factors are important in calculating the cost of public lighting, including the cost of intelligent lighting. This can be seen on the definitions page of the DSS. No additional costs/benefits can be taken into account, however. Nor is there the option to assign value to the to be replaced lighting system.

Meier et al. (2014) dedicates a chapter to performing a public lighting SCBA. However, due to a lack of available information, the SCBA is not conducted nor is there any practical advice given for road authorities regarding the (re)placement of public lighting. Instead, the importance of the SCBA in the context of public lighting is stressed. This means that it is of no use as a DSS and thus this thesis can still provide novel insights if it succeeds in answering the research question and creating a DSS. Furthermore, it states that "It should be noted from the beginning that accurate quantification of every effect of outdoor lighting is impossible. The relations and dependencies within and between the cost and benefit categories are immense and often unclear and do not allow for an economic review so far" (Meier et al., 2014). The authors also state: "The complexity of the topic, its impacts on various disciplines and the many relations and chain reactions of light and light pollution seem to be too complicated to be fully understood." (Meier et al., 2014). Despite this pessimism, it is believed by Meier et al. (2014) that quantifying and monetizing the effects is the only way of creating objectively better decisions regarding lighting solutions and state that in the future, lighting plans should incorporate the found costs and effects (Meier et al., 2014). Meier et al. (2014) believes that quantifying and monetizing the effects is best done by creating a breakdown of factors that may influence the effects. No additional relevant SCBA/DSS citations regarding public lighting were given.

2.2 Reason for a lack of public lighting research

As can be read in the previous subsection, this thesis will provide novel work if it succeeds in its goals. However, as can be read in the paper by Cacciatore et al. (2017), public lighting accounts for 19% of global energy consumption. This means that enormous amounts of funds are involved in the sector and potentially much wealth can be generated/saved by optimizing public lighting. Therefore, to understand why a SCBA DSS currently does not exist, the history of the field is elaborated upon.

The cost of lighting was decreasing for a long time (Roser, 2022). Furthermore, negative effects of public lighting were not considered until recently (e.g. (Marchant, 2017), (American Medical Association, 2016)), (Meier et al., 2014). This means that for the largest part of large-scale public lighting implementation the idea was that adding more lights would be better due to (problematic according to Marchant (2017)) research into the effects proving that more light would be beneficial. Due to decreasing cost of light (due to cheaper electricity and production advances (Roser, 2022)) there also was money in the budgets to do so. The idea that more lighting is better has only changed in recent years because climate change (or most other forms of pollution), is only the international agenda since late in the 20th century (UCAR, 2022). Furthermore, as already mentioned, negative effects of public lighting were not considered until recently (e.g. (Marchant, 2017), (American Medical Association, 2016)), (Meier et al., 2014). This means that only for the last few years, there has been any interest in the environmental impact of lighting and other negative effects. And as can be seen in the work by Meier et al. (2014) it has indeed been attempted to create such a SCBA that includes these effects and new power-saving lighting technology. However, as is also seen in the work by Meier et al. (2014), this attempt at creating a SCBA was not successful due to a lack of available information and a high degree of complexity. This means that it is currently not possible to look at a single piece of literature and find concrete evidence for the net effects of public lighting.

This uncertainty is combined with the fact that while the total amount of funds involved and wealth effects caused by public lighting is enormous, the effects and costs for individual owners of public lighting systems are limited. This is the case since the road authorities owning the public lighting systems are often municipalities (Rijkswaterstaat, 2016). With this in mind, the lack of research does align with one of the main reasons not to conduct a SCBA according to Boardman et al. (2018). Namely, conducting the SCBA is perceived as not cost-effective.

The creation of DSSs and SCBAs is also not done often by scientists due to their practical approaches and applications making it hard to publish results. This is the case since a SCBA often requires making many assumptions (considering what effects to include and how to perform the monetization) and is considered more of an art than an exact science (CPB & PBVL, 2013). The individual effects are, however, investigated by scientists (mostly in recent years) as can be seen in Section 5.1 and 5.2. This leaves manufacturers, who have a clear conflict of interest, students, whose work is unlikely to be published or indexed, and publicly funded research agencies, who have not gotten around to creating a SCBA DSS for this purpose (CBA is made (U.S. Office of Energy Efficiency & Renewable Energy, 2017)), to create an SCBA DSS for public lighting.

It should also be noted that SCBA DSSs are hard to find in general due to the stage of a project of which SCBAs are usually commissioned. It is common to use a SCBA as verification for an already made decision (Rienstra, 2008). This means that a SCBA DSS capable of optimization is no longer useful and thus not created.

2.3 Summary of literature review

To summarize, it can be said that this thesis will provide novel work if it succeeds in realizing its goals and providing an answer to the research questions. Novel work is provided since no DSS using SCBA methods in the context of public lighting currently exists. This view is also corroborated in Meier et al. (2014). A useful DSS is provided in United States Department Of Transportation (2014), however, this DSS does not include effects. Perkins et al. (2015) does include these effects, however, no DSS is provided.

A DSS using SCBA as its decision analysis model for public lighting has not been created in the past due to a lack of interest, a lack publishable scientific data that can be gathered using them, and because the organizations implementing public lighting are of such a small scale, that from a cost perspective, performing a SCBA (and implementing it into a DSS) is perceived not to make sense. This leaves the companies manufacturing public lighting, students, and publicly funded research agencies such as TNO or the Institute for Highway Safety to perform said research. Companies manufacturing public lighting have a clear conflict of interest and would not publish results that state that public lighting should be reduced. Students can perform such research but, likely, the results are not published publicly and/or cannot be found. Publicly funded research agencies have not gotten around to creating a SCBA DSS for this purpose.

Chapter 3

DSS theory and framework

In this chapter, the Decision Support System (DSS) theory and the used framework will be explained. This chapter will cover the information required to create DSS except for most of the data required for the database component. This information is covered in Chapter 4, 5, and 6 in the case of the generic reusable information and in Section 7.1 for the case specific information.

3.1 DSS theory

Sub-question 1 asks how the different social costs and benefits, operational costs, and policies should be implemented and combined in a DSS. Any DSS has four basic components according to Power (2002). Namely the database component, model component, communications component, and user interface component. These components and their relations can be seen in Figure 3.1. For this thesis, it is also relevant to know that due to the inclusion of Social Cost-Benefit Analysis (SCBA) in the model component, the DSS is a Model-driven DSS. For a model-driven DSS, it is recommended by Power (2002) to design it for one user on a local computer.

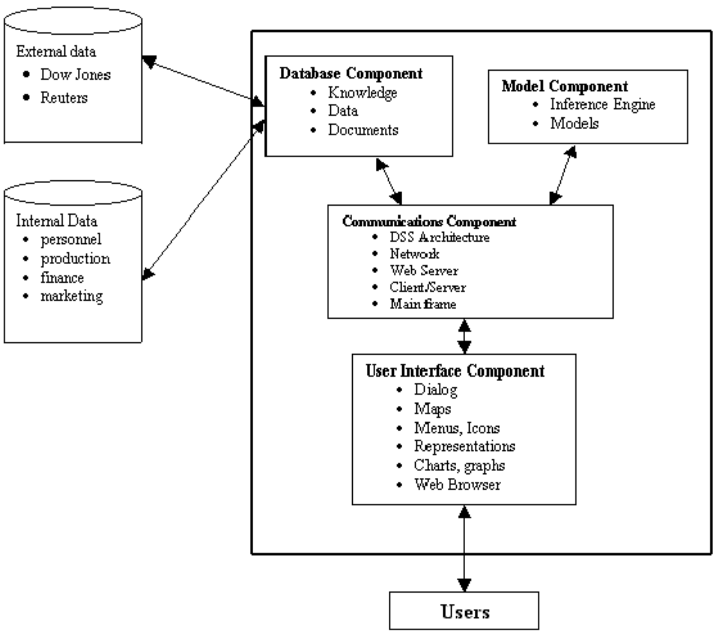

Figure 3.1: Different DSS components, (Power, 2002)

3.2 Construction of the DSS framework

In this section, the DSS components and structure will be explained to answer sub-question 1. The DSS is structured after Power (2002).

How the DSS should be made can be answered by analyzing user requirements (Power, 2002). The requirements of the user, in this case, are to be able to see when public lighting in a certain area should be replaced/maintained and what it should be replaced for based on various conditions. The user (road authority personnel) must be assumed not to be too technical (Power, 2002). Therefore, to keep the developed DSS as accessible as possible, while also being in an easy-to-understand, and in a much-used format, a spreadsheet file that is compatible with for instance Excel, LibreOffice, and OpenOffice is used to make the entire DSS in. This also aligns with the recommendation from Power (2002) to design the model-driven DSS for one user on a local computer.

Since it was decided to build the DSS in a spreadsheet program, the components (from Power (2002)) are divided among several sheets within a workbook file. Instead of covering all these component sheets as part of the user interface, these sheets will be covered in the pieces about their respective function as DSS components. In Figure 3.2, an overview of the sheets (in blue) and the other functions (grey) in the DSS can be seen. First, the model component (including the SCBA as the decision analysis model) will be discussed, then the database component, next the communications component, and finally the user interface component.

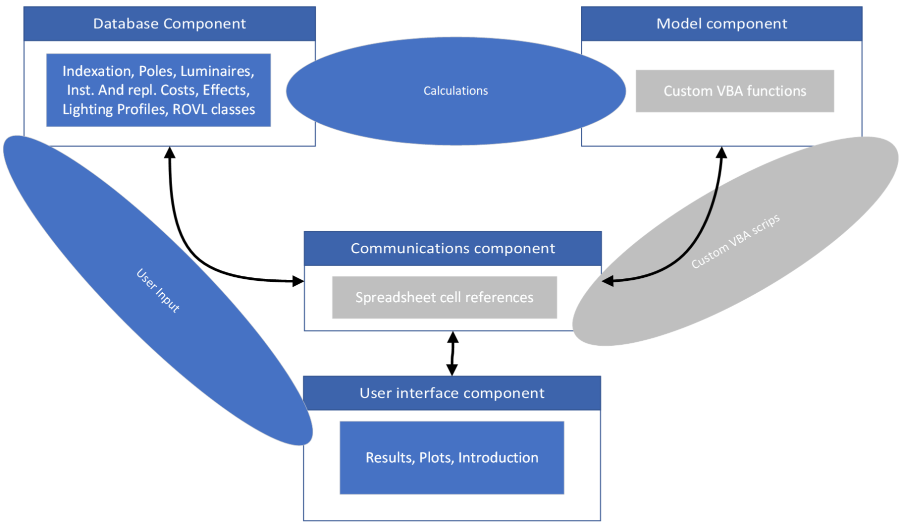

Figure 3.2: DSS structure from Power (2002) as it is implemented in this thesis.

3.2.1 Model component

The structure of the model component will now be discussed. For every part, it will also be discussed how this is implemented in the spreadsheet program. In Figure 3.3, a schematic representation of the model component can be seen. As can be seen, this structure is composed of various (sub)components. The main individual (sub)components and their interactions will now be discussed. Furthermore, some information will be given on how the nominal costs and nominal monetized effects are converted into the Net Present Value (NPV).

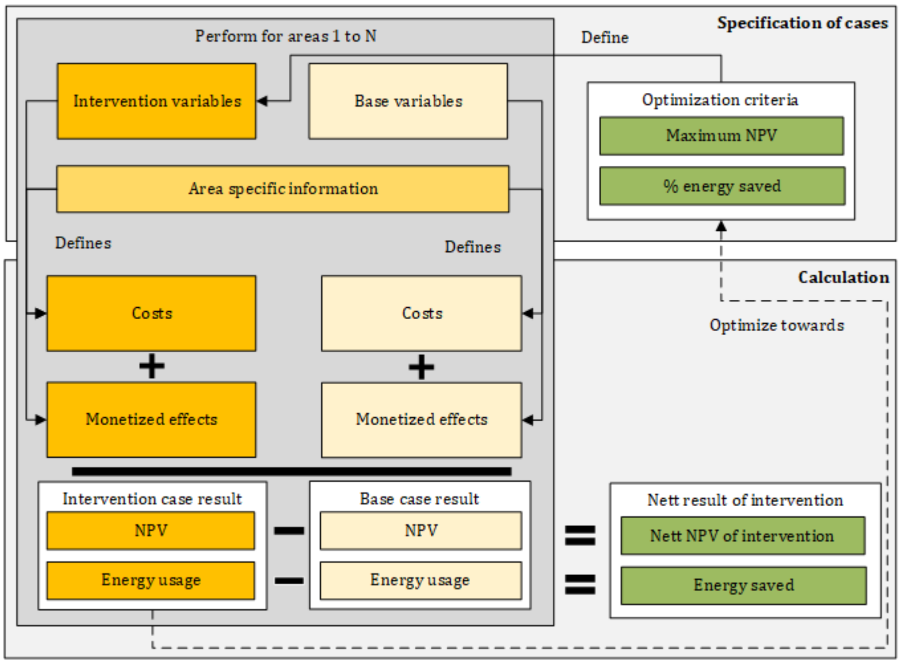

Figure 3.3: Model component structure

Specification of cases

Since the model uses discrete optimization to arrive at the goal of being able to tell the user when public lighting in a certain area should be replaced/maintained and with what lighting system it should be replaced, cases need to be specified. Case specifications consist of area specific information, such as what lighting system is present and how old this system is, and the intervention/base variables, such as when the lighting systems are to be replaced and for what system. In practice, this input is entered in the user interface component and transferred to the model component by the communications component. How this is structured, is, therefore, explained in the corresponding sections.

However, this is not the only part of the specifications of cases that needs explanation, as can be seen in Figure 3.3. It should also be explained that the optimization criteria define the intervention variables since in the DSS, to reach the goal of the optimization criteria (maximum NPV, % of energy saved), the intervention variables have to change. In practice, this change is performed by the model component within certain boundaries. These boundaries are calculated on the "calculations" Sheet. The intervention variables are bound by the base-case. This is the case since they center around the base variables. The amount they deviate can be set. This is done on the "Calculations" sheet (Cells K83-K93). Additional explanation on deviations is given in subsection 7.1.5.

Calculation

The calculation component of the model component works by calculating the NPV (and the energy usage) for all cases. It does so by adding the costs and the monetized effects. These costs and benefits are determined by the area specific information and the intervention variables.

All of the calculations performed to achieve a case result are present on the "calculations" sheet (with the help of custom Visual Basic for Applications (VBA) functions). To do so, the required data from the "User Input" sheet is copied (by a VBA script) to the calculations sheet. Then the calculations required to calculate the monetized effects and costs are performed.

These calculations are based on the research performed in the costs and effects found in Section 4.2 and 5.2. Below that the calculated capital expenses (CAPEX), operational expenses (OPEX), and monetized are given. Finally, these are summarized into the format given in Subsection 3.2.4. The knowledge required for the calculations is contained within the database component of the DSS. The data is retrieved by the communications component.

To be able to reach the optimization criteria goals, these calculations must be repeated for all of the cases. Furthermore, to calculate the net benefit, the base-case should also be calculated. To do so, custom VBA scripts were written that run the base-case and iterate over the set intervals for the intervention variables. VBA is a programming language found in spreadsheet programs such as LibreOffice Calc and Microsoft Excel. It can be used to automate tasks. After every case is run, the VBA scripts check if the current intervention case is an improvement for any of the optimization criteria. The results that exceed the current "best" case saved for an optimization criteria are saved (in the "Results" sheet). This is done until every possible case (within the set boundaries) has been calculated and the intervention variables needed for best matching a policy goal are known.

Perform for area 1 to N

The perform for area 1 to N rectangle is present to visualize the fact that the DSS cannot just optimize the public lighting according to a policy goal for one area, but instead, this can be done for multiple areas (as many can be entered before the spreadsheet program runs out of columns). In practice, the iteration over the areas is done by another VBA script. Once completed, the best results for all areas and optimization criteria can be seen on the "results" sheet (part of the user interface component).

Transforming nominal value into NPV

The optimization criteria for a SCBA is the NPV. Therefore, the method to calculate the NPV is included here in the explanation of the model component. The DSS can also calculate energy usage. However, since this is not required by SCBA theory and requires more background knowledge this is discussed in Subsection 4.2.1.

The (nominal) value of an effect changes over time. Therefore, the costs and monetized effects need to be indexed (converted into the real value). However, future assets are also worth less than present assets. Therefore the NPV needs to be calculated. This is also in line with SCBA theory (Boardman et al., 2018). To calculate the NPV, the expected inflation/discount rate (INF), the time (t) that the expense/income occurs, the current price (Pr_{cur}), as well as the discount rate (DR), need to be known. If these quantities are known the NPV can be calculated using Equation 3.1 (Boardman et al., 2018).

$$NPV = (Pr_{cur} \cdot (1 + INF)^t)/((1 + DR)^t) \tag{3.1}$$

The recommended discount rate (DR) of 4.5% is recommended for all Dutch governmental format social cost-benefit analyses (SCBAs) with investment into physical goods and substantial costs over time (MKBA-informatie.nl, 2015). However, there is discussion on what discount rate to use, and the recommended rate is subject to change (MKBA-informatie.nl, 2015). With inflation (INF), different rates can apply depending on the expense/revenue/cost. Therefore, several different inflation rates will be used for calculation (in the DSS). These will now be covered.

In this thesis, due to the diversity of the effects, the average Euro inflation percentage is used for the inflation of all monetized effects. With data from Inflation Tool (2021), it is calculated that from 1991 to 2021 the average inflation was 1.9% annually.

For most costs in this thesis, the general construction cost inflation is used. According to Bouwkostenkompas (2021) the average increase in construction costs from 2007 through 2021 was 1.8% annually.

One case in which a different inflation index will be used is in the case of Light Emitting Diode (LED) cost. This is done since it is predicted that they will become cheaper over time. According to P. Pattison et al. (2020) between 2019 and 2035 the annual decrease in price will be 6.8% (deflation in practice).

The other cost for which a different inflation index is used is electricity cost. Between 1995 and 2020 the average annual price increase was 3.4% (BMWi, 2021). All of these indexation parameters are in the "Indexation" sheet in the DSS (part of the database component).

3.2.2 Database component

The database component of the DSS will be implemented within the spreadsheet in several sheets. These sheets contain almost all the information that the model component requires. The sheets have the following names: "Poles", "Luminaires", "Inst. and repl. costs", "Effects", "Lighting profiles", "ROVL classes", "Indexation" and "User Input". No external data links are made. This is done since most data is road authority dependent and should be user-replaceable. This is not possible if the data used is present in a linked document that is not user-accessible. The fact that the data consists of numbers on a spreadsheet also helps with user replaceability for non-technical users since they can use the graphical user interface of the spreadsheet program. For every sheet, it will now be shortly discussed what information is present in that sheet and why.

Poles, Luminaires, and Lighting profiles sheets

Within the "Poles", "Luminaires", and "Lighting profiles" sheets the relevant information about their similarly named components is entered. At the top of all of these sheets, a summarizing table is provided. These tables are used by the communications component to extract the data. This is done using "LOOKUP" functions. Scrolling down on these pages the calculation methods for the values within the summarizing table can be seen. The methods and the information within these sheets is covered in Subsection 4.2.1, 4.2.2, 4.2.3, 4.2.4, and 4.2.7.

ROVL classes sheet

On the "ROVL classes" sheet the relevant information about the ROVL classes is provided in a table that can be extracted by the communications component (using "LOOKUP" functions). This information is used for the effect calculation seen in Subsection 5.2.1

Effects (and Calculations) sheet(s)

On the "Effects" sheet, information regarding the effects is given. Both the local and the global monetization are given. This information is based on the information in Section 5.2. The additional information required for calculating the quantification and monetization of the effects is on the "Calculations" sheet.

Indexation sheet

The "Indexation" sheet covers the information required for the various indexations performed in the DSS. It stores indexation parameters from information from Subsection 3.2.1 and 4.2.1. Additionally, it stores the currency conversion data used in Section 5.2 and the "Effects" sheet.

Inst. and repl. costs sheet

The "Inst. and repl. costs" sheet covers the installation, replacement, and other relevant costs for public lighting systems. The information in this sheet can be found in Subsections 4.2.1, 4.2.6 and 4.2.5.

User Input sheet

The "User Input" sheet contains the area information as well as some other relevant general input. What information is contained on this sheet can be seen in Appendix C. The used case input for the case study of this report can be seen in Section 7.1.

3.2.3 Communications component

The communications component for this DSS is provided by the spreadsheet program. This is the case since the spreadsheet program allows for the direct linkage of data, for linking data using "LOOKUP" functions, and for linking data using VBA scripts. All three methods are also used in the DSS. To do all of this locally and refrain from using separate programs that link together is also logical since this is advised by Power (2002) for model-driven DSSs.

3.2.4 User interface component

The user interface component is the component responsible for asking for and presenting information to the user. It consists of several sheets with their respective functions. These sheets and their functions will now be covered. How to use the user interface is not discussed here. To help users use the user interface component see Appendix C.

Introduction sheet

First of all, there is a sheet called "Introduction" where the purpose of the DSS is explained. On this sheet, a general introduction, an overview of the sheets and their purpose, and a list of the limitations are presented.

User input sheet

Second, there is a sheet called "User Input". In this sheet, the user will be able to input the relevant general parameters (including SCBA settings) and area-specific information. On this sheet, the option to run the DSS as well as restore the workbook functionality if something goes wrong is also present. An example of the data that must be entered here can be seen in Appendix C and Section 7.1.

Results sheet

Third, there is a "Results" sheet. In this sheet, the calculated results can be seen for several policy goals. The way these results are presented will now be elaborated upon.

The results presented to the user must contain an overview of the costs and benefits (per situation) (step 7 of a Dutch governmental format SCBA) and present the results (step 8 of a Dutch governmental format SCBA) for the DSS to have a full SCBA contained within as prescribed in the introduction. The intervention variables, costs, monetized effects, and power consumption are, therefore, presented for the optimized interventions for the various optimization criteria.

Enough intervention variables are presented to be able to run the case manually. The cost is presented divided into CAPEX and OPEX. The CAPEX are subdivided further into the lost capital, and new investments required. The lost capital is presented separately since this is the lost value if components are replaced before they are depreciated and this aspect is mentioned explicitly by municipalities as a boundary for implementation of LED on a large scale as told in the introduction. The new investment required includes the costs for the placement of new systems. The OPEX is subdivided into electricity and maintenance costs. These are separated to give insight into the cost savings due to power savings.

The monetized effects are presented separately for every category of effects found in Section 5.1. Finally, the sum of all the costs and monetized effects is given. The power consumption is also listed. This since it is required for the power-saving intervention policies.

The results of the risk analyses are also presented in the "Results" sheet. These risk analyses are presented using the intervention variables from the various optimization criteria. Again the costs, monetized effects, and power consumption are presented. This is done in the same manner as before.

Plots sheet

Lastly, in the "Plots" sheet, some plots are given based on the results or the base-case for several parameters to aid in the presentation of the results. For any case presented on the "Results" sheet, plots can be made. The plots that are presented are a plot of the NPV and the total power usage for the different types of luminaires. Additionally, plots are presented for the NPV and power usage for different luminary replacement years and fixture replacement intervals. Finally, pie charts are presented about the absolute values of the different effects. These pie charts are presented to help with the understanding of the limitations of the DSS. It can be used for this since it displays the absolute values of the direct and the indirect quantified and order of magnitude estimated effects.

An example of the fixture type plots can be seen in Figure 3.4 and 3.5. These contain the results for area 1 as presented in Section 7.1 for global costs and local illumination policy.

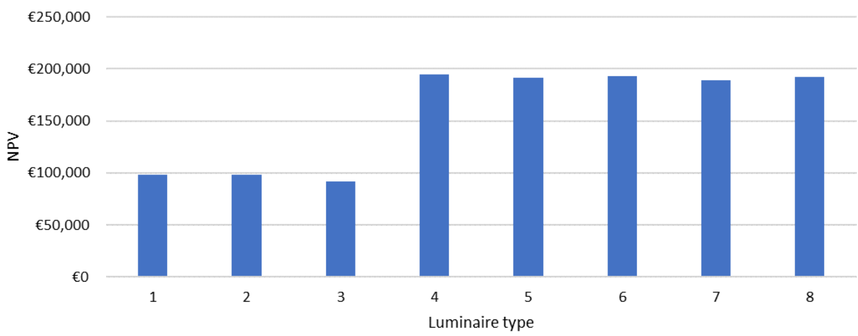

Figure 3.4: Example plot: NPV for various luminaire types

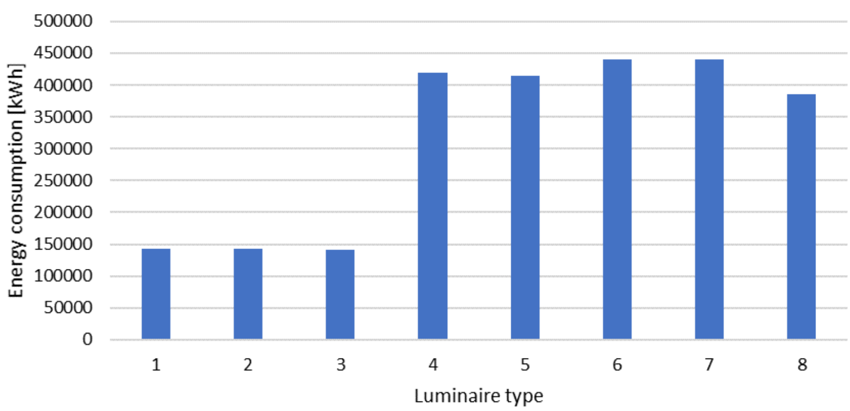

Figure 3.5: Example plot: Energy consumption for various luminaire types

Chapter 4

Lighting systems and policies included in the DSS

In this chapter, current lighting systems along with their cost are identified. The existing and possible future scenarios for use in the Decision Support System (DSS) are also defined. This is combined since this way all information regarding the current situation (except future cost prediction) is combined.

4.1 Current and available lighting systems

In sub-question 2.1 and 3.1, the installed and available lighting systems should be identified. In the case of this Social Cost-Benefit Analysis (SCBA), this is done by looking at the data provided by the road authority (Nuenen), van der Kolk (n.d.-a), and Lamp.nu (2021). A lighting system typically consists of a pole (or other height-gaining device), a fixture, and a light source. Other parts such as sensors and power sources also can/need to be included. More information on the components can be found in Appendix D. An overview of the relevant performance metrics can be found in Appendix E. In this section, the parts will only be named and it will be explained why they are (not) taken into account for further analyses. The included lighting system components and the relevant information can be found in the "Poles" and "Luminaires" sheets in the DSS.

Most public lighting poles are made of steel and aluminium. However composites, wood, iron, and concrete are examples of materials that can also be used to construct poles. However, only steel, composites, and aluminium are taken into account for the installed lighting systems since they cover the vast majority of systems in the Netherlands.

Currently, a selection of High Pressure Sodium (HPS), Low Pressure Sodium (LPS), Induction (IND)/Fluorescent (FL), and Light Emitting Diodes (LED) lights are used in Nuenen and most of the Netherlands. Furthermore, Metal Hydrate (MH) lights can also be used, they are however not used in Nuenen (or much at all in the Netherlands) and therefore, not taken into account further due to a lack of available data (and usefulness if it were to be added).

Other components, such as ballasts, sensors, and lighting support beams are also present in some systems. Due to their additional costs, they are taken into account.

4.2 Cost of lighting systems

To answer sub-questions 5.1 and 5.2, the costs of the individual lighting systems identified in Section 4.1 and electricity needs to be known, as well as how to index these costs. The costs for the respective parts and operations can be seen below. The cost indices are covered in Subsection 3.2.1. It should be noted that all prices are excluding V.A.T. since this can (mostly) be reclaimed by municipalities in the Netherlands (through the "BTW compensatie-fonds").

4.2.1 Cost of electricity

The cost of electricity is taken from data belonging to the municipality of Nuenen. This data, should, however, be representative of the Netherlands as a whole. There is a difference in the wealth effect this cost has between the municipality and the national government. This difference is caused by the "energiebelasting" and the "ODE". The local variable cost of electricity is €0.17 per kWh, nationally this is €0.05 per kWh. The annual costs for a grid connection are assumed to be €15. This information is contained in the Decision Support System (DSS) in the "Inst. and repl. costs" sheet.

Relevant specifications for calculating energy consumption

To calculate the power consumption, some more information regarding the lighting is also required aside from the case information. Since this information is more general and can be used more universally, it is not covered in the case information. Most of the required data can be seen in Table 4.1 and Table 4.2 (included in the DSS in the "Luminaires" sheet), Appendix F, and Appendix G.

In the Appendix F, the used lighting profiles are elaborated upon. In Appendix G, the used traffic profiles for calculating the power usage with intelligent dimming are elaborated upon. The information presented in both these appendices is included in the "Lighting profiles" sheet of the DSS. Additionally, some indexation information is needed about the decay of light sources due to dirt and grime on the fixtures, the increase of new LED efficacy over time, and the reduction in electrical efficiency over time. For calculation simplicity, it is assumed that all occur linearly since the effects are all relatively small and most compound a limited number of times this also does not influence the results much. This information is contained on the "Indexation" sheet. Finally, some additional information and assumptions are required for calculating the energy usage when adaptive dimming is used. This information is contained on the "Calculations" sheet.

Fixture decay occurs due to dirt/grime and plant buildup over time. van der Lugt (2008) gives the approximate decay at various points in time (called maintenance factor). Using linear deprecation over the longest period seen in van der Lugt (2008), the yearly light decrease due to dirt/grime and plant buildup over time is 4.2%. Fixture decay can be undone by cleaning the fixture.

The efficacy for new LEDs increases (Kusuma et al., 2020). If linear approximation is used from 2010 to 2040 using the data from Kusuma et al. (2020), the yearly increase in efficiency will be 2.9%. There is, however, a maximum to LED efficacy. This limit is 330 lm/W (P. M. Pattison et al., 2018).

Efficacy loss occurs in all types of light sources due to wear. The extend does, however, differ from type to type. For LED this was calculated using the average for the light types used in Nuenen using data from Lampdirect (2021). The decrease in efficiency is 0.00014% for every hour in operation. For FL lights data from Rensselaer Polytechnic Institute (2006) is used. The found decrease is 0.00043% per operating hour. Finally for HPS (and LPS due to lack of found data), using data from Stouch Lighting (2016), an hourly decrease in efficiency of 0.0011% was found.

Table 4.1: Average lighting specifications (based on Nuenen lighting systems and specification from Lampdirect (2021)

Type of lighting system	Lum. flux initial [lm/W]	Sys. Eff.	Lifespan lamp 5-10% fail. rate [kh]
LED	184	88%	100
LED static dimming	184	88%	100
LED intelligent dimming	184	88%	100
FL	74	93%	20
FL static dimming	75	93%	20
HPS	110	92%	35
HPS static dimming	110	92%	35
LPS	136	86%	20

Table 4.2: Intelligent dimming profile settings

What	Unit	Value
Seconds ahead to light	s	8
Seconds behind to light	s	30
Percentage dimmed if no traffic	%	75%
Minimum maintained brightness	%	20%
Minimum traffic brightness	%	30%

4.2.2 Pole cost

To keep the DSS applicable across all kinds of circumstances, a price function was derived for poles. Since height, price, and material were the only provided variables for poles by Nuenen (and most retailers of poles), it was decided to make a scatterplot for each material with height on X-axis and cost on the Y-axis. Then based on the quality of fit (highest R squared) a function type was decided upon. The best-fitting function type was exponential. The plots for these functions are given in Figure 4.1. The cost equations are given in Equations 4.1, 4.2, and 4.3 for steel, aluminium, and composites respectively. In these, h is the height in meters and p the price in Euro indexed to 2021. The R^2 for these are 0.55 (n=20), 0.96 (n=6), and 0.98 (n=4) respectively. The raw data is not provided since most data was provided by the municipality of Nuenen confidentially.

In addition to a pole, for some lighting systems, a lighting support beam (NL: uithouder) is required. The cost of a lighting support beam is assumed to be €95.1 irrespective of the material. Both the cost for lighting support beams and poles are included in the "Poles" sheet of the DSS.

$$p_{steel} = 191.93 \cdot e^{0.1252 \cdot h} \tag{4.1}$$

$$p_{alu} = 159.62 \cdot e^{0.1523 \cdot h} \tag{4.2}$$

$$pcomp = 116.53 \cdot e^{0.2433 \cdot h} \tag{4.3}$$

4.2.3 Fixture cost

Similar price functions to the ones derived for poles were also derived for fixtures. This time, the cost is plotted over the wattage of a fixture. This was done because this resulted in the

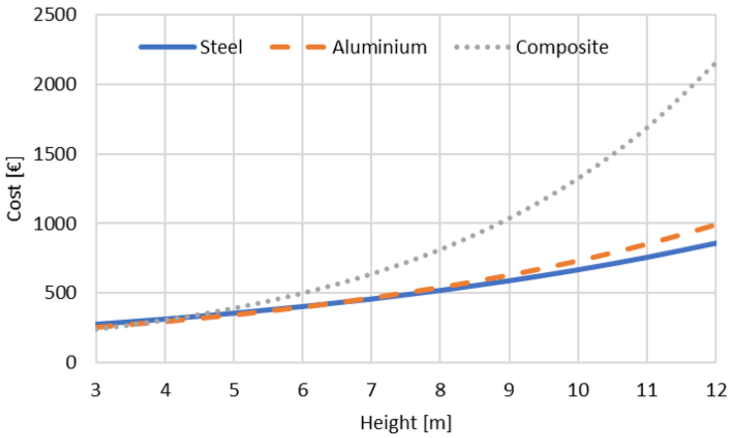

Figure 4.1: Cost functions lighting poles

best function fits. The best-fitting function type was exponential. The plots for these fixture type-specific functions are given in Figure 4.2. The equations are given in Equations 4.4 and 4.5 for LED (including light source) and conventional (excluding light source) fixtures respectively. In these, P is the power in wattage and p is the price in Euro indexed to 2021. The R^2 are respectively 0.46 (n=21) and 0.93 (n=9). The raw data is again not provided since most data was provided by the municipality of Nuenen confidentially. LED light sources are included in the fixture cost since they are rarely user-replaceable and/or sold separately. The cost for fixtures are included in the "Luminaires" sheet of the DSS.

In addition to a fixture, a light source is needed for a conventional luminary. This is covered separately, however. What is also covered in that section is the cost of the ballast required for conventional light sources. This is covered at the light sources since the ballast is dependent on the light source. The same goes for sensor compatibility (and thus potential cost).

$$p_{LED} = 223.71 \cdot e^{0.013 \cdot P} \tag{4.4}$$

$$p_{conv} = 151.29 \cdot e^{0.0088 \cdot P} \tag{4.5}$$

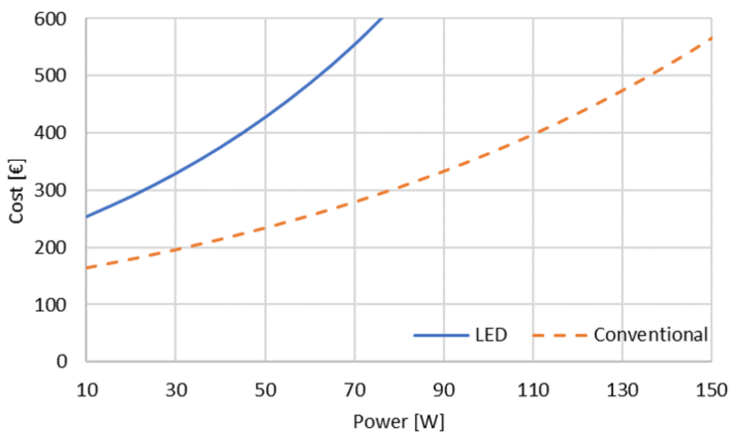

Figure 4.2: Cost functions fixtures

4.2.4 Light source cost

Similar price functions as derived for poles and fixtures were also derived for light sources. This time, the cost is plotted over the wattage of a light source. This was done because this resulted in the best function fits. The best-fitting function type was exponential. The plots for these functions are given in Figure 4.3. The equations are given in Equations 4.6, 4.7 and 4.8 for FL, HPS, and LPS light sources respectively. In these, P is the power in wattage and p is the price in Euro indexed to 2021. The R^2 are respectively 0.17 (n=9), 0.68 (n=8), and 0.36 (n=14). The raw data is again not provided since most data was provided by the municipality of Nuenen confidentially.

As already mentioned the ballasts and sensors are also covered here. The average cost of these, for the different lighting systems, can be seen in Table 4.3. These costs are again averages to obfuscate the data provided confidentially by Nuenen. The cost for light sources, ballasts, and sensors are included in the "Luminaires" sheet of the DSS. The calculations on the cost (and lost value due to premature replacement) are calculated on the "Calculations" sheet.

$$p_{FL} = 1.89 \cdot e^{0.0014 \cdot P} \tag{4.6}$$

$$p_{HPS} = 13.55 \cdot e^{0.0022 \cdot P} \tag{4.7}$$

$$p_{LPS} = 18.36 \cdot e^{0.0042 \cdot P} \tag{4.8}$$

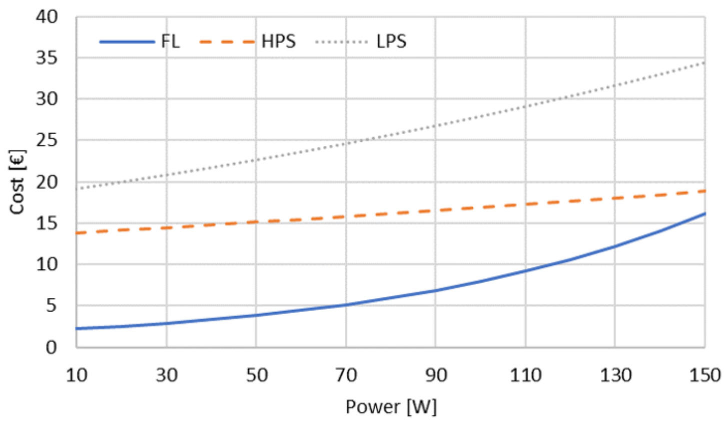

Figure 4.3: Cost functions light sources (LED included in fixture)

Table 4.3: Average cost of additional lighting system components based on pricing information from Nuenen

Type of lighting system	Ballast cost [€]	Sensor cost [€]
LED	incl.	n/a
LED static dimming	incl.	n/a
LED intelligent dimming	incl.	237
FL	15	n/a
FL static dimming	119	n/a
HPS	47	n/a
HPS static dimming	186	n/a
LPS	95	n/a

4.2.5 Placement cost

The cost for various (re)placement operations can be seen in Table 4.4. The planned replacement intervals are case-dependent and therefore listed in Section 7.1. The price information is contained in the DSS in the "Inst. and repl. costs" sheet.

Table 4.4: Average (re)placement operations costs based on pricing information from Nuenen

What	Height min. [m]	Height max. [m]	Cost [€]
Replacing lighting object (pole+luminaire) n=1	0	5	€ 242.8
Replacing lighting object (pole+luminaire) n=1	5	8	€ 265.6
Replacing lighting object (pole+luminaire) n=1	8	12	€ 284.9
Replacing lighting object (pole+luminaire) n>=2	0	5	€ 139.1
Replacing lighting object (pole+luminaire) n>=2	5	8	€ 182.6
Replacing lighting object (pole+luminaire) n>=2	8	12	€ 208.6
Replacing luminaire/fixture	0	5	€ 30.0
Replacing luminaire/fixture	5	8	€ 27.5
Replacing luminaire/fixture	8	12	€ 27.5
Placing objectnumber (incl. material)	0	12	€ 3.1
Inputting revisions/changes into registration system	0	12	€ 7.8
Reconnecting grid	0	12	€ 146.2

4.2.6 Maintenance cost

The cost for various maintenance operations can be seen in Table 4.5. Note that if, for instance, a pole needs to be replaced as part of a failure restoration, the cost for a lighting object replacement, inputting revisions/changes into the registration system, placing an objectnumber (incl. material), and the cost of the pole also need to be taken into account. The planned maintenance intervals are again case-dependent. The maintenance cost information is contained in the DSS in the "Inst. and repl. costs" sheet.

Table 4.5: Average maintenance operations costs based on pricing information from Nuenen

What	Height min. [m]	Height max. [m]	Cost [€]
Lamp replacement	0	8	€ 8.2
Lamp replacement	8	12	€ 8.4
Cleaning fixture	0	8	€ 14.3
Cleaning fixture	8	12	€ 12.9
Cleaning pole	0	8	€ 18.7
Cleaning pole	8	12	€ 23.1
Painting pole (incl. materials)	0	5	€ 48.8
Painting pole (incl. materials)	5	8	€ 91.5
Painting pole (incl. materials)	8	12	€ 134.3
Restore failure (excl. additional labour)	0	12	€ 25.1
Restore failure high priority (excl. add. labour)	0	8	€ 82.7
Restore failure high priority (excl. add. labour)	8	12	€ 84.5

4.2.7 Failure rates

Maintenance and (re)placements do not only occur at scheduled intervals due to failures. To predict when a(n unscheduled) failure occurs (and thus the cost) a Weibull modulus can be used (Sparks, 2019) if failure data is available. In this case, Nuenen has failure data available. In figures 4.4 through 4.8 the fitted Weibull functions and the quality of fit can be seen for the various components (in Nuenen). Using the a and b from these linear equations (of the form $y = ax + b$) the fraction of failed components (f_{fail}) at any time (t) (in years) can be calculated using Equation 4.9.

$$f_{fail} = e^{-e^{a \cdot ln(t)+b} \cdot (e^{e^{a \cdot ln(t)+b}} - 1)} \tag{4.9}$$

To arrive at figures 4.4 through 4.8 some intermediate steps are required. While the axis titles give almost all the required explanations, the quantity Fr warrants further explanation.

Fr is a measure of rank. This is calculated using Equation 4.10. In this equation, F_N is the number of the failure in chronological order and F_T is the total number of failures. However, the total number of failures needs to be calculated since only a fraction of lighting system components fail before they are replaced. However, it is known how many failures there are in a year and how long (on average) components are used before they are replaced. The total number of failures can, therefore, be estimated. It should be noted that this is not accurate to the point that all components have failed. For the replacement interval, however, it should be accurate.

$$Fr = (F_N - 0.5)/(F_T) \tag{4.10}$$

Now that the number of failures is known, the new components required for the failures can also be calculated. For poles and conventional fixtures, it is assumed that for 40% of their respective failures a new pole/fixture is required. For conventional light sources, it is known from the data provided by Nuenen that in 14% of the light failures a new ballast is required, and in 78% of the cases, a new light source is required. For led luminaires, a new luminaire is required in 92% of the light/fixture failures.

Additionally, it should be noted that LED fixtures typically have a ten-year warranty period. For the first five years, there is full coverage. This coverage then reduces linearly to zero from the sixth to the tenth year.

The failure data for the poles, lights, and fixtures are included in the "Poles" and "Luminaires" sheets respectively. The cost calculations are performed in the "Calculations" sheet.

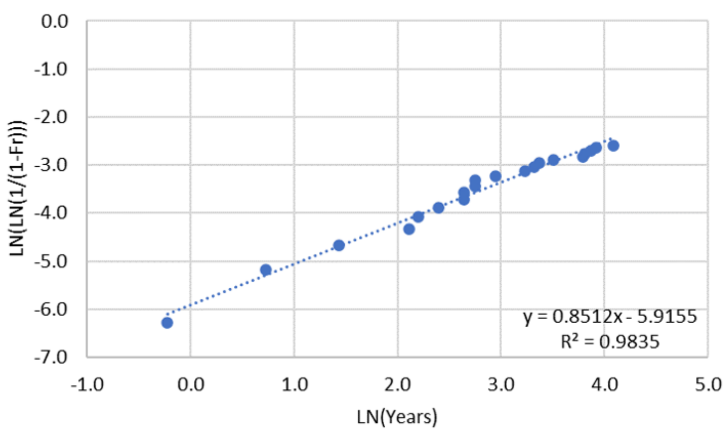

Figure 4.4: Plot of pole Weibull function (n=20) using failure information from Nuenen

4.3 (Intervention) lighting policies

Since the goal of this thesis is to develop a DSS that helps municipalities in deciding on what replacements for public lighting systems to get and when to implement them according to a

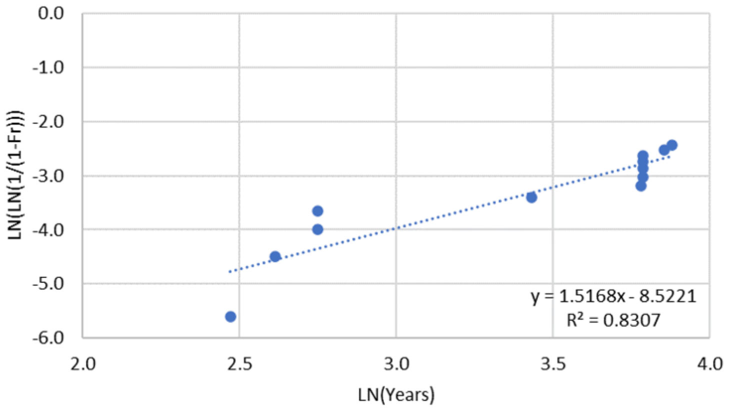

Figure 4.5: Plot of conventional fixture Weibull function (n=12) using failure information from Nuenen

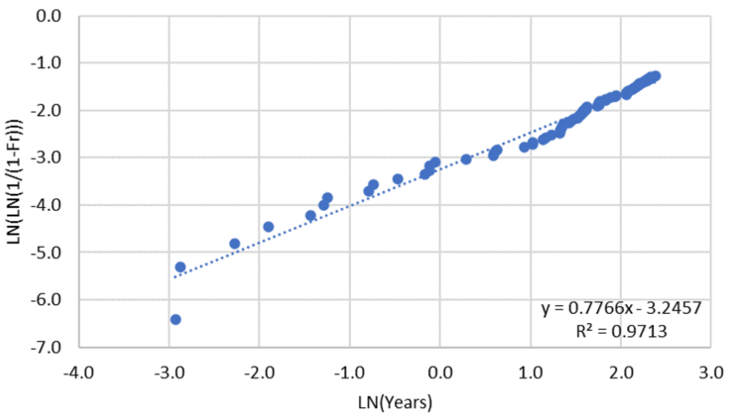

Figure 4.6: Plot of led fixture+light source function (n=75) using failure information from Nuenen

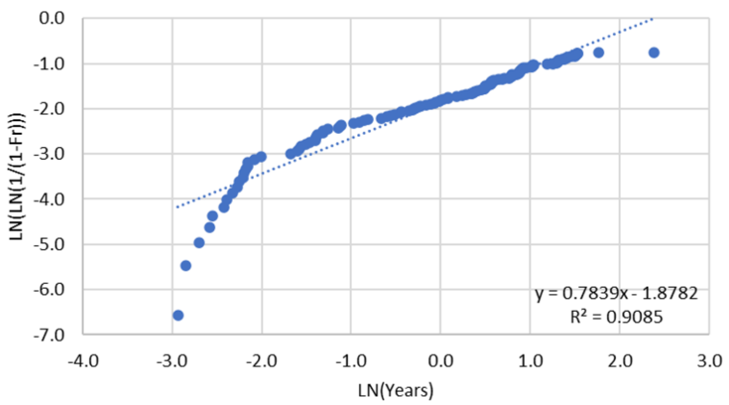

Figure 4.7: Plot of FL light source function (n=136) using failure information from Nuenen

SCBA, the current and intervention scenarios need to be known. To do so, policy goals and current policies need to be analyzed. This is done first. Second, the implementation in this DSS is covered.

4.3.1 Public lighting policy (goals) in the Netherlands

(Scientific) Research relating to policy goals and existing policy was not found. Therefore, the policy documents of several Dutch municipalities are analyzed. The policy documents of municipalities are analyzed since in 2016 municipalities in the Netherlands controlled 94%

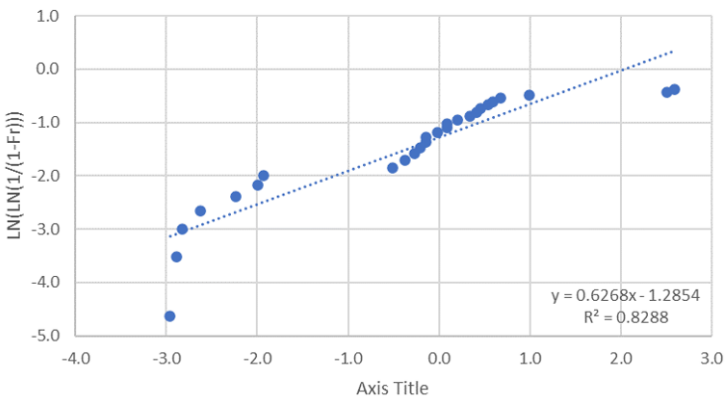

Figure 4.8: Plot of HPS/LPS light source function (n=136) using failure information from Nuenen

of the country's total public lighting (as already mentioned in the introduction) (Rijkswaterstaat, 2016). The question that should be answered by analyzing the policies is what the current policy is regarding the replacement of public lighting is and what the policy goals are.

As Ziut Advies B.V. (2015), Boomsluiter and Mus (2018), Boomsluiter and Mus (2019), Janssen and Vos (2019), Nobralux (2017), and Janssen and Vos (2017) point out, multiple public lighting replacement scenarios are usually considered by municipalities. Usually, the scenario without intervention is (continuing) to replace lighting once it is depreciated for the option that is deemed the most cost-effective (often LED with static dimming). The intervention scenarios often entail that more luminaires and poles are replaced to save additional power. It seems that most municipalities would like to reach the 2030 energieakkoord goal of saving 50% of the electricity used by public lighting when compared to 2013. Reaching this goal is also what the additional power-saving scenario is often based on. All scenarios always state that safety must be guaranteed (read that lighting levels must remain in accordance with the ROVL 2011 (NSVV, 2011), or its successor the NPR 2016 (NSVV, 2016), for fear of legal consequences). The total public lighting expenditures of the scenarios are then calculated in a cost-based model.

In general, these models have many assumptions. For instance, the price level is assumed to not change for multiple years or even decades and the discount rate is set at zero. In the studied policy documents no optimization of the public lighting systems is performed to check for a potential optimal between different plans. In practice, optima could exist due to decreasing cost and increasing efficacy, for instance. However, since both (cost and efficacy) are assumed constant in the seen models, checking for an optimum with the cost models displayed in policy documents would be fruitless. Meanwhile, the motivation for choosing a certain public lighting system is often heavily cost-based.

The (societal) effects of public lighting are also quickly glossed over in municipal policy documents by the authors of these documents. Most policy documents state that public lighting is essential for traffic safety, the perception of safety, quality of life, and the prevention of crime. However, how large these benefits are and how the social costs and benefits change when, for instance, dimming the lighting, was not found in any of the documents. In practice, the choice for dimming is often based on the amount of traffic and the Dutch public lighting guidelines (ROVL 2011 (NSVV, 2011), or its successor the NPR 2016 (NSVV, 2016)). The guidelines, however, are also not based on the social costs and benefits of public lighting, but instead, on acceptable levels of visibility and safety (van Ratingen, 2016).

In summary, it can be said that municipalities try to adhere to the Dutch public lighting guidelines for liability reasons. The current policy is based on what is thought to be the cheapest. The intervention policy is often to reach the Energieakkoord goals if it does not cost too much based on a (simple) cost model. However, (social) cost optima are not located and the choice for the scenarios to be included in analyses is based on expert opinion.

4.3.2 Implementation in the DSS

Existing policy choices were identified in Subsection 4.3.1. The conclusion from that section was that the existing policy is often to replace lighting once depreciated (for a specified option). This is also what is implemented in the DSS as the scenario without intervention. This is implemented in the DSS on the "Calculations" sheet.

The intervention scenarios will, however, be a product of optimization based on the policy choices as explained in Subsection 3.2.1 and Section 4.3.1. It will not be set beforehand what type of lighting systems will be used. Instead, the goal will be set and the lighting systems will be determined. Implemented goals are reaching a maximum NPV (Net Present Value) and reducing energy usage X% for the lowest NPV. These are included since the goal of an SCBA is to reach optimum NPV. To help municipalities reduce energy usage the second goal is also included. While not required for SCBA, many municipalities do have this a goal (logical in regard to the "energieakkoord" goals). Additionally, the minimum NPV, minimum energy usage, and maximum power usage are also implemented in the DSS. This is done since it was relatively little extra effort and it can provide valuable insights. The policy goals are implemented in one of the Visual Basic for Applications (VBA) scripts in the DSS.

Chapter 5

Effects included in the DSS

In this chapter, sub-questions 4.1 through 4.5 are answered. Since sub-question 4.1 only requires literature research this sub-question is answered separately.

5.1 Effects of public lighting

To investigate what effects should be taken into account in the Decision Support System (DSS) (and answer sub-question 4.1) aside from the effects stated in municipal policy documents and already found documents a literature search was conducted using a custom query in the TU/e variant of WorldCat Discovery. How this search was performed, can be read in Appendix H. With the effects found in the literature uncovered by this search, all the effects mentioned in Meier et al. (2014) are covered except the economy. Additionally, a list of effects as published by the World Council on City Data is also completely covered (Beaton & Lynch, 2020). The effects mentioned by the municipalities in the policy documents referenced in Section 4.3.1 are also covered. With the conclusion of this analysis, it can be safely assumed that the list of effects that will be investigated further for sub-questions 4.2 through 4.5 is reasonably exhaustive.

- Perceived safety e.g. Fotios and Castleton (2016), Willis et al. (2005)
- Economy e.g. Meier et al. (2014), Gallaway et al. (2010)
- Impressions of the environment e.g. Meier et al. (2014), Simpson and Hanna (2010)
- Mobility e.g. Foster et al. (2016), Markvica et al. (2019)
- Road safety e.g. Christie (1970), Beyer and Ker (2009)
- Crime e.g. Chalfin et al. (2019), Painter and Farrington (1999)
- Animals e.g. Straka et al. (2019), Desouhant et al. (2019)
- Human health e.g. American Medical Association (2016), Maierova (2018)
- Energy usage e.g. Janssen and Vos (2019), Boomsluiter and Mus (2019)
- Environment e.g. Bennie et al. (2016), Dale et al. (2011)

5.2 Implementation of the effects in the DSS

Sub-questions 4.2-4.5 ask questions regarding the area of effect, quantification, and monetization. The research needed to answer question 4.1 is already performed in Section 5.1.

Therefore, it is known what effects to include. The areas of effect, quantification, and monetization will now be provided for these effects (sub-questions 4.2-4.5). A literature review for every effect has been performed on how and if an effect can be quantified and monetized. If possible, the quantification and monetization are also performed using literature. An effect can be quantified and monetized based on the impact of public lighting directly. However, indirect effects in which one effect influences another also occur. Since these relations between the effects are important for the quantification and monetization these resulting indirect relations are also investigated here. Furthermore, if an effect cannot be quantified or monetized using public lighting literature, an alternate method using logical assumptions is presented to be able to judge the order of magnitude of that effect.

These steps will be performed according to the following structure. For every effect as found in Section 5.1 a subsection is presented. If this effect can be quantified and monetized without further explanation using literature or it can be explained why this cannot be done with the current knowledge base all the information is contained within this subsection without further subdivision. If however, multiple causes need to be identified or an effect influences another effect, a quick introduction is given and the causes and influences are covered under separate headers. At the end of this chapter (Section 5.3), an overview of the found and included effects can be seen.

All information regarding the monetized effects is included in the DSS in the "Effects" sheet. All the calculations required for the quantification are performed on the "Calculations" sheet. The additional information required for the quantifications is also provided on that sheet unless it is area, pole, or luminaire specific.

Please note that the effects are monetized for a lighting system located in the Netherlands. This is done since the Netherlands is the country wherein the chosen case lies. (See Section 7.1 for more information on the case.) The monetary values are expressed in Euros indexed to 2021 unless stated otherwise. The currencies in this chapter are converted from USD to EUR using Macrotrends (2021), from CAD to EUR using OFX (2021), and corrected to the correct year using Inflation Tool (2021). To calculate localized monetized effects for an effect with a global area of effect, the total costs or benefits have to be multiplied by the fraction of the world population living in the desired area of effect. The monetary values are expressed in willingness to pay (WTP) or social cost/benefit but not both. This is done since both monetize the same quantified effect and should in theory be the same if people value their willingness to pay correctly and rationally and the social cost is measured correctly (Boardman et al., 2018). In practice, this will not be the case due to the inability of people, in general, to properly value an asset/burden and the difficulty of accurately modeling the social cost (Boardman et al., 2018).

5.2.1 Effect of public lighting on perceived safety

Perceived safety is influenced directly by public lighting. In addition, perceived safety affects mobility.

Effect of lighting on perceived safety

Public lighting has a direct effect on the perceived safety of road users (Fotios & Castleton, 2016), (Marchant, 2017), and of the people in adjacent buildings (Willis et al., 2005). This means that only the people near the light source(s) are affected. There is scientific consensus surrounding this topic/effect since publications that state otherwise have not been found. However, the definition of improved lighting is problematic. According to Willis et al. (2005)

for instance, no definition of better/improved lighting is given beyond what type of lights were used. Furthermore, Fotios and Castleton (2016) demonstrate that judgments of lighting are relative. This means that the same and equally lit area is perceived as less or more safe depending on what other lit areas a person has seen. To correctly measure the perceived safety the day–dark difference was proposed (Fotios & Castleton, 2016). The method works by having people judge/perceive the safety during the day as well as the night at the same location on a (Likert) scale and then subtracting the night from the day score.

Much previous research into this topic and government guidelines are based on the (incorrect) assumption of absolute scales, and not the (correct) day–dark difference method (Fotios & Castleton, 2016). The only known works (to the author) using this method for residential areas are Unwin (2018) and Fotios et al. (2018). Both studies find the minimum illuminance to be significant (Unwin, 2018), (Fotios et al., 2018). Additionally, Unwin (2018) found longitudinal uniformity, the length of horizontal illuminance of <1 lux on pavement, vertical luminance, and indirect illuminance at the eye significant. Fotios et al. (2018) found that added to the minimum illuminance, the absolute uniformity, as well as the mean illuminance, are significant. Due to the inconsistency in these findings, only the minimum illuminance will be taken into account for further analyses. It must also be noted that in both studies, the spectral power distribution and dependent parameters such as color temperature, Color Rendering Index (CRI), and SP factors are not taken into account (Unwin, 2018), (Fotios et al., 2018). These factors effects on the perceived safety are taken into account in Saad et al. (2020). However, in this study, only the feeling of safety at night is measured instead of the day–dark difference. Its results are, therefore, not taken into account.

To quantify the direct effect of public lighting on perceived safety, research into the monetization of this effect should be done. This is the case since if the perceived safety measurement uses different units than the monetization, they cannot be combined. Unfortunately, no research into the value of perceived safety due to public lighting could be found aside from Willis et al. (2005). However, as stated previously, Willis et al. (2005) does not quantify the improvement of lighting beyond what types of lights will be used. Furthermore, it does not state what fraction of the total WTP is caused by perceived safety. Therefore, the effect public lighting has on perceived safety is currently not accurately expressible in monetary terms. A rough (partial) order of magnitude estimate can be attained by taking the willingness to pay for a 20% perceived reduction in car accident risk from McDaniels et al. (1992). This is €145 per inhabitant on average. If it is assumed that 20% is indeed the perceived risk decrease this value can be used to monetize the perceived safety.

The effect of intelligent lighting on perceived safety is estimated to be positive when descending brightness is used (Haans & de Kort, 2012). While the results are hard to generalize due to the small test site (one street) and unrepresentative participants (students), it is safe to assume that when dimmed using the descending brightness profile used in Haans and de Kort (2012), the perceived safety will not be negatively influenced.

Effect of perceived safety on mobility

As already mentioned, perceived safety has an effect on mobility (thus resulting in an indirect effect) (Foster et al., 2016). Mobility, which is covered under in Subsection 5.2.4, in turn, affects human health, and the environment. The effect of perceived safety on mobility is quantified in literature (Foster et al., 2016). According to Foster et al. (2016), every one-point increase in perceived safety on a five-point Likert scale results in 18 minutes of additional walking per person in a week. While this is a general effect and not lighting specific, lighting can contribute to this feeling of safety. Since Foster et al. (2016) uses a similar five-point Likert scale to Unwin (2018) the results concerning minimum illuminance and perceived safety found in Unwin (2018) can be combined. In Figure 5.1, the found relation in Unwin (2018) can be seen. The equation for the trend-line is approximately $y = -0.5 \cdot ln(x) + 0.5$. In this equation, y is day–dark difference in perceived safety and x is the lowest illuminance in lux. With this equation, lighting levels can be matched to levels of perceived safety.

However, before practical application, the minimum illuminance is also required. This can be calculated as described in Appendix E. A less accurate, less computationally complex alternative to get to know the minimum illuminance is to use the classifications given to roads as seen in the ROVL 2011, (NSVV, 2011) or its successor the NPR 2016 (NSVV, 2016). In both, the minimum illuminance is given directly for Pedestrian lighting (P) classes. This class is the most relevant since the P class is used for roads with pedestrians. Additionally, this method can be used for Conflict (C) classes since the average illuminance and uniformity are both given. Conflict classes are typically used at intersections or on mixed-use streets. Motor vehicle classes (M) are defined using luminance instead of illuminance making simple conversion impossible. However, in the Netherlands M class lighting is not supposed to be used on streets with pedestrians, making this a non-issue since walking can, therefore, not be influenced. The reasoning behind the differences in measurements used is explained in Appendix E.

If the mode of transport and the purpose of a trip is known, the effect of perceived safety on car mobility can also be calculated. Using data from Spinney et al. (2012) and Tudor-Locke et al. (2005), it is assumed that 30% of walking trips are transport trips and 70% are recreational. Furthermore, it is assumed that transport trips are full substitutions for car trips. This assumption means that for every one-point increase on a five-point Likert scale for perceived safety every person walks 5.4 minutes more for transportation purposes every week. This in turn means that around 442.8 meters of car travel are prevented per inhabitant per week, based on an 82 meters per minute walking speed (Mohamed & Appling, 2020).

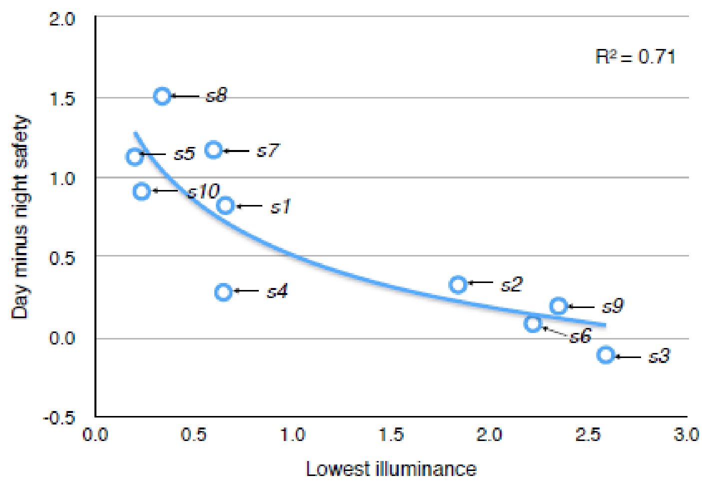

Figure 5.1: Day minus night mean safety rating and minimum illuminance (Unwin, 2018)

5.2.2 Effect of public lighting on the economy

The effect of public lighting on the economy is not investigated much (Meier et al., 2014). The effect is caused by two main economic effects occurring due to public lighting (Meier et al., 2014). The effect of public lighting on consumers spending money and the effect of the acquisition, placement, and maintenance of public lighting systems on the economy. Both of these effects also influence mobility.

The effect of public lighting on consumers spending money

It is expected that public lighting increases the economic activity in an area since it lowers the barrier for conducting activities when it is dark (Meier et al., 2014). This is currently interpreted as a direct effect, however, it could be made up of multiple indirect effects such as increased perceived safety and perception of the environment. A study that illustrates the link between lighting and economic activity is presented in Gallaway et al. (2010). In this study, it is proven that light at night and economic activity are tightly connected. However, the causal direction of this relationship is unclear. This makes accurate quantification and monetization impossible. For accurate quantification, causal relations have to be present, and causation is not quantification.

For an idea of the possible order of magnitude, it can be assumed that by placing public lighting between € 0.10 and € 10.00 of additional consumer surplus is created on average every week per person. While the effect can not be included reliably it can at least be used to see the potential influence the effect can have. € 0.10 and € 10.00 are selected since they can offer a realistic order of magnitude. This order of magnitude is somewhat realistic since it is the additional willingness to pay someone would have for an activity/purchase when public lighting is present. For instance, if one goes shopping in the evening in the dark once a week, a value of € 0.10 to € 10 intuitively does not seem as too low or too high of an additional price to pay for some light along the way. The estimated value is set at € 1 for further calculations. This is done since this is in the middle of the estimated range when looking at order of magnitudes.

The effect of consumer spending on mobility

The likely change in the consumer surplus also affects mobility, resulting in an indirect effect of pubic lighting. This change in mobility will occur since a shift of the demand curve upward (due to higher WTP) in a supply-demand graph occurs. This will, with most supply curves, also increase the quantity. The more horizontal the supply (and demand) curve the more pronounced the effect of spending on mobility will be. A visualization of the explained effect can be seen in Figure 5.2. While it is impossible to quantify this increase in demand without knowing the elasticities and the price points, the increase should occur.

The approximate order of magnitude can be estimated since it is illogical if there is little to zero effect. It is also illogical if there is a huge shift in the number of trips. The latter is illogical since one does not go to a supermarket/restaurant more than ten times a week in the evening. Therefore, it is currently estimated by the author that for every € 2 of additional WTP a trip is made (WTP_{trip}). For the assumed € 1 additional WTP per week (WTP_{week}), this results in 26 additional trips per year. The length of these trips is set as the distance the average inhabitant of the Netherlands needs to travel to a supermarket and back (1800 meters) (D) (Baydar et al., 2010). It is assumed that the model split between car (MS_{car}) and bike/pedestrian (MS_{walk}) is 50% and 50% respectively (CBS, 2020a). The walking speed is assumed to be 82 meters per minute (V_{walk}) (Mohamed & Appling, 2020). It is assumed that cycling speed is equal to walking speed for this approximation. It is also assumed that the average car transports 1.2 people during a trip (O_{car}).

Using this information the additional minutes of walking (t_{walk}) and additional kilometers of car travel (D_{car}) can be calculated fairly easily using Equations 5.1 and 5.2 respectively.

$$t_{walk} = WTP_{week} \cdot 52/WTP_{trip} \cdot D \cdot MS_{walk}/V_{walk} \tag{5.1}$$

$$D_{car} = WTP_{week} \cdot 52/WTP_{trip} \cdot D \cdot MS_{car}/O_{car} \tag{5.2}$$

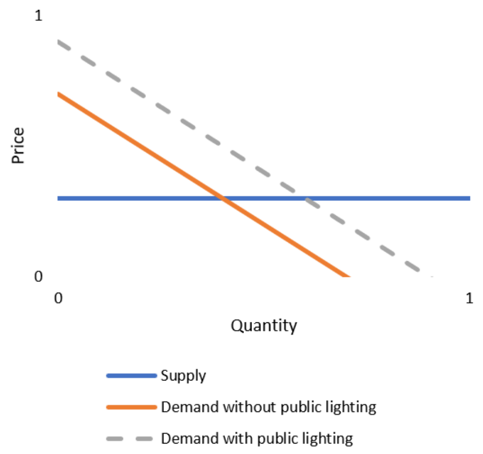

Figure 5.2: Assumed supply and demand curve shapes

The effect of acquisition, placement, and maintenance of public lighting systems on the economy

The acquisition, placement, and maintenance of public lighting systems can act as an impulse to the economy since it creates jobs (Meier et al., 2014). However, at a global scale, the effect is negative because the money gained for the jobs and the placement comes from the same community that pays for the lighting systems (Boardman et al., 2018) and there are opportunity cost due to, for instance, the lost leisure time of newly employed workers and the materials used (Meier et al., 2014). In conclusion, the direct cost of acquisition, placement, and maintenance should be included as the opportunity cost if the supply curve is perfectly elastic (price does not change by the caused increase in demand) and the market is perfect (Boardman et al., 2018). In practice, these assumptions most likely hold for a municipality wanting to replace (part of) their public lighting system. This is the case since there is competition in the public lighting market and the "order" one municipality places for public lighting systems is small compared to the total market.

The effect of placement and maintenance of public lighting systems on mobility

Placement and maintenance of public lighting systems affect mobility. This means that it is an indirect effect of lighting. This effect is caused by the fact that the poles need to be placed at a certain location and maintained at that location after placement.

The distance that needs to be covered during installation can be calculated if the number of poles/fixtures/lights that can be placed in a day is known (N_{day}) together with the number of poles in an area (N_{area}), the spacing of the poles (D_{poles}) and the distance to the depot (D_{depot}). All of these variables are dependent on the case and do not have fixed values. The equation to calculate the distance travelled ($D_{placement}$) can be seen in Equation 5.3. It is assumed that the placement is done using a 2016 fuel-inefficient Euro 6 LCV in an urban environment.

$$D_{placement} = N_{area}/N_{day} \cdot 2 \cdot D_{depot} + N_{area} \cdot D_{depot} \tag{5.3}$$

The distance that needs to be traveled for a single maintenance action is twice the distance to the depot. The amount of maintenance operations is dependent on the light source components used and will be covered in Chapter 4.2.

5.2.3 Effect of public lighting on impressions of the environment

Lighting also influences how we (can) perceive the environment. One often pointed out drawback of public lighting is that the night sky is no longer fully visible (Meier et al., 2014). Alongside this decrease in the perception of the stars, people also do not like the cold appearance (of the environment) when blue light sources are used (Davidovic et al., 2019). Both direct effects of public lighting are covered here.

The effect of public lighting night sky visibility

Due to light pollution (caused partially by public lighting), only a small percentage of the stars visible with the naked eye in an unpolluted area can be seen by the majority of humankind (Meier et al., 2014). Aside from creating an obvious benefit for astronomers, a not-insignificant percentage of people also desire to see an unpolluted night sky (Meier et al., 2014), (Simpson & Hanna, 2010). In the latter paper, research is conducted into the WTP for a reduction and the prevention of an increase in sky glow (caused by light pollution). For a decrease in light pollution, WTP means of $50 to $100 were reached. For the prevention of an increase in light pollution, the mean WTP was much lower at around $5 (Simpson & Hanna, 2010). These WTPs cannot be transferred to lighting values since artificial images for generating the WTPs were used. Another issue with quantifying the impact of light sources on light pollution is that the area of effect is hard to measure. This is hard to quantify since light glow and the effect of a few light sources in an already polluted environment is quite limited (Meier et al., 2014). The WTPs can, however, be used as an order of magnitude approximation if an larger area is lit or not lit. The impact for a local area is currently set at zero.

The color spectrum of a light source is also of major importance in regards to the light glow it causes (Meier et al., 2014). Heavily blue emitting LED, for example, can cause up to three types the light glow when compared to Low Pressure Sodium (LPS) (Luginbuhl et al., 2009). This effect is, however, not included in the thesis since light glow is not quantified in this thesis.

The effect of public lighting on (public space) appearance

Implementers of public lighting often refrain from implementing too blue LEDs because they fear the resulting public outcry (Davidovic et al., 2019). In the same study, it can also be read that people prefer 3000K LEDs over 4000K. This preference was also found in Davidovic et al. (2018). The WTP/social cost for this, however, is not investigated in those or other studies. Other aesthetic effects of public lighting have also not been quantified or monetized. This makes it hard to give an estimation of even the order of magnitude. If this were to be done, the area of effect would mostly be small, since as one can imagine, the WTP/social cost for people from other streets, neighborhoods, cities, regions, and countries declines rapidly.

5.2.4 Effect of public lighting on mobility

There are only indirect effects on mobility due to public lighting. These effects are caused by the increased economic activity, a change in the impressions of the environment, or an increase in the perceived safety as can be read in various previous subsections. The found monetization for these already quantified effects can be used for these and other (undiscovered) causes of mobility as well. The monetization of mobility effects is split up into the opportunity cost of driving as well as congestion cost since these were the monetizable costs found by the author. The effect mobility has on the environment, road safety, and human health is also quantified and monetized in this subsection. These will result in indirect lighting effects since they occur through changes in mobility and not as a direct result in lighting.

Opportunity cost of car mobility

The overall opportunity cost per kilometer for a car owner is taken as the social cost since it is a result of several effects. This cost is € 0.48 per kilometer (Nibud, 2021), however, this cost includes taxes. These should be (partially) deducted in a Social Cost-Benefit Analysis (SCBA) if the tax receiving government layer and the government layer paying for the project do not match Boardman et al. (2018). It is assumed that € 0.19 per kilometer of the cost are taxes since this is the tax-deductible amount for driving a private car for business uses (Belastingdienst, 2021). Those taxes are collected at a national level. Therefore, if the level of government over which to apply the DSS is chosen as the national government, those taxes should be (fully) deducted. The exact amount to be deducted in the case of a municipality is the level of government over which to apply the DSS is dependent on the budget distribution of the (in this case) national government. For simplicity, it is assumed that none of the tax is distributed back to the municipalities.

Social cost of congestion

An increase in motor traffic also generates an increase in congestion. For a 2016 Euro 6 fuel-inefficient petrol car in an urban environment (assumed for all car traffic), the cost is € 0.41 per kilometer (CE Delft, 2019). Furthermore, for every kilometer that needs to be driven during placement and maintenance, € 0.99 is incurred due to an increase in congestion (assuming a 2016 fuel-inefficient Euro 6 LCV in an urban environment) (CE Delft, 2019). The areas of effect depend on where the vehicle is driven. However, it can be assumed that for both, the vast majority of trips will be local. This is the case since most trips are within 10 kilometers (Vehicle Technologies Office, 2018), and the placement can only be done locally.

Effect of mobility on the environment

An effect with both local and global consequences is pollution due to changes in mobility. A 2016 Euro 6 fuel-inefficient petrol car in an urban environment is assumed to be used for the changes in car mobility demand. The cost is € 0.03 per kilometer for global effects and € 0.01 per km for local effects (CE Delft, 2019). Aside from the environmental impact due to changes in mobility demand (caused by perceived safety changes), maintenance and placement also require mobility. The social cost for this can again be taken from CE Delft (2019). The total cost per kilometer is € 0.05 and € 0.02 per vehicle kilometer respectively for global and local effects (assuming a 2016 fuel-inefficient Euro 6 LCV in an urban environment).

Effect of mobility on road safety

The social cost caused by collisions in the Netherlands is estimated to be € 17 billion (SWOV, 2020). This is over 137 billion kilometers driven (CBS, 2020b). This means that on average, a kilometer of motor vehicle travel costs €0.12. If it is assumed that all trips are local trips, this cost can be used irrespective of the area considered in the SCBA.

Effect of mobility on human health

Mobility influences the health of humans is through an in/decrease time spent walking/cycling. According to WHO (2019) 4.61E-07 premature deaths per year per person are prevented for every minute spent walking/cycling if the Dutch average of 9.82 minutes of walking per person per day is taken as a base-case. This average is taken from WHO (2018). If a value for a statistical life is given the effect can be quantified. According to WHO (2019) a statistical life is valued at € 3800000.

5.2.5 Effect of public lighting on road safety

Safety is often considered as one of the main reasons for the placement of public lighting. Its direct effects on safety are, therefore, investigated. It should be noted that changes in mobility caused by the effects of public lighting also influence road safety. However, these are already covered in Subsection 5.2.4.

Historically, the scientific community found that improved public lighting reduces accidents quite significantly (Christie, 1970). In more recent years, this is still the case (Beyer & Ker, 2009), (Bullough et al., 2009). However, research stating that a reduction in lighting does not cause an increase in collisions can also be found (Perkins et al., 2015). This conclusion is not shared broadly (Fotios & Gibbons, 2018). It should, however, be noted that the data and methods of Perkins et al. (2015) are valid, and, therefore, it should not be disregarded. Instead, an attempt should be made to identify the cause of the differences and hopefully explain them.

To speed up the process of attempting to unify the knowledge base, meta-analyses reviewing Perkins et al. (2015) were sought. One such meta-analysis, however, only states the conclusions found in the scientific minority whilst not pointing to possible causes (Fotios & Gibbons, 2018). Marchant (2017) praises Perkins et al. (2015) for being one of the only studies that follow scientific principles such as transparency about conflict of interest, correcting for regression to the mean, and publishing the full data-set correctly. Furthermore, Marchant (2017) claims that there is evidence for publication bias in the public lighting field due to funder influence. Whilst being published before the study by Perkins et al. (2015), the poor methodological quality of most public lighting safety studies has also been pointed out by Beyer and Ker (2009). A later study by Marchant corroborates the results found by Perkins et al. (2015), (Marchant et al., 2020). This study uses the methodology as suggested by Marchant (2017). Marchant et al. (2020) point out that the reduction in accidents found in many studies may simply be the decrease of accidents over time in general. This is illustrated in Figure 5.3. The suggestion for future research is to conduct additional research to try to replicate the earlier works using a better methodology and open data sets. Furthermore, there remain questions over the most appropriate statistical approach and on how to calculate the accidents ratio during darkness (e.g. 24 hours vs. darkness vs. daylight adjusted darkness accident rate) (Marchant et al., 2020). In summary, since there is no scientific consensus on the direction of the effect, the effect of public lighting on road safety is not included (as an order of magnitude estimation).

It is also deemed that there is inconclusive evidence to accurately quantify (and monetize) the effects of scotopic vision, color temperature, or color rendering index (Marchant et al., 2020), (Fotios & Gibbons, 2018). The same inconclusive evidence is also a problem in identifying, quantifying, and monetizing the impact of intelligent/dimmable lighting. A large case study is currently being finalized in the US regarding this topic (Virginia Polytechnic Institute and State University, 2019). Once these results are published better conclusions can perhaps be reached. However, if the results of Perkins et al. (2015) and Marchant et al. (2020) are to be believed, the impact of dimming is non-existent. This non-existent effect is also shared by the U.S. Department of transportation as can be read in United States Department Of Transportation (2014).

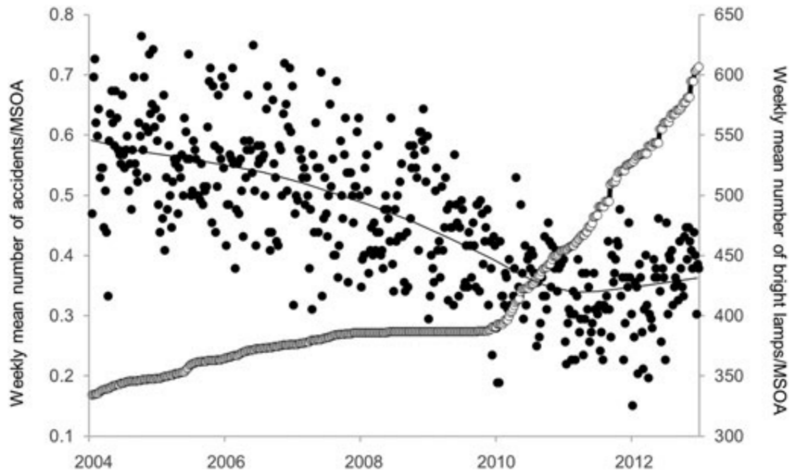

Figure 5.3: Accidents (black dots) and number of bright lights (white dots) (Marchant et al., 2020)

5.2.6 Effect of public lighting on crime

For the effect of public lighting on crime, the narrative from the effect on safety can mostly be repeated. It is regarded as one of the most important direct effects. It is also generally accepted that an increase in lighting decreases crime (Chalfin et al., 2019), (Painter & Farrington, 1999), (Clarke, 2008). However, it is also found that a reduction in lighting does not increase crime (Perkins et al., 2015), (Davies & Farrington, 2018). This is an issue since this way, crime can in theory be reduced by dimming lights and then increasing the lighting again. Since this is (obliviously) not true, more research is needed. This is also recommended by scientists in the field (Perkins et al., 2015), (Davies & Farrington, 2018). Furthermore, little research has been done into the relation of light intensity, temperature, CRI, and crime. Therefore, the effect lighting has on crime is not reliably quantifiable (or monetizable) with current literature. Since there is again also no scientific consensus concerning the direction of the effect, no order of magnitude estimation can be made.

5.2.7 Effect of public lighting on animals

The direct effects of lighting on animals cannot be taken into account in a SCBA since the effects included in a SCBA should only influence humans. The effect this has on humans can be quantified through other routes, however.

For instance, the influence of insect populations on a public lighting SCBA is potentially very large since the WTP/social cost of food shortages seems high, intuitively. The risk of food shortages is present since insects are in large part responsible for pollination, and thus for the food supply (Rader et al., 2015) That public lighting influences this is suspected since insect populations are decreasing rapidly (Potts et al., 2010), and nocturnal insect populations are the largest contributor to this decline (Langevelde et al., 2018), and open habitat invertebrates are affected more than closed environment invertebrates (Öckinger et al., 2006). This is all as one would expect if Artificial Light At Night (ALAN) has an influence (Desouhant et al., 2019).

Additionally, there is a WTP for biodiversity (Bhandari & Heshmati, 2010), which may further sway the balance of a SCBA that includes the effects of public lighting on animals. Such a WTP also relates to animals that are less critical to the ecosystem.

Furthermore, specific species will have individual WTPs concerning their quality of life (Martín-

López et al., 2008), these WTPs should also be included based on the effects of public lighting.

All of this is, however, not possible without knowing the quantified effects of public lighting on (all types of) animals. However, information on the long term effects of ALAN on animals is difficult to gather due to the differences between animal species, their evolutionary capacity, and the fact that light is usually only specified according to the visible human spectrum (Owens & Lewis, 2018), (Desouhant et al., 2019), (Owens et al., 2020). The evolutionary capacity is especially a problem since it can change the behavior within the human timescale (Owens & Lewis, 2018), (Desouhant et al., 2019), (Owens et al., 2020). An order of magnitude estimate can, however, be given based on some assumptions for the three indirect effects mentioned in this subsection.

While not generally applicable for all animals and surroundings, the effect of dimming has been investigated in Bolliger et al. (2020). This paper states that dimming can help with mitigating some of the negative effects of light pollution on animal populations. This is, however, not implemented in the DSS since the effect is not quantified. Still, it could mean that in many situations, no public lighting or aggressive dimming could become the best option.

Pollinator population decline social cost estimation

If it is assumed that due to public lighting 10% of pollinators could die, this would result in an approximate 0.5% increase in food price (Ritchie, 2021). Price elasticity is assumed to be around 0.4 resulting in an approximate 0.3% increase in food spending overall (Andreyeva et al., 2010). On average, 13% of total income is spent on food in the Netherlands (Logatcheva, 2020). The average Dutch income is € 30800 per year (Randstad, 2021) annually. This means that on average around € 12 per year of consumer surplus is lost per inhabitant annually due to public lighting. However, if only one street/area is lit, the effects are zero. This is the case since the global food supply is then not affected in any meaningful way.

Biodiversity WTP estimation

The next order of magnitude estimation will be for the biodiversity. It is assumed that people have a WTP for biodiversity of around € 10 per person based on Surendran and Sekar (2010). It is assumed that around 5% of biodiversity is lost due to light pollution from public lighting. This means that to prevent public lighting the WTP could be around €0.50 per person. However, if only one street/area is lit, the effects are again zero. This, again, is the case since the global biodiversity is then not affected in any meaningful way.

Animal welfare WTP estimation

It is assumed the WTP for animal welfare increase by not having public lighting is the same as the WTP increase for beef when the cows are kept in better conditions. The WTP for better welfare beef is 20% over the annual spending on beef (Sans & Sanjuán-López, 2015). The annual spending on beef (1221 million in 2020) is taken from Statista (2021b). The Dutch population is assumed to be 17 million. In total, this gives a WTP for animal welfare of € 14.36 per person per year. However, if only one street/area is lit, the effects are again zero. This once more since global animal welfare is then not affected in any meaningful way.

5.2.8 Effect of public lighting on human health

Light exposure at night has severe impact (direct effect) on human health (American Medical Association, 2016), (Maierova, 2018). For example, there is an increased chance of certain types of cancer (Pauley, 2004). Furthermore, sleep rhythms are disturbed (Czeisler, 2013). Light can also influence health due to indirect mobility effects (indirect), these are covered in Subsection 5.2.4.

Both the cancer development and sleep rhythm disruption (and most other lighting health effects) are caused by the suppression of melatonin production (Czeisler, 2013), (Pauley, 2004). Maierova (2018), states that the production of melatonin is especially hindered by blue light sources. It can also be seen how different light sources compare. For instance, it is stated that Light Emitting Diode (LED) (2167K) public lighting reduces the amount of melatonin produced to around 50% when compared to High Pressure Sodium (HPS) (2057K) public lighting (Maierova, 2018). This conclusion is, however, not shared with (National Cooperative Highway Research Program, 2021). National Cooperative Highway Research Program (2021) found no difference between HPS and LED public lighting. This difference in findings is yet to be explained by the scientific community. However, it is thought that the intensity of the light is of importance (National Cooperative Highway Research Program, 2021). However, until this is included in the literature, the effects of public lighting on melatonin production cannot be quantified or monetized accurately using literature.

To assign a potential order of magnitude to the direct effect of public lighting on health (regardless of the technology used) it is assumed that some percentage of insomnia is caused by public lighting. Currently, it is assumed that this percentage is 0.5%. While the percentage is an assumption, there is a significant relation between insomnia and light pollution (Min & Min, 2018). Cost of insomnia per person per year is estimated to be around €1900 in total.€9.5 is, therefore, the cost of public lighting (assuming a population in the Quebec province of 7.3 million) (Skaer & Sclar, 2010).

Despite this uncertainty, the order of magnitude estimation is such that a potential best practice is warranted. This best practice would be to limit the extent of exposure to blue light for humans (and other animals) using a dimmer and using different spectra of light at different times (Maierova, 2018). If there is little to no blue light, then melatonin production is not/marginally limited and the negative effects are thus prevented (Maierova, 2018).

5.2.9 Effect of public lighting on energy usage

Public lighting systems as well as the production of the components require energy, making the energy consumption a direct effect. While the cost of the energy used during operations is covered under costs and the cost of energy used during production is already included in the purchasing price for these items, the societal cost of the production of the energy is not (making it an indirect effect). Therefore, the energy consumption (during production) should be quantified. However, due to the way pollution is calculated in the literature used, this is not required for production since power generation pollution is already included. Therefore, only the energy usage during operation is covered in this thesis. The indirect effect of lighting on the environment is monetized in this subsection.

Effects of public lighting use on energy usage

Public lighting uses energy. The amount of energy is dependent on the amount of light that is emitted and the type of light source that is used. Every light source has a luminous efficacy [lumen/watt]. By combining this quantity with either the power draw or the light emitted the other can be calculated. The power draw when dimmed can, of course, also be calculated in this manner. Furthermore, the power draw of other components in a public lighting system should be taken into account. To monetize the amount of electricity used, the cost per unit of energy needs to be multiplied by the amount of energy used. The cost again depends on the size of the area considered in the SCBA. If it cannot be assumed that the energy cost is imported, the opportunity cost should be used (Boardman et al., 2018). This is what is done in Subsection 4.2.1.

Effects of energy usage on the environment

The electricity usage of a lighting system also has global environmental effects. This is an indirect effect of lighting. As can be seen in EEA (2008), the impact of the Dutch and German power mix is quite similar. Furthermore, the Dutch and German grids are heavily interconnected (Tennet, 2021), meaning that there is quite the chance that German-generated power will be used. Karkour et al. (2020) gives the social cost of power usage for G20 countries (including Germany). While the value from EEA (2008) could be used, Karkour et al. (2020) is used due to fact that it is much more recent, includes clearer methods, more cost factors, and an extensive literature review. If it is assumed that the power mix of the Netherlands is similar to Germany, the social (indirect) cost of electricity is around 0.019 €/kWh.

5.2.10 Effect of public lighting on the environment

The environment is influenced by public lighting in several ways. In this subsection, the direct effects of public lighting on plants are covered, the direct public lighting effects of hazardous materials in public lighting systems, and the impact of public lighting production on the environment (direct effect). Other indirect effects of lighting on the environment were covered in different subsections. These are the indirect effects of mobility on the environment (Subsection 5.2.4) and the indirect effects of energy usage on the environment (Subsection 5.2.9).

Effect of public lighting on plants

Locally, an environment is lit up by public lighting. Alongside other potential effects, this has an effect on the plants in the vicinity of the light source (Bennie et al., 2016). The impact this has is of importance since it has been estimated that the UK has more than twice the area of verge compared to natural or semi-natural grassland in the wider countryside (Bennie et al., 2016). Of this verge area, a large portion is lit by public lighting. There is little information about the precise effects that ALAN has on plants (Bennie et al., 2016). Therefore, this effect cannot be quantified for a SCBA. It does, however, have the potential to influence entire ecosystems since flowering and growth are both proven to be influenced by ALAN in specific plants (Bennie et al., 2016).

Effect of public lighting on hazardous materials

Another direct effect is the potential introduction of hazardous materials into the environment. This can, for example, happen when a fluorescent lamp breaks open due to the inclusion of mercury in those lights. A typical fluorescent lamp contains between 10-50 mg of mercury (IMERC, 2021). It was estimated in 2010 that every kg of leaked mercury costs $1500 (Pacyna et al., 2010). This is approximately €2250 per kg in 2021. This means that for every improperly disposed of/opened fluorescent lamp between €0.002 and €0.01 of damage occurs. The costs can occur locally as well as globally depending on the dispersion of the mercury (Pacyna et al., 2010). This makes it hard to implement into a SCBA with a local area of effect.

Lead is also present in most lamps due to the presence in the majority of solders. The societal impact of the lead in these solders is, however, not currently monetizable. It is hard to quantify due to the lack of research into this topic, the variation of solder used, and the amount of solder used from one light source to another. It can, however, be assumed that the impact is limited. This can be said since the main contributors to lead pollution are lead paint and lead piping, which both offer much more exposure (Ecology Center and the Michigan Network for Children's Environmental Health, 2018). Other potentially hazardous materials are also present in LEDs such as copper, iron, lead, nickel, and silver (Lim et al., 2010). The social cost for the amounts released is, however, not monetizable due to a lack of found research.

Effect of luminary production on the environment

The combination of fixtures and lights of public lighting systems are called luminaires. The production of these luminaries causes an (environmental) social cost. The comparative environmental impact for HPS (comparable to other electric gas lighting technologies due to similar components), Metal Hydrate (MH), Induction (IND) (comparable in technology to Fluorescent Lighting (FL) due to similar components), and LED luminaires can be found in Dale et al. (2011). The overview can be seen in 5.4. However, since the publication is from 2011 it can be assumed that LEDs have progressed. Expressing the exact extent of the improvement is impossible due to unclear inputs for the calculation methods in Dale et al. (2011). Therefore, another, more recent LCA for entire luminaires is located (Tähkämö & Halonen, 2015). This LCA clearly states its calculation methods and inputs. Only HPS and LED luminaires are covered here and a different LCA method is used (TRACI instead of ECO-I-99). Therefore, the results can not be accurately combined. However, the combination should give a sufficiently accurate representation for the SCBA.

The quantification (using information from Tähkämö and Halonen (2015)) and monetization of the various pollutants emitted during HPS and LED production can be seen in Table 5.1. The monetization is calculated using the data seen in Table 5.2. As can be seen in Table 5.2, the found ranges for some pollutants are quite wide. Additionally, no data is present for IND lights. Looking at 5.4, however, it can be said that HPS and IND are somewhat similar. Therefore, it is assumed that the monetized environmental impact is also similar.

Currently, the median values from Table 5.2 are used in Table 5.1. However, if the minimum and maximum values are used the social costs are €2.19 per Watt and €15.46 per Watt for HPS and €44.64 per Watt and €317.59 per Watt for LED respectively.

Finally, it should be noted that all effects under the current header have a global area of effect. Their contribution to the people in the local environment can however not be disregarded due to the relatively large social costs.

Table 5.1: Manufacturing impacts of HPS and LED luminaires (Tähkämö & Halonen, 2015)

Pollutant	**HPS [g/W]**	**LED [g/W]**	**HPS [€/W]**	**LED [€/W]**
SO_2 eq.	1.81	16.92	0.060	0.557
CO_2 eq.	406	4289.38	0.014	0.150
PO_4 eq.	1.18	10.46	0.006	0.052
$1,4-DCB$ eq.	2077	14560	16.952	118.814
C_2H_4 eq.	0.14	0.88	0.004	0.027
$CFC-11$ eq.	0.09	0.29	0.012	0.039
Sb eq.	4.04	28.69	0.041	0.293
Total			**17.09**	**119.93**

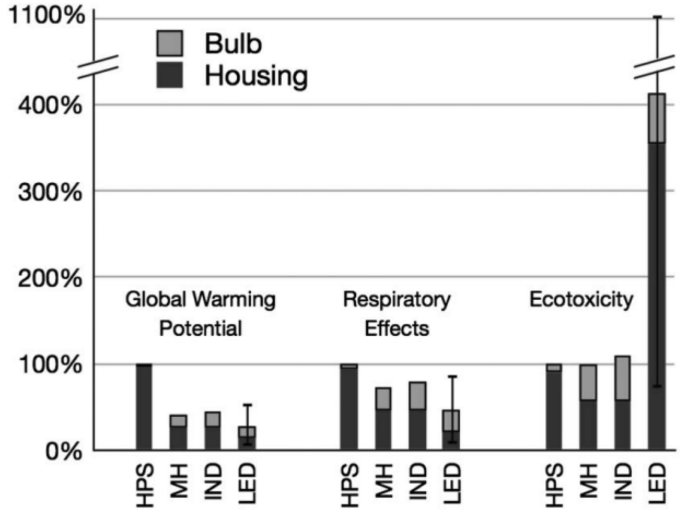

Figure 5.4: Materials impacts, with use phase not included, for HPS, MH, IND, and LED technologies; normalized by impacts of high-pressure sodium technology (Dale et al., 2011)

Table 5.2: Social cost of different pollutants

Pollutant	**Cost [CUR/kg] (min-med-max)**	**Cost [€/kg]**
SO_2 eq.	20 [2007 USD] (Shindell, 2014)	32.9
CO_2 eq.	-0.013-0.031-2.4 [2019 USD] (Wang et al., 2019)	0.035
PO_4 eq.	4.7 [2014 EUR] (Hautakangas et al., 2013)	5.02
$1,4-DCB$ eq.	1-8-17 [2019 EUR] (Arendt et al., 2020)	8.16
C_2H_4 eq.	0-30-763 [2019 EUR] (Arendt et al., 2020)	30.6
$CFC-11$ eq.	120 [2011 EUR] (Sustainability Impact Metrics, n.d.)	133.2
Sb eq.	0-10-18000 [2019 EUR] (Arendt et al., 2020)	10.2

The effect of pole production on the environment

The impact of the production of poles should also be quantified. However, most LCA studies for public lighting do not include poles since they are generally the same irrespective of the luminaire used. Therefore, a rudimentary material breakdown will be made.

Most poles in the Netherlands are either made of steel or aluminium (van der Kolk, n.d.-c). However, composite poles are becoming increasingly relevant (van der Kolk, n.d.-c). Steel poles for a height of 5.75 meters to 13.7 meters weigh between 73 and 416 kilograms respectively (Transpower, 2021). Aluminium poles weigh 41 and 91 kilograms for 6 and 10 meter poles (MHL, 2021). Composite poles weigh 32 and 90 kilograms for 7 and 12 meter poles. If it is assumed that the relationship is a power function, then the weights can be calculated for any height. A power function is the most logical option since then at a height of zero, the weight is also zero. Additionally, when a pole gets higher, more weight per height increase is required in the power function (same as in reality). The plot of the functions with the equations included can be seen in Figure 5.5. Now that the weight is quantified for all pole heights, the pollution per unit weight can be used to quantify the social cost. With the values from Table 5.2 for steel and aluminium, Table 5.3 was made. For composites, information from Statista (2021a) and DeWit et al. (2021) is used. If the minimum and maximum social costs are used, the costs per kilogram are € 0.05 and € 4.34 for steel and € 2.97 and € 49.83 for aluminium respectively. For composites, it is currently assumed that the poles will not affect marine environments. If they are do, however, the societal cost could increase to €6.38 (Statista, 2021a), (DeWit et al., 2021).

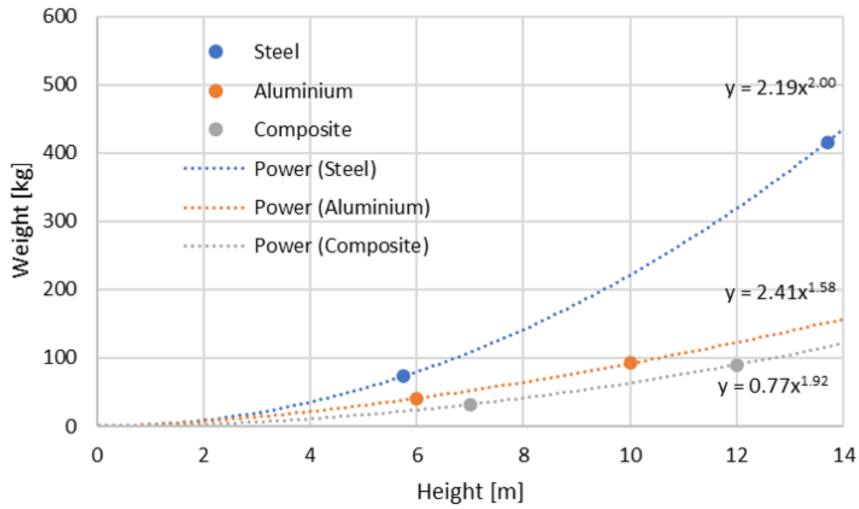

Figure 5.5: Weight of different material poles (Transpower, 2021), (MHL, 2021)

Table 5.3: Social cost of steel, Aluminium, and composite production (Nunez & Jones, 2015), (Hu et al., 2014), (Statista, 2021a), (DeWit et al., 2021)

Pollutant	Steel [kg/kg St]	Aluminium [kg/kg Al]	Steel [€/kg St]	Aluminium [€/kg Al]	Composite [€/kg Al]
SO_2 eq.	1.1E-03	1.3E-01	3.6E-02	4.3E+00	
CO_2 eq.	1.0E+00	1.7E+01	3.7E-02	5.8E-01	
PO_4 eq.	-	1.1E-02	-	5.5E-02	
$1,4-DCB$ eq.	3.4E-03	-	2.8E-02	-	
C_2H_4 eq.	8.6E-04	8.5E-03	2.6E-02	2.6E-01	
$CFC-11$ eq.	-	2.9E-10	-	3.9E-08	
Sb eq.	-	-	-	-	
Total			**0.13**	**5.17**	**0.39**

5.3 Overview of the implemented and missing monetized effects

In this section, an overview of the found effects, quantifications dependencies, and monetizations is given. In Figure 5.6, the found relations between the different effects can be seen. In Table 5.4, the monetized effects can be seen for a global lighting policy and a global area of effect as well as a local area off effect for the monetization (based on the number of inhabitants of Nuenen). In Table 5.5, the changed monetized effects can be seen for a local lighting policy. Although a distinction between direct and indirect effects is made (in Table 5.4 and 5.5), this distinction is not used in further stages. This distinction is not used in further stages since CPB & PBVL (2013) state that indirect effects which affect wealth significantly should always be included in a SCBA. Some effects were found, however, the direction of the effect was unclear. In that case, a question mark (?) was entered for the monetization in Table 5.4. These effects should be taken into account, however, it is not possible with the current knowledge base.

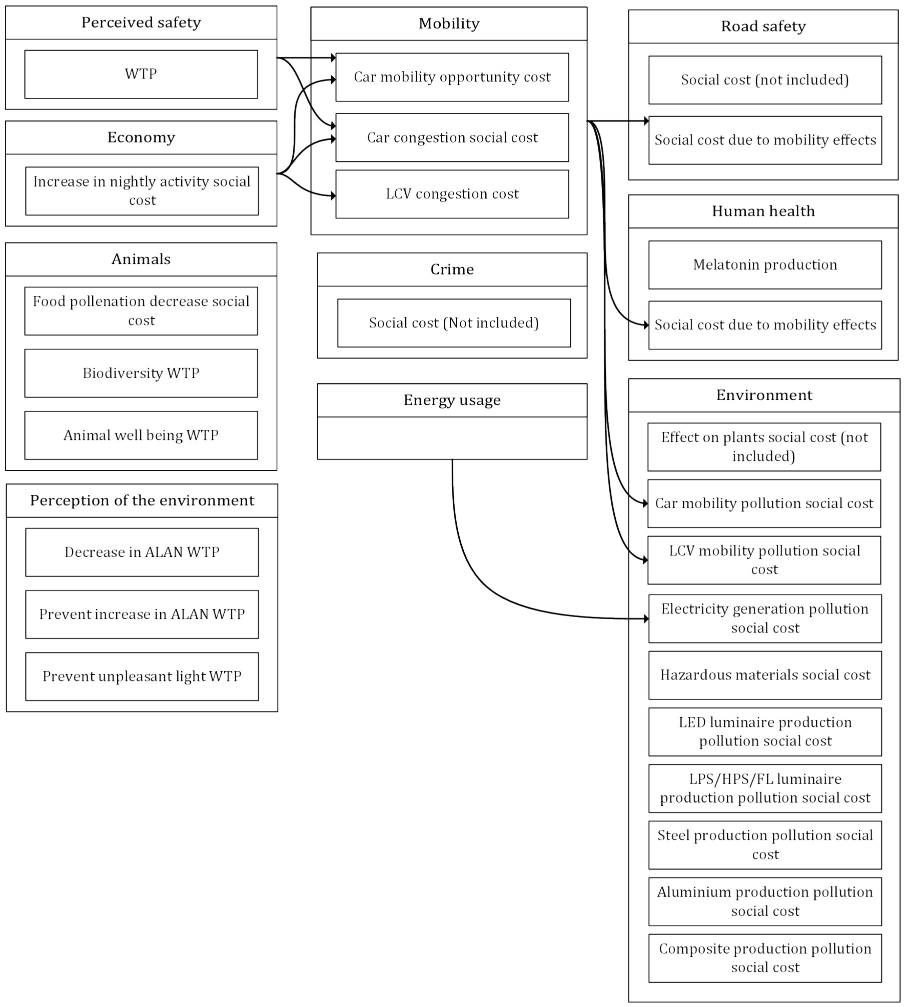

Figure 5.6: The included effects and relations between the effects in the DSS

Table 5.4: Monetized effects of public lighting for a global lighting policy

What	**Unit**	**Global**	**Local**	**Direct**	**Indirect**
Percieved Safety					
- WTP	$€/inh$	145	145	X	
Economy					
- Increase in nightly activity social cost	$€/inh/y$	52	52	X	
Impressions of the environment					
- Decrease in ALAN WTP	$€/inh$	50	50	X	
- Prevent increase in ALAN WTP	$€/inh$	5.0	5.0	X	
- Unpleasant light WTP		?	?	X	
Mobility					
- Car mobility opportunity cost	$€/km_{car}$	-0.67	-0.48		X
- Car congestion social cost	$€/km_{car}$	-0.41	-0.41		X
- LCV congestion social cost	$€/km_{lcv}$	-0.99	-0.99		X
Road Safety					
- Road safety social cost		?	?	X	
- Change in R.S. through mobility social cost	$€/km_{car+lcv}$	-0.12	-0.12		X
Crime					
- Crime social cost		?	?	X	
Animals					
- Food pollenation decrease social cost	$€/inh/y$	-12	-12	X	
- Biodiversity WTP	$€/inh$	-0.50	-0.50	X	
- Animal well being WTP	$€/inh/y$	-14	-14	X	
Human Health					
- Melatonin production social cost	$€/inh/y$	-9.5	-9.5	X	
- Change in mobility social cost	$€/min_{dailywalk} \cdot inh/y$	1.8	1.8		X
Environment					
- Effect on plants WTP/social cost		?	?	X	
- Car mobility pollution social cost	$€/km_{car}$	-0.03	-6.0E-03		X
- LCV mobility pollution social cost	$€/km_{lcv}$	-0.05	-1.9E-02		X
- Electricity generation pollution social cost	$€/kWh$	0.02	5.4E-08		X
- Hazardous materials social cost	$€/light_{FL}$	-0.01	-1.4E-08	X	
- LED luminaire production pollution social cost	$€/W$	-119	-3.4E-04	X	
- LPS/HPS/FL luminaire production pollution social cost	$€/W$	-17	-4.9E-04	X	
- Steel production pollution social cost	$€/kg$	-0.13	-3.7E-07	X	
- Aluminium production pollution social cost	$€/kg$	-5.2	-1.5E-05	X	
- Composite production pollution social cost	$€/kg$	-0.39	-1.1E-06	X	

Table 5.5: Changed monetized effects of public lighting for a local lighting policy

What	**Unit**	**Global**	**Local**	**Direct**	**Indirect**
Impressions of the environment					
- Decrease in ALAN WTP	$€/inh$	0	0	X	
- Prevent increase in ALAN WTP	$€/inh$	0	0	X	
Animals					
- Food pollenation decrease social cost	$€/inh/y$	0	0	X	
- Biodiversity WTP	$€/inh$	0	0	X	
- Animal well being WTP	$€/inh/y$	0	0	X	

Chapter 6

Risks analyses included in the DSS

In this chapter, sub-questions 6.1 and 6.2 are answered. Sub-question 6.1 is answered first (Section 6.1). Second, the focus of this section will be to explain how the selected method for risk assessment is applied and give the risks for the expenses, costs, and benefits (Section 6.2).

6.1 SCBA risk theory

As already mentioned in Section 1.4, several options regarding risk assessment for social cost and benefit analyses (SCBAs) are mentioned by CPB & PBVL (2013) and Boardman et al. (2018). What is not mentioned there is that several types of uncertainties exist of which the risks need to be assessed (CPB & PBVL, 2013). These risk types are knowledge-uncertainties, policy-uncertainties, and future-uncertainties. In this section, each type of uncertainty will be covered. This will be done by first explaining what these types of uncertainties are and then, an advised method of controlling the risk occurring as a result of this uncertainty will be given.

6.1.1 Knowledge-uncertainty

Knowledge-uncertainty occurs due to (a lack of) knowledge (CPB & PBVL, 2013). This manifests itself in deviating predictions of costs and effects. Monetized effects and prices can, for instance, be higher or lower than in reality. Furthermore, effects that should be included may also be missed. Both are likely the case in the conducted SCBA since some effects are not included and others are only order of magnitude estimations. The best remedy for the latter is to perform the research thoroughly and make sure that all effects are identified and included. To combat the former, a sensitivity analysis should be conducted. While this may be done with for instance a Monte Carlo analysis, this is often not practical due to the high data requirement (CPB & PBVL, 2013). Therefore, it is advised that several key parameters are changed within a certain bandwidth (CPB & PBVL, 2013).

6.1.2 Policy-uncertainty

Policy-uncertainty occurs due to changes in other government policies (not related to the SCBA) that affect the evaluated project (CPB & PBVL, 2013). For example, infrastructure projects in the Netherlands are often calculated with and without "Kilometerheffing" (CPB & PBVL, 2013). "Kilometerheffing" is given as an example since it is thought to have major consequences on car usage (reduction) and the usage of other types of mobility (increase) in the Netherlands (Hilbers et al., 2007). It might, therefore, for instance, sway the decision in an SCBA deciding between a new road and train connection. However, in the case of public lighting, no such influential policy changes are currently being considered. Therefore, policy-uncertainty is not covered further in this thesis.

6.1.3 Future-uncertainty

Future-uncertainty influences a project's projections for future welfare (CPB & PBVL, 2013). When these are only project-related, they are irrelevant since the average deviation over all projects can be assumed zero (CPB & PBVL, 2013). However, macroeconomic changes do need to be accounted for in a variability analysis. Macroeconomic changes manifest themselves in changes in for instance inflation, price levels, rate of economic growth, national income, gross domestic product, and changes in unemployment (Investopedia, 2020). These factors can respectively change due to (recovery from) a global pandemic or a war (European Central Bank, 2021), (Ziffer, 2022).

To account for macroeconomic changes, future scenarios should be implemented with differing economic growth rates (CPB & PBVL, 2013). Since the research load of investigating the effects of future uncertainty for all on all of the costs and benefits is high, an alternative is used.

The alternative is to alter the discount rate. The discount rate determines the current value of future costs/effects. If the discount rate is lower, the NPV will be higher, and vice versa. This somewhat represents future economic growth since if growth is low, the future cost will be valued higher. Therefore, a low discount rate is advisable as the little growth scenario and the high discount rate scenario is advisable as the large economic growth scenario.

6.2 Implementation in the DSS

6.2.1 Knowledge-uncertainty

As could be read in Section 6.1 it is advised that several key parameters are changed within a certain bandwidth and that the search for the effects is conducted thoroughly. The latter was done in Section 5.2. The former will also be done for the results found in this thesis. Since the probability intervals are unknown for the monetized effects and the costs, educated guesses regarding the intervals will have to be made. For the effects that are believed to have accurate quantification and monetization, 50% and 150% of the quantified amount will be used as the probability interval. For order of magnitude quantity/monetary estimations, the probability range will be 10% to 1000% of the original quantity to incorporate an order of magnitude deviation. The effects will be sorted into positive and negative categories to arrive at best and worst cases. In Appendix I an overview of the quantification ranges per effect can be seen.

The expenses are not varied since the author perceives the current pricing and quantification implementation as much more accurate than that of the effects. This would lead to such a small range that the costs/benefits of the project as a whole are not affected much.

In the Decision Support System (DSS), the knowledge-uncertainty analyses in conducted by one of the Visual Basic for Applications (VBA) scripts. The results of the risk analyses are presented in the "Results" sheet. The ranges from Appendix I used are present on the "Calculations" sheet.

6.2.2 Future-uncertainty

As could be read in Section 6.1, a low discount rate is recommended as the little growth scenario and the high discount rate scenario as the large economic growth scenario. Therefore, the discount rate of 4.5% will be in- and decreased by three percentage points.

In the DSS, the future-uncertainty analyses in conducted by one of the VBA scripts. The results of the risk analyses are presented in the "Results" sheet. The percentage point ranges used are present on the "Indexation" sheet.

Chapter 7

Applying the DSS

In this chapter, the main research question will be answered for several areas. The answer provided for the main research question has to be limited to several areas (and thus circumstances) for the report since all possible circumstances cannot be taken into account in a report (variation is possible in the Decision Support System (DSS)). Therefore, the question of whether or not, in the circumstances of these areas, the not-yet depreciated public lighting can be replaced with intelligent Light Emitting Diode (LED) lighting will be answered. To do so, the DSS is, run for several areas and optimized towards the policy goals.

First, what areas were picked for analysis will be explained. Second, the results for these areas will be presented. Finally, the risks for these areas will be reviewed.

7.1 Selected areas

As already mentioned in this thesis, cases are needed for demonstrating the DSS in the report, and a municipality (or other road authority) is useful for supplying in-depth data. A road authority was, therefore, chosen and contacted, and three areas were picked for optimization. The first area has not yet depreciated Fluorescent Lighting (FL), the second High Pressure Sodium (HPS) lighting, and the third LED lighting.

Optimization can take place since incidental replacements are more expensive than group replacements and the older a part becomes the more likely it is to fail. This can thus result in savings/costs. Furthermore, as mentioned in Section 5.2, LEDs have become more efficient since 2011. Therefore, it might not be best to wait until the lights have been fully depreciated for replacement, due to possible savings in energy cost.

The municipality of Nuenen was chosen and contacted due to their experience with and data concerning intelligent lighting (since 2013 (TVI, n.d.)). They have provided access to their data concerning public lighting. The information that is shared includes but is not limited to financial data, energy usage data, and placement data. They are willing to share this information since it is not (privacy) sensitive and in return for their cooperation, a part of their municipality is used for the area study and the results will be shared. The current and future scenarios used in the area study will also be (partly) based on the preferences of the municipality of Nuenen and past choices.

In this section, some general information applicable for all three areas will be given first, then the input for the individual areas will be discussed. Last, the used optimization ranges will be discussed.

7.1.1 General data Nuenen

Some data is relevant for all areas (within Nuenen), to prevent repetition, this data is located here. This data will be placed in the general input and area input on the "User Input" sheet of the DSS. While it is in the "User Input" sheet it is part of the database component as soon as it is entered.

- It is assumed the lighting depot is located 20 km from the area.
- It is assumed that Nuenen has 20000 inhabitants and the world has 7 billion (used for calculating localized global effects).
- The end date for all Net Present Value (NPV) calculations is set at 2070.
- Poles are painted/cleaned every 12 years in Nuenen.
- LED Luminaries are cleaned every 6 years in Nuenen. Classic Luminaires are cleaned when the bulb is replaced.
- The intended life of the existing fixtures is 25 years.
- The intended life of the led lights is also 25 years.
- The intended life of the existing poles is 50 years.
- On average 20.5 poles are connected to a single grid connection in Nuenen.
- It is assumed all the areas have a ROVL class of P2.
- According to the municipality of Nuenen, for bulk purchases, a 25% material discount should be taken into account.
- It is assumed that global and local opportunity costs are the same.

Additionally, some information and assumptions are required for calculating the energy usage when adaptive dimming is used. For calculating the traffic flow it is assumed that every resident leaves their house for a trip 3.57 times a day (Sánchez et al., 2014). An average of 2.1 persons live in a household (Volksgezondheidenzorg.info, 2021). It is assumed that an average of 100 people visit commercial addresses daily. When people leave their home/visit and address it is assumed that people travel through half of the area he/she is living in when doing so (average in a dead-end street). It is assumed that there is no through traffic in an area.

7.1.2 Case old LEDs: Eeneind-Oost

The first selected area is Eeneind-Oost. This area was selected since it is one of the first sites where static dimming LED lighting was implemented. The data listed here will be placed in the area input field on the "User Input" sheet of the DSS.

- The lighting was placed in 2011, and is, as such, not yet depreciated.
- The total road length is approximately 700 meters.
- Along these 700 meters of road 37 light points were placed.
- These light points are 30 watt dimmable LED luminaires placed atop a 3.5 meter steel pole.
- The Eeneind-Oost development consists of 64 residential addresses, therefore approximately 134.2 people live in Eeneind-Oost.
- The average lighting point sees 3354 traffic participants a week (calculated using the information and assumptions given in Subsection 7.1.1).

7.1.3 Case HPS: Pastoorsmast

The second area (only one street) is the Pastoorsmast. This area was selected since it is one of the last installed streets with HPS lighting in Nuenen. The data listed here will be placed in the area input field on the "User Input" sheet of the DSS.

- The lighting was placed in 2008, and is, as such, not yet depreciated.
- There are 7 industrial/commercial addresses along the Pastoorsmast, therefore no people live here.
- The total road length is approximately 400 meters.
- Along these 700 meters of road 11 light points were placed.
- These lightpoints are 50 watt HPS lights atop 5 meter steel poles with a lighting support beam in 70 watt fixtures (no dimming used).
- The existing light replacement interval is 4 years. The lights were last replaced in 2019.
- In total 4900 traffic participants a week are present in the area. (calculated using the information and assumptions given in Subsection 7.1.1).

7.1.4 Case FL: Larikslaan

The third area (only one street) is the Larikslaan. This area was selected since the lighting here was one of the last newly placed fluorescent lighting systems in Nuenen. The data listed here will be placed in the area input field on the "User Input" sheet of the DSS.

- The lighting was placed in 2008, and is, as such, not yet depreciated.
- There are 37 residential addresses along the Larikslaan, therefore approximately 77.7 people live in the Larikslaan.
- The total road length is approximately 400 meters.
- Along these 490 meters of road 22 light points were placed.
- These lightpoints are 36 watt dimmable FL lights were placed atop 5 meter poles steel in 36 watt fixtures (static dimming used).
- The existing light replacement interval is 4 years. The lights were last replaced in 2017.
- In total 1942 traffic participants a week are present in the area. (calculated using the information and assumptions given in Subsection 7.1.1).

7.1.5 Optimization ranges

To make the DSS quicker, optimization ranges have been defined. The time needed to run the DSS increases quite rapidly with an increased optimization variables range. Therefore, a balance has to be struck between run-time and usability of the results. The number of different options for the optimization variables can be seen Table 7.1. The minimum and maximum values for the optimization criteria are dependent on the case and, therefore, not listed here. It can be said, however, that values all are centered around the base-case. If the number is even then an extra option with a value higher than the base-case exists. The interval for all variables except the pole replacement interval and the pole replacement year is 1. The pole replacement interval and year are linked to the fixture (re)placement. This means that poles can only be placed when the fixture is also replaced. This was done to increase the performance of the DSS, and since this is the way poles are replaced in reality, it is a small sacrifice. The number of lighting configurations is determined by multiplying the number of poles, possible luminaires, and applicable dimming profiles.

As can be seen in Table 7.1, the ranges are quite limited for most variables. However, the most important variables are kept most variable. These variables are when the fixtures are to be replaced initially and what the interval of replacement is thereafter. These variables were selected since they have the largest impact on the monetized effects and costs and define what type of light is used when. Fixtures are the most expensive part of a lighting system to purchase and place. They also have the largest influence on the effects due to their pollution during production.

It should also be noted that for a fair comparison, the light output is not varied. This has to be the case because little of the monetized effects are sufficiently quantified to be able to distinguish between different light levels, therefore, the result of DSS would be to have the minimum amount of light in all cases to reduce cost.

Table 7.1: Number of different options for the optimization variables

What	**LED**	**Conventional**	**Total**
Replacement year of existing fixtures	7	5	
Replacement year of existing lights	1	3	
Replacement interval of new fixtures	6	6	
Replacement interval of new lights	1	3	
Luminaire cleaning interval new lights	3	3	
Replacement year of existing poles	3	3	
Replacement interval of new poles	3	3	
Number of lights per fixture	1	2	
Lighting system configurations	*144*	*168*	
Total	163296	2449440	2612736

7.2 Results for the areas

In this chapter, an overview of the results required to answer the main research question will be given. The results required to do so are what fixtures give the highest NPV and when to replace the current fixtures to reach the highest NPV. The full results as seen in the DSS are given in Appendix J. The DSS will be run with a selection of settings. The first setting is to run the DSS for global costs and benefits and global lighting policy (EGG). The second setting is to run the DSS for global costs and benefits with a local lighting policy (bound to the area) (EGL). Third, the boundaries of the DSS costs and benefits will be set to local (municipal boundaries) (ELL). Fourth, all effects will be disabled, thus creating a Cost-Based Analysis (CBA) (for municipal cost boundaries) (CLL).

As can be seen in Table 7.2, Low Pressure Sodium (LPS) and LEDs with static dimming result in the highest NPVs. Thus, intelligently dimmed LEDs are not worth the additional costs for the circumstances found in these areas according to a Social Cost-Benefit Analysis (SCBA). It can also be seen that LEDs with intelligent or static dimming use the least energy. Which dimming regime uses less energy is dependent on the dimming profiles used and the amount of traffic (see Appendix G).

In Table 7.3, it can be seen that when global effects are taken into account, replacing the lighting systems before the old systems are depreciated does not result in an optimum NPV. When only local effects are taken into account, depending on the current lighting technology, it can be more efficient to replace the current lighting system before it is deprecated.

The difference between the different settings (local and global effects) is caused by the fact that the global environmental cost of LEDs is quite high compared to that of other lighting technologies. The difference between the areas is caused by the circumstances in the area. Replacement for Eeneind-Oost is most likely not possible due to lower electricity cost due to the more efficient LEDs currently being used. The same theory can also explain the difference between the Pastoorsmast and the Larikslaan since in the Larikslaan more powerful lights are currently being used resulting in larger potential savings and thus, earlier replacement.

Table 7.2: Fixtures with the highest NPV

Setting\Area	**Eeneind-Oost**	**Pastoorsmast**	**Larikslaan**
EGG	LPS	LPS	LPS
EGL	LPS	LPS	LPS
ELL	LED Static	LED Static	LED Static
CLL	LED Static	LED Static	LED Static
Lowest energy	LED Intelligent	LED Static	LED Intelligent

Table 7.3: Fixture replacement years with the highest NPV

Setting\Area	**Eeneind-Oost**	**Pastoorsmast**	**Larikslaan**
EGG	2039	2035	2035
EGL	2039	2035	2035
ELL	2039	2031	2033
CLL	2039	2031	2033
Base	2036	2033	2033

7.3 Risks in regard to the areas

As could be read in Section 6.1, the risks will be investigated by presenting the risk uncertainty, future uncertainty, as well as the combination of both. Since the risks for the global effects and lighting policy are the largest, only these will be presented for the three areas. Since the risks are also an order of magnitude larger than the total costs and benefits, only the base-case will be presented for every area. In the DSS, the other risks can, of course, also be seen.

7.3.1 Case risks: Eeneind-Oost

As can be seen in the "Total NPV" column of Table 7.4, the uncertainty ranges for Eeneind-Oost are large. The knowledge uncertainties are a different order of magnitude larger than the costs and benefits in the positive and negative directions. The ranges for future uncertainty are much smaller. However, they remain large enough to offset the negative NPV of the original base-case into a positive.

Table 7.4: Risks for the base-case in Eeneind-Oost

						Worst	Best	Worst	Best
What	**Unit**	**Worst**	**Best**	**-3%**	**+3%**	**-3%**	**-3%**	**+3%**	**+3%**
CAPEX									
- Lost capital	€	0	0	0	0	0	0	0	0
- New investment	€	-17368	-17368	-43936	-7949	-43936	-43936	-7949	-7949
OPEX									
- Electricity	€	-4866	-4866	-9606	-2955	-9606	-9606	-2955	-2955
- Maintenance	€	-6769	-6769	-12994	-4046	-12994	-12994	-4046	-4046
Effects									
- Perceived safety	€	1942	194176	19418	19418	1942	194176	1942	194176
- Economy	€	20057	2005724	384016	124577	38402	3840159	12458	1245770
- Impressions of the environment	€	-67033	6039	-6039	-6039	-67033	6039	-67033	6039
- Mobility	€	-917384	169901	41735	13509	-1756359	325314	-569819	105518
- Road safety	€	-101751	18840	4619	1495	-194805	36074	-63201	11701
- Animals (incl. food)	€	-1016339	-10163	-194527	-63151	-1945269	-19453	-631510	-6315
- Human health	€	-352734	102970	-7375	-2393	-675345	197145	-219086	63955
- Environment	€	-195519	-51984	-240690	-60389	-411469	-111904	-106945	-27456
Total									
- Total NPV	€	-2657764	2406500	-65379.9	12075.66	-5076473	4401015	-1658145	1578438

7.3.2 Case risks: Pastoorsmast

As can be seen in the "Total NPV" column of Table 7.5, the uncertainty ranges for the Pastoorsmast are smaller than for Eeneind-Oost. The knowledge- and future-uncertainties are of the same order of magnitude as each other also differ less from the original NPV. This difference between the uncertainties between the cases has to do with the fact that the Pastoorsmast has no inhabitants and many of the effects are calculated per inhabitant of an area.

Table 7.5: Risks for the base-case in the Pastoorsmast

						Worst	Best	Worst	Best
What	**Unit**	**Worst**	**Best**	**-3%**	**+3%**	**-3%**	**-3%**	**+3%**	**+3%**
CAPEX									
- Lost capital	€	-110	-110	-156	-78	-156	-156	-78	-78
- New investment	€	-7305	-7305	-16362	-3843	-16362	-16362	-3843	-3843
OPEX									
- Electricity	€	-2865	-2865	-4824	-2003	-4824	-4824	-2003	-2003
- Maintenance	€	-3628	-3628	-6549	-2306	-6549	-6549	-2306	-2306
Effects									
- Perceived safety	€	0	0	0	0	0	0	0	0
- Economy	€	0	0	0	0	0	0	0	0
- Impressions of the environment	€	0	0	0	0	0	0	0	0
- Mobility	€	-678	-226	-625	-363	-937	-312	-545	-182
- Road safety	€	-82	-27	-76	-44	-114	-38	-66	-22
- Animals (incl. food)	€	0	0	0	0	0	0	0	0
- Human health	€	0	0	0	0	0	0	0	0
- Environment	€	-71744	-23915	-93621	-27863	-140432	-46811	-41795	-13932
Total									
- Total NPV		-86412	-38076	-122212	-36500	-169373	-75051	-50636	-22365

7.3.3 Case risks: Larikslaan

As can be seen in the "Total NPV" column of Table 7.6, the uncertainty ranges for the Larikslaan are large. The knowledge uncertainties are once again a different order of magnitude compared to the costs and benefits in the positive and negative directions. The ranges for the future uncertainty are much smaller, however, and do give a positive NPV for both the low growth and high growth scenario.

Table 7.6: Risks for the base-case in the Larikslaan

						Worst	**Best**	**Worst**	**Best**
What	**Unit**	**Worst**	**Best**	**-3%**	**+3%**	**-3%**	**-3%**	**+3%**	**+3%**
CAPEX									
- Lost capital	€	0	0	0	0	0	0	0	0
- New investment	€	-12361	-12361	-28046	-6437	-28046	-28046	-6437	-6437
OPEX									
- Electricity	€	-2809	-2809	-5018	-1874	-5018	-5018	-1874	-1874
- Maintenance	€	-6956	-6956	-12684	-4391	-12684	-12684	-4391	-4391
Effects									
- Perceived safety	€	1124	112426	11243	11243	1124	112426	1124	112426
- Economy	€	11613	1161287	222340	72128	22234	2223401	7213	721284
- Impressions of the environment	€	-38811	3497	-3497	-3497	-38811	3497	-38811	3497
- Mobility	€	-531794	98157	23664	7450	-1017659	188102	-330474	60908
- Road safety	€	-58990	10882	2614	820	-112880	20856	-36660	6752
- Animals (incl. food)	€	-588447	-5884	-112628	-36564	-1126284	-11263	-365636	-3656
- Human health	€	-204228	59618	-4270	-1385	-391016	114145	-126848	37029
- Environment	€	-85250	-20780	-91295	-27198	-166142	-40760	-50270	-12014
Total									
- Total NPV		-1516909	1397076	2422	10297	-2875183	2564654	-953063	913525

Chapter 8

Conclusions

In this chapter, the created Decision Support System (DSS) will be discussed and an attempt will be made to answer the main research question. However, as already mentioned in the introduction, the main research question cannot be answered in a report for all circumstances and neither is the report intended to do so. The main research question is only fully answerable by the DSS. Despite this, it is attempted to draw parallels between the case study results to answer the main research question to the fullest possible extent. Before this, however, the created DSS will be discussed.

8.1 DSS

In this thesis, a Decision Support System (DSS) has been made that can help save road authorities time by informing them on what decisions to make concerning public lighting system replacement according to a Dutch governmental format Social Cost-Benefit Analysis (SCBA). As can be read in the main body of this thesis, the DSS is implemented in a spreadsheet file and the DSS can be applied to areas. When applied to an area it presents the user with optimized replacement configurations. It is optimized when the current system needs to be replaced, with what it needs to be replaced, and when maintenance needs to be performed. It does this by maximizing the Net Present Value (NPV) (for X% of energy saved) for the costs and monetized effects.

Therefore, aside from the limitations (see Section 9.1), the DSS has succeeded in answering the main research question. This also means that novel work has been provided in this thesis since previously uncombined information has been combined (in an SCBA). Novel conclusions and practical and research recommendations can, therefore, be made based on the provided work. The conclusions can be read below and the recommendations can be read in Section 9.2.

8.2 General conclusions (based on Nuenen)

In the areas in Nuenen, results were gathered. In total, three areas within the municipality of Nuenen (one with Light Emitting Diode (LED) lighting, one with Fluorescent (FL) lighting, and one with High Pressure Sodium (HPS) lighting) have been optimized for three possible types areas of effect for the costs and effects and policy areas of effect (global effects and lighting policy, global effects and local lighting policy, local effects and local lighting policy) and in local Cost-Based Analysis (CBA). The boundary for the local costs and effects was the municipality of Nuenen and the boundary for local lighting policy is the analyzed area's borders. Using these results, generalized conclusions are formed.

The case study shows that intelligent LED lighting is not worth the additional investment from a cost perspective since it never achieved the highest NPV. Thereby, a partial answer to the main research question is given.

The case study also shows some patterns regarding the replacement dates and life cycles of public lighting systems that can further help in answering the main research question. From the case study, it has become clear that the later the replacement of the fixtures (and poles) the higher the NPV if global effects were taken into account. While the range over which this was tested was quite limited due to computational limitations and limitations in the failure data, the results should be valid for small increases in the replacement date of fixtures and poles. If only local wealth effects are taken into account, however, more efficient LED lighting could be implemented before the current lighting system is depreciated depending on the lighting system. For the HPS and FL cases, this was possible. For the already relatively efficient LED case replacing the lighting system before it is depreciated did not result in a higher NPV. These conclusions, regarding the replacement dates, complete the already given partial answer to the main research question.

In conclusion (based on the case study), intelligent lighting is likely not worth its cost premium. For the case study using global effects, lighting systems can not be replaced for more efficient LED lighting solutions according to the currently implemented SCBA analysis due to higher environmental social costs. If only local effects are taken into account, then replacing the current (less efficient) lighting system for more efficient ones before the current system is depreciated can result in a higher NPV if the efficiency difference and light requirements are large enough. The limitation affecting these conclusions is that some effects are not properly quantified (see Section 9.1 for a more detailed explanation). Therefore, the answer to the research question is not definitive. To give an answer with certainty, more research is needed. What research is necessary and the advised actions for road authorities until this research is performed will be covered in Section 9.2.

A conclusion that can be drawn, not related to the main research question, is that the efficacy of a lighting technology is not a good metric for the social costs and benefits. This is mentioned since, currently in most policy documents, a reduction in power consumption is seen as needed for the good of society. This while using efficacy as a measure of societal good has the potential to severely decrease societal wealth. The (practical) implications of this conclusion will be discussed in Section 9.2.

The case study also shows that depending on pole height, a different material might become better in terms of social costs and benefits due to differences in weight and pollution during production. Furthermore, for the areas in the case study, it is demonstrated that depending on the pollution during production and whether or not it is included in the SCBA, thought to be obsolete lighting technologies such as Low Pressure Sodium (LPS), can suddenly become viable again due to lower purchasing cost and its production being not as polluting.

Chapter 9

Discussion

In this chapter, the limitation of the thesis as well as the recommendations for further research and road authorities are given.

9.1 Limitations of the thesis and developed DSS

While this thesis presents novel results and the Decision Support System (DSS) reaches the goal of being able to answer the main research question, there are limitations. In this section, these limitations and their potential implications will be discussed. This will be done in the subsections below.

9.1.1 Unknown effects

A major limitation for using the developed DSS as a practical applicator of Social Cost-Benefit Analysis (SCBA) is the fact that direct road safety and crime effects are not included in the effects due to a lack of consensus in the existing literature. These supposed effects are, however, an important motivator for municipalities to place public lighting (See Subsection 4.3.1). This limitation means that while the SCBA analyses performed by the DSS are useful as a justification for further research, using it for its intended purpose (what lighting systems to use and when to install and maintain it) will likely result in sub-optimal lighting systems.

9.1.2 Unquantified effects

As could be read in Section 5.2, quite some included effects are order of magnitude estimations without quantification. This is problematic since these effects are not related to the lights used. Therefore, any brightness light has the same positive and negative effects. The fact that these effects are not related to the lights used also limits the usefulness of the Decision Support System (DSS) since now only similar lighting systems can be evaluated. For the same reason, lighting profiles are not kept variable. Both mean that the DSS cannot be used to compare lighting systems with different lighting characteristics (exception is made for dimming since no negative effects were found and it is required by the main research question).

Another, more pressing, issue is the chance that the order of magnitude estimated effects portray the actual social cost/WTP for the used lighting system. This chance is slim at best, and as can be seen in Appendix J, they do represent a large part of the total Net Present Value (NPV). These limitations combined again mean that the SCBA analysis performed by the DSS is useful as a justification for further research. However, using it for its intended purpose will likely result in sub-optimal lighting systems.

9.1.3 Disregarded lighting specifications

As already mentioned in Section 5.2, several specifications of lighting systems are currently not taken into account. For instance, no effects are currently attributed to differences in lighting spectra. However, due to, for instance, scotopic vision, using different lighting profiles has an influence on the road users' vision and thus, for instance, safety (see Appendix E). The blue-er color lighting this requires, however, does have its effects on animals, environment, perception of the environment, and human health (see Section 5.2). However, since both safety and the other affected effects are only included as an order of magnitude estimation, these specifications, are not included in the DSS. This severely limits the applicability of the DSS as a SCBA. This limitation on its own again means that while the DSS is useful as a justification for further research, using it for its intended purpose will likely result in sub-optimal lighting systems.

9.1.4 Only one technology switch

The way the DSS is currently set up only one change in lighting systems can occur. This change occurs when the current system is replaced. This limitation means in practice that, a cheaper intermediate option will not be included in the results since the overall NPV for the entire duration of the SCBA of another lighting system was lower.

9.1.5 Fixed end date

Another limitation has to do with the end date for NPV calculations within the conducted SCBA. Setting the end date in a SCBA for projects that have the same starting date and deprecation duration across all the alternatives is straightforward. The end date is set as the date when the project is fully deprecated. However, in the case of the developed DSS for this thesis, the deprecation duration and the placement date are subject to optimization. The end date, however, cannot be variable. Since, if it is kept variable, the duration over which light is provided is different for the various options making a fair comparison impossible.

To solve this, the same end date is set for all calculations. This solution, however, has the problem that the alternative lighting systems have different ages at the end of their life. In addition, the power requirements might be different for the different (not yet deprecated) lighting systems at the end of their life. Meaning that the residual value, as well as the future energy cost, differs. Due to the inclusion of a discount rate, this can be combated by setting the end date very far in the future (as long as the discount rate is higher than the expected inflation). However, new lighting system technologies will most likely occur in the coming decades. Therefore, different systems will likely be used in the future that are not incorporated in the DSS. Since these yet-to-be-discovered technologies are not incorporated in the DSS, this invalidates the results.

Keeping both in mind, a balance was struck. Currently, this balance is to calculate all cases until the year 2070. This year was chosen since for the cases selected and the range of optimization variables tested, this resulted in the same number of scheduled replacements for all fixtures and is sufficiently long to reduce the value of a cost/benefit to 12% of its original value (for a 4.5% discount rate).

9.1.6 Uncertainty estimations

As can be seen in Section 6.2, uncertainty estimations are not based on fact but rather on rough assumed worst and best-case scenarios and coarse macroeconomic predictions. This means that the information is not usable as an actual DSS for risk assessment but rather it again shows the need for more in-depth research into the effects of public lighting.

9.2 Recommendations

In this section, the recommendations for future research into the topic of road lighting are given as well as the recommendations for road authorities (practical implications) are given. These recommendations are based on the (new) insights gained by the combination of previously uncombined knowledge in this thesis and the constructed DSS.

9.2.1 Recommendations for future research

As already mentioned in Section 9.1, the current body of knowledge is limiting to such an extent that the constructed DSS should not be used for accurate SCBA based decision making due to missing, unquantified, and estimated input. While it is useful for cost-based decision making this was not the goal of this thesis, nor should it be the basis for decision making regarding public lighting systems. The reason that this should not be done is, as demonstrated in Section 7.2, that the sum of the effects is an order of magnitude larger than the sum of direct costs. In Section 7.3, this is demonstrated even clearer. In the worst and best case estimations, the potential gains and losses due to effects to be had are two orders of magnitude larger compared to the sum of the costs.

To be able to create usable SCBA DSSs in the future, one main recommendation can be given. The main recommendation is that much more research is needed on the effects of public lighting as well as the quantification and monetization of these effects. For all effects, it is also important to investigate the effects of different spectra and intensities of light. Furthermore, for creating a reliable risk analysis it is of importance to also investigate the probability densities of the effects and their sensitivity to macroeconomic developments.

Once this recommendation has been followed, a complete SCBA DSS can be made. Ideally, this SCBA DSS should be incorporated in the design software currently being used by planners of public lighting to estimate light levels to serve as a DSS that includes social costs and benefits and can, thereby, what automatically recommend a suitable light level and lighting system based on SCBA methods.

9.2.2 Recommendations for road authorities

Cost-based decision making is what is currently being used to make decisions regarding public lighting by most road authorities (see Subsection 4.3.1), the DSS developed in this thesis can be used for this method of decision making. This should not be done as is discussed in Section 8.2 and the next paragraph. However, the developed DSS has the added benefit of having the ability to optimize a replacement lighting system automatically. The made DSS is, therefore, useful for municipalities wanting to continue using cost-based decision-making.

While the limitations are too severe to use the DSS as intended it can be said that, based on the large (estimated) effects found for public lighting (Sections 7.2, 7.3), it is best not to continue using cost-based decision making. Instead, a move towards SCBA based decision making in the space of public lighting should be made. While SCBA in this field is still in its infancy, it can be said that, based on the information gathered in this thesis, public lighting should be implemented with caution due to the monetized effects being order(s) of magnitude larger than the costs (See Appendix J and the tables in Section 7.3). With this in mind, some most likely beneficial advice can be given.

Whilst much is unknown, using the effects and the monetization found in this thesis it can be said that Artificial Light At Night (ALAN) harms animals, plants, and health. Furthermore, according to Section 5.2, intelligent dimming has little to no negative impact while reducing ALAN under most conditions. The conditions where intelligent dimming could not be useful is if there is lots of traffic (see Appendix G.2). Therefore, the general recommendation for road authorities is to use lighting with intelligent dimming if the traffic profile is such that lighting levels are reduced when used. When this is done, the spending will likely increase, but this is almost guaranteed to increase the welfare of society as a whole due to an order of magnitude difference in the spending increase and the monetized effects decrease.

Furthermore, if the lighting is applied in an urban area, there are many people on which the lighting has an effect. While this effect is not per definition positive, it is more likely that lighting overall has a positive effect if more people can benefit. Compare this to lighting in a rural area where lighting, most likely, affects fewer people and more animals (negatively). In these rural areas, lighting (even intelligent) should be given extra thought.

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Appendix A

Finding relevant literature

A.1 Finding relevant scientific literature

To evaluate the existing scientific material regarding public lighting Decision Support Systems (DSSs) and social cost-benefit analyses (SCBAs) library searches are done using custom queries. The search tool used is the TU/e variant of WorldCat Discovery. WorldCat Discovery is a cloud-based application that helps people easily find resources available at their library and in libraries worldwide through a single search (OCLC, 2020). The queries used can be seen below. The first query is included without SCBA/DSS arguments since they might restrict what results are found, and any work that goes into the deprecation of public lighting is most likely an economic analysis of some sort.

(ti:(Street) OR ti:(Public)) AND ti:(Lighting)) AND (fc:(depreciated) OR fc:(depreciation) OR (ab:(depreciated) OR ab:(depreciation))

(ti:(Street) OR ti:(Public)) AND ti:(Lighting)) AND (fc:(DSS) OR fc:(CBA) OR ab:(DSS) OR ab:(CBA))

As can be seen, both queries use a couple of different arguments. The *ti* argument means that a certain piece of text needs to be in the title. *ab* and *fc* are for the abstract and full text respectively. The brackets are present to group different statements together.

The first query yielded one relevant result from 2000 through 2020 in a global search. This result is Mahmoud (2018). The second query yielded two results from 2000 through 2020 for a global search. One is deemed on topic. This is Perkins et al. (2015).

The query *(ti:(Street) OR ti:(Public)) AND ti:(Lighting))* yielded more than 100000 results since 2000 through 2020 for a global search. The majority also appears to be relevant for this query. This information is provided since it proves that the first part of the queries is not too stringent. Since the latter part only requires the occurrence of certain words in the abstract or even the full text (also not very stringent), it can be said with certainty that little relevant literature exists.

A.2 Finding other relevant material

Aside from the scientific community, governments and the private sector can also produce and publish knowledge. Furthermore, this work is not always published in academic papers/books. For such a practical topic as public lighting, this might especially be true. Therefore, a thorough search through more general sources has also been conducted. The topic of search is again DSSs and SCBAs for retrofitting public lighting systems.

Using various queries related to this topic for Google searches, some relevant DSSs were indeed found. No usable SCBAs were found, only (mislabeled) cost analyses or incomplete SCBAs. Of these, few are of sufficient quality to be of much practical use. One found exception is U.S. Office of Energy Efficiency & Renewable Energy (2017). Another exception found is Meier et al. (2014).

Appendix B

MKBA and SCBA

As already mentioned in the research design, a Dutch governmental format Social Cost-Benefit Analysis (SCBA) consists of eight steps. While the steps have been taken into account in creating the research questions, they will be covered here in more detail. This is important since SCBAs are often seen as black boxes by the users (CPB & PBVL, 2013). This reduces the support base for the conducted SCBA, and thereby, its usefulness (CPB & PBVL, 2013). The main differences between SCBA and a Dutch governmental format SCBA (referred to as Maatschappelijke Kosten-Batenanalyse (MKBA) for the remainder of this appendix) theory will also be pointed out.

B.1 MKBA step 1: Analysis of the problem

The problem analysis is the first step in any MKBA. It is quite an important step since it answers the question of whether or not to conduct the MKBA. It is responsible for recognizing a problem that will occur without (government) intervention. If a problem is expected to solve itself, then an MKBA should not be conducted. This step also aligns with the methods present in a general SCBA as seen in Boardman et al. (2018). In this thesis, step 1 is covered in the introduction.

B.2 MKBA step 2 and 3: Identifying the different alternatives

In the second step of an MKBA, the situation without intervention is identified. In the third step, the possible intervention steps are analyzed. This differs from SCBA theory since according to Boardman et al. (2018), this is only one step. In this step, both the situation without intervention and the intervention situations are identified. In this thesis, this step is covered by answering sub-question 2.1-3.2. The situation without intervention needs to be identified to check whether or not the intervention improves the wealth.

B.3 MKBA step 4 and 5: Determining benefits and costs

In step 4 of an MKBA, the effects are identified, quantified, and monetized for a certain area of effect (the standing). In an MKBA, it is important to take all of the effects into account, but also whom the effects will influence. The latter is important since it can influence the decision-makers. For example, a policy redistributing wealth needs wealth to end up at the intended people. This is also discussed in Boardman et al. (2018), however, it is stated that it is impossible to see this effect in the numbers and, therefore, not true to SCBA. To solve this the value of wealth is changed for different groups of people. Poorer people, for example, will probably value €1 more than the rich.

For an MKBA and a SCBA, it is important to quantify and monetize as many of the found effects as possible. Where SCBA and MKBA theory differs, however, is in allowing for effects to also be expressed qualitatively. In MKBA, if an effect cannot be quantified or monetized, it is to be included as a qualitative effect. For both SCBA and MKBA only the additional costs/benefits compared to the situation without intervention need to be taken into account. The thesis will slightly deviate from this since the situation without intervention is also variable. However, the difference in cost will still be presented.

In step 5 of an MKBA, the costs are determined. Steps 4 and 5 of an MKBA are split up in a SCBA into 3 steps. These steps are: Identify the impact categories, catalog them, and select metrics; Predict the impacts quantitatively over the life of the project; and Monetize (attach dollar values to) all impacts. As can be seen, this describes the contents of what needs to happen more accurately. It also blurs the line between costs and benefits as is often the case in real life. In this thesis, these steps are performed by answering sub-questions 4.1-5.

B.4 MKBA step 6: Analyze the risks

In step 6 of an MKBA, the uncertainties for the identified costs and benefits need to be analyzed and incorporated in a risk analysis. The proposed methods for this are varying the discount rate and other factors that have a major influence between the ranges of what is expected. Alternatively, a Monte Carlo analysis can be conducted for all of the situations. In practice, however, a Monte Carlo analysis is rarely conducted due to the complexity of collecting the required data (probability distributions). In a SCBA, a similar step that proposes similar methods exists. The main difference between SCBA and MKBA in this step is that in an MKBA the risks are identified before the results of the situations are given and calculated to the same base year. In a SCBA the Net Present Value (NPV) is calculated before analyzing the risks.

B.5 MKBA step 7: Making an overview of the costs and effects

In a SCBA, the costs and benefits are calculated to the same base year before the risks are analyzed and the overview is created. In the MKBA, this is done afterward as already mentioned. Furthermore, in the MKBA it is also important to list the unquantified and unmonetized effects. Additionally, in the MKBA manual, it is stated the NPV is not the only decisive factor, the unquantified/unmonetized effects should also be weighed in some fashion.

B.6 MKBA step 8: Presenting and interpreting the results

In both the MKBA and SCBA formats, the last step is there to present and interpret the results. Again in MKBA, other factors aside from the NPV need to be taken into account for the presentation of the overview and the interpretation of the results. This is the case since it might not be possible to quantify and monetize all of the relevant effects. In SCBA, however, it is argued that only the NPV and the efficiency should be taken into account. One should consider the efficiency to check whether or not lower NPV options can, for instance, be combined for a higher NPV for the same or lower budget.

Appendix C

Using the DSS

In this appendix, a description of how to use the developed Decision Support System (DSS) is given. It will do so by working through the steps as any user would if he/she wanted to use the DSS. The DSS can be downloaded from:
https://1drv.ms/x/s!AnVbYLjK815OoSCTA51sOo5GlCrR?e=YaNo7N

C.1 Entering required data

To start using the DSS, the first step is to enter the required data. This can be done in the "User Input" sheet. First, some general input should be entered. This general input is regarding the parameters of the Social Cost-Benefit Analysis (SCBA) and is shared across the different areas over which to conduct the SCBA. In Figure C.1, the field for the general input can be seen.

Input for all cases				
	General input			
		What	**Unit**	**Values**
		Current year		2021
		End year of calculations		2070
		Use social costs and effects		TRUE
		- Use Order of magnitude approximations		TRUE
		Count Global/Local NPV		Local
		Local/Global illumination		Local
		Local population		20000
		Global population		7000000000
		Global opportunity cost percentage		100%
		Large scale placement material discount		25%
		High priority issues percentage		25%

Figure C.1: General input field on the "User Input" sheet

The next step of entering the required data is filling out the area-specific information. This can be filled in, below the general information on the "User Input" sheet. For every new configuration of public lighting or changing area circumstances, a new area should be filled in. Say, for instance, a neighborhood uses two types of public lighting, then the areas where these are deployed need to be entered separately. The same goes if the same public lighting system is installed along roads with, for instance, vastly different traffic profiles. The area-specific data that needs to be entered contains fields for the area, the pole currently being used, the luminaire currently being used, and the base-case replacement scenario. The ROVL class, lighting profile, lighting profile, pole type, and luminaire type need to be entered as numbers (or other unique identifiers) corresponding to the ones they are given in their respective tabs. The areaID should be a unique identifier. In Figure C.2 and C.3, the full fields for the area input van be seen.

Area specific input					
	Area input				
		What	Unit	Values	Values	Values
		AreaID		1	2	3
		Distance to lighting depot	km	25	25	25
		Inhabitants		134.2	0	77.7
		Power savings goal	%	50%	50%	50%
		Total street length	km	0.7	0.4	0.49
		Number of poles		37	11	22
		Poles per grid connection		20.5	20.5	20.5
		ROVL class		8	8	8
		Lighting profile current		2	1	2
		Weekly traffic	traffic/week	3353.7	4900	1941.7
		Seconds ahead to light	s	8	8	8
		Seconds behind to light	s	30	30	30
		Percentage dimmed if no traffic	%	75%	75%	75%
		minimum maintained brightness	%	20%	20%	20%
		minimum traffic brightness	%	30%	30%	30%
	Existing Pole input					
		What	Unit	Values	Values	Values
		Pole type		1	1	1
		Uithouder		0	1	0
		Luminaires per pole		1	1	1
		Pole placement	year	2011	2008	2008
		Pole intended life	years	50	50	50
		Pole height	m	3.5	5	5
		Pole last cleaned	year	2011	2008	2008
		Pole cleaning interval	years	10000	10000	10000
		Pole last painted (add. cleaning for alu.)	year	2023	2020	2020
		Pole painting interval (add. cleaning for alu.)	years	12	12	12

Figure C.2: Area input field on the "User Input" sheet (1/2)

Luminaire input					
	What	Unit	Values	Values	Values
	Luminaire type		2	6	5
	Fixture placement	year	2011	2008	2008
	Fixture intended life	years	25	25	25
	Fixture power	W	30	70	36
	Number of lights per fixture		1	1	1
	Lights power	W	30	50	36
	Luminaire last cleaned	year	2017	2019	2017
	Existing Luminaire cleaning interval	year	6	4	4
	Lights last remplace	year	2011	2019	2017
	Existing lights replacement interval	year	25	4	4
Base Case variables					
	What		Values	Values	Values
	Type of new poles		1	1	1
	Type of new luminairies		2	2	2
	Number of lights per fixture		1	1	1

Figure C.3: Area input field on the "User Input" sheet (2/2)

C.2 Editing general data

In case the ROVL class, lighting profile, lighting profile, pole type, and luminaire type needs to be changed, the specifications can be changed on their respective sheets. If a new type needs to be added, another option needs to be removed (without removing the row) or a row needs to be inserted between the first and last option. This needs to be done this way to not break the lookup relations.

Effects can also be edited, removed, or added. While the latter is more complicated since it requires changing the calculations page and the Visual Basic for Applications (VBA) scripts, the former can be done easily from the effects sheet as long as concerns monetization. On this sheet, one can edit an effect's monetization by changing the values in the F and G columns. The quantifications of effects can be changed in the "Calculations" tab. These are defined in cells G:365-G:441. Please note that they are defined automatically, so respect the links when changing the quantification in order to retain that (important) functionality.

The indexes used can also be changed. This is done on the "Indexation" sheet. This is done by editing the values in the E column. However, some cells in the E column link to cells in the A through D columns. If this functionality needs to be preserved then edit the data in the A through D columns.

C.3 Accessing the DSS functions

Once all the data is entered correctly, various DSS functions can be used by pressing the buttons on the "User Input" sheet and modifying the numbers in the green cells to the right of these buttons. These buttons and the function of the operations they perform will now be covered. In Figure C.4 the buttons can be seen.

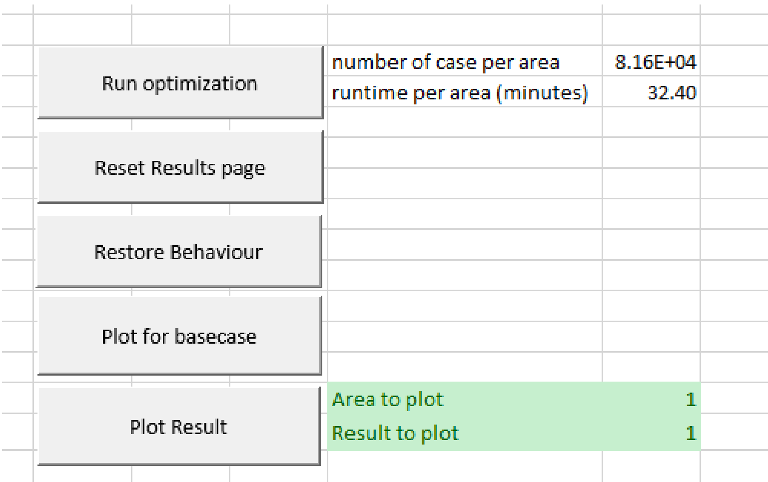

Figure C.4: Buttons on the "User Input" sheet

C.3.1 Run optimization

The "Run Optimization" button is responsible for activating the main feature of the DSS. When this button is pressed, the optimization is started. An estimation of the runtime per area can be seen to the right of this button. The runtime is influenced by the ranges that are incorporated for the optimization variables. If these ranges need changing this can be done in the "Calculations" sheet in cells K84 through K90 and K94.

Once the operation has succeeded, the "Results" tab should be filled. In this tab, the results can be seen for the base-case (first column) and various policy goals. The maximum Net Present Value (NPV) while saving X% of energy goal may still contain the base-case. In that case, the desired energy savings percentage could not be reached. The energy-saving goal is part of the input on the "User input" sheet.

C.3.2 Reset results page

This button can be pressed to clear the "Results" sheet. Whilst this is also done automatically when the run optimization button is pressed it may be useful to clear the results if "Run Optimization" was aborted or the cases changed to avoid confusion.

C.3.3 Reset behavior

The "Reset Behavior" button is useful to restore auto display update behavior of the spreadsheet program that is turned off during the operations some of the other buttons activate. The button may, therefore, be needed when, for instance, the other programs crash or are aborted.

C.3.4 Plot for base-case

The "Plot for base-case" button is used to plot some results for the base-case. The resulting plots can be seen in the "Plots" sheet. The area to plot for can be entered on the right in cell M19.

C.3.5 Plot for Result

The "Plot for results" button is used to make some useful plots for the specified results. The resulting plots can be seen in the "Plots" sheet. The area to plot for can again be entered on the right in cell M19. The result for which to plot can be edited in Cell M20. If the results page is empty, this button will automatically run the optimization.

C.4 Debugging and troubleshooting

This section is written to help solve problems in case an error occurs or unexpected results occur. To troubleshoot, go to the "Calculations" sheet and enter the general, area, and optimization variables that cause issues in the E column (until E97).

All calculations are performed (or referenced to) on this page. Therefore, it is possible to spot where the error occurs. Some functions on this page are custom. If an error occurs within a cell that uses such a function it might be useful to look at the code. This code can be viewed in the macro editor of the spreadsheet program. In the case of Microsoft Excel, this can be opened by first enabling the developer tab in the ribbon and then clicking on Visual Basic within the developer tab on the ribbon.

Appendix D

Public lighting components

In this appendix, required and optional components for a public lighting system will be elaborated upon.

D.1 Light sources

As already mentioned in the introduction of this thesis, gas discharge lamps (High Pressure Sodium (HPS) and Low Pressure Sodium (LPS)) and Fluorescent lamps (FL) are still in widespread use in combination with Light Emitting Diodes (LED)s. In this section, the working principles and general performance of these technologies will be discussed.

D.1.1 Gas discharge lamps

Gas-discharge lamps generate light by sending an electric pulse through an ionized gas (RP-Photonics, n.d.-b). Ionization of the gas is maintained by a continuous flow of current (RP-Photonics, n.d.-b). This flow of current is usually induced by two electrodes but it can also be done externally (RP-Photonics, n.d.-b). The lamps work only with high enough current densities (a function of the voltage) (RP-Photonics, n.d.-b). This means that gas discharge lamps can only be dimmed to a limited extent (RP-Photonics, n.d.-b).

To get the gas to be ionized initially a starter pulse is required (RP-Photonics, n.d.-b). This is often done with a separate (external) starter electrode supplying a spike in voltage (RP-Photonics, n.d.-b). In addition to a starter, a current regulator is also needed (RP-Photonics, n.d.-b). This is the case since the lamp's impedance is not stable during an operation cycle (RP-Photonics, n.d.-b). The type of starter and the current regulator are often lamp-type specific (van der Kolk, n.d.-b). Both components are often combined in a ballast.

In general, gas discharge lamps can be very efficient albeit at a reduced color spectrum broadness (RP-Photonics, n.d.-b). Another characteristic is that they need time to reach peak brightness. In some cases, this is longer than 10 minutes (RP-Photonics, n.d.-b). Common types of gas lamps used in Dutch public lighting are SON (HPS), SONT (HPS), and SOX (LPS) (van der Lugt, 2008).

D.1.2 Fluorescent lamps

Fluorescent lamps work by having atoms be exited by an electric current via inelastic scattering of electrons (RP-Photonics, n.d.-a). During a collision of an electron with (usually) a mercury atom, part of the energy is converted into radiation (RP-Photonics, n.d.-a). The radiation emitted in this process is, however, ultraviolet (RP-Photonics, n.d.-a). A phosphor coating on the inside of the glass tube absorbs this ultraviolet radiation and converts (most of) it into light (RP-Photonics, n.d.-a). This latter step is also what differentiates fluorescent lights from normal gas discharge lights (RP-Photonics, n.d.-a) (RP-Photonics, n.d.-b).

Electricity is usually introduced into the lamp with two tungsten filaments (RP-Photonics, n.d.-a). Just like with gas discharge lamps, the lamps need to be started with a high-voltage spike from a starter. A current regulator is also needed due to the varying impedance during an operating cycle (RP-Photonics, n.d.-a). Both components are often combined in a ballast.

In general, fluorescent lamps have high efficiencies and a relatively wide color spectrum (RP-Photonics, n.d.-a). If only a narrow color spectrum is needed gas discharge lamps can be more efficient (RP-Photonics, n.d.-a). Common types of fluorescent lamps in the Netherlands are QL, HPLN, PL, and PLL (van der Lugt, 2008).

D.1.3 LED

LEDs are a relatively new type of light source and are viewed as the main replacement for gas discharge and fluorescent lighting, not only in public lighting but also at home and in other situations. In general, LEDs are very efficient at a broad color spectrum (RP-Photonics, n.d.-c). LEDs also have a long lifetime (Lamp.nu, 2021), (RP-Photonics, n.d.-a). Furthermore, LEDs have the added benefit of being easily and efficiently dimmed with either Pulse Width Modulation (PWM) or voltage control and are also easily switched on compared to the older alternatives (RP-Photonics, n.d.-c). The latter is the case since no starter or current regulator is required (RP-Photonics, n.d.-c), only a LED driver creating a constant DC electricity source. The ease of dimming and switching on is also the reason that LEDs are well suited for intelligent public lighting purposes. Therefore, LEDs have the potential for energy savings. The easy dimming means that the cost premium for a dimmable LED lighting system is most lower compared to dimmable systems equipped with different light sources.

D.2 Power sources

All of the lighting technologies mentioned previously use electricity to produce light. This electricity can be supplied through a grid or generated and stored locally. Both options will be covered below.

Most public lighting systems are connected to the grid. This can be done in several ways. First off, the public lighting can be connected to a small sub-grid with one switchable connection to the main grid (Dijkstra, n.d.). The alternative is connecting the public lights individually to the grid (or sub-grid without switch-gear) (Dijkstra, n.d.). This is often done nowadays since new fixtures often have integrated switch-gear. For safety and operational reasons, circuit breakers are also included for every light source. These make sure that if one lighting system component short circuits, only one light source is affected instead of the entire area (van der Lugt, 2008). The breakers are usually located inside the pole (van der Lugt, 2008).

It is also possible for public lighting to not be connected to a grid (Nixon et al., 2021). In this case, a power source (often a solar panel), and a battery are included in the lighting system (Nixon et al., 2021). This is a relatively new option that can provide lighting in remote locations where a grid is not feasible (Ciriminna et al., 2016). However, the technology faces major problems. First off, it is not very suitable for locations far from the equator due to seasonal variability (Lagorse et al., 2009). Second, there is often a lack of knowledge and parts to effectively repair these public lighting systems in the communities where they are deployed (World Bank, 2010).

D.3 Fixtures

With just a light and power source, a lighting system is not yet complete, a fixture to place the light source in is also required. Fixtures are responsible for protecting the components within as well as distributing the light. In general, public lighting fixtures are divided into two categories. These categories are functional- and comfort-lighting fixtures (van der Lugt, 2008). Functional lighting fixtures are meant for increasing traffic safety (van der Lugt, 2008). Their main objective is to light the road (van der Lugt, 2008). Comfort lighting is primarily used for increasing social safety, this is achieved by lighting to such an extent that recognizing faces is possible (van der Lugt, 2008). Whether or not a fixture is meant for comfort lighting or functional lighting (or both) is defined by how light is refracted/reflected internally and by the height at which the fixture is placed (van der Lugt, 2008). The reflection/refraction provided by the fixture is also responsible for making sure that the shape of the lit area is correct for the situation (van der Lugt, 2008).

Fixture types are (usually) bound to a single type of light source (van der Lugt, 2008). This is caused by the fact that a fixture has a certain type of fitting and most fittings are specific to only one type of lighting technology. This in turn is caused by the starter and current regulator (ballast) requirements of certain lighting technologies. Modern LED fixtures often include light sources. This is done due to a similar expected lifetime for the LEDs, the LED drivers, and the fixtures. The combination of light sources and fixtures are referred to as luminaires.

D.4 Height gaining devices

To illuminate a larger area and reduce glare lights are placed at heights (van der Lugt, 2008). This can be done in several ways. By far the most common option is to use a pole. (van der Lugt, 2008). The pole can also be an existing telephone/power pole. Poles can be made from a range of materials (usually steel or aluminium) and can have a range of coatings and footings (van der Lugt, 2008). Alternatively, light sources (in the fixtures) can be suspended by a cable. Such a cable is often suspended between poles or buildings (van der Lugt, 2008). Another alternative is to mount fixtures to buildings directly.

Some lighting systems require an overhang. to achieve this a lighting support bracket (NL: uithouder) can be used.

D.5 Additional components

Aside from the already mentioned components, some optional components can also be included in lighting systems.

D.5.1 Dimmers and motion sensors

To save power, some lights can be dimmed. However, this cannot be done without additional circuitry. To dim at all, at least a dimmer is required. The working principle of such a dimmer varies with the lighting technology used.

Dimmable public lighting is a lighting system that can dim or switch on or off based on various circumstances. The circumstances under which dimming or switching occurs can vary from time-based (static) to traffic-based (intelligent) dimming (Cacciatore et al., 2017), (Mahoor et al., 2020), (Lloyde, 2020). To be able to achieve these dimming methods, additional components are required in the public lighting system aside from a dimmer. These range from a timer to a motion sensor respectively. These components can be included in or be mountable to the fixtures (Lloyde, 2020). However, systems placed separately or pole mounted systems are also available (Lloyde, 2020). With intelligent lighting, energy is saved by preventing that areas are unnecessarily lit. In practice, this means that when traffic is limited, the lights can be dimmed.

D.5.2 Other sensors and smart infrastructure

Aside from the already mentioned sensors other sensors and smart infrastructure can be placed on the poles or within the fixtures of public lighting systems (e.g. WiFi access points). However, since these do not contribute to the function of public lighting, these are not covered.

Appendix E

Relevant performance metrics for public lighting design

A public lighting system is considered as the lighting system responsible for the lighting of public spaces such as streets, roads, and squares. However, not every public lighting system is created equally as could be seen in Appendix D. In this appendix, the performance metrics used in the Netherlands for matching a public lighting system to a specific location will be covered. This will be done by first covering the required specifications for calculating the performance metrics and then elaborating on said metrics. The abbreviations as used in the Netherlands for the performance metrics will be given.

E.1 Specifications

E.1.1 Geometry

In Figure E.1, an overview of relevant geometric concepts and quantities can be seen. Of these quantities, the most important are the luminaire (fixture + light source) lighting height, the overhang, the upcast/tilt angle, and the carriageway lighting design width. These are the most important since they define the position of the light source and width of the surface to be lit respectively. If these quantities are combined with the distance between poles measured along the length of the road and the arrangement of the poles then the lighting level can be calculated for a straight road assuming the luminaire details are also known. For corners, the corner radius is also required (van der Lugt, 2008). Possible arrangements of poles can be seen in Figure E.2. For area lighting, the positions of the individual luminaires need to be known (van der Lugt, 2008), (Energex, 2010).

E.1.2 Lighting

For the luminaire, several factors are important. First off, the amount of light produced per unit time is important. This is measured in lumen (lm). This is different from the amount of radiation actually produced since light is corrected for what the human eye perceives. In Figure E.3, the amount of radiation for several light sources can be seen.

It is also important on what frequencies the light is produced. This is important since the human eye is not equally sensitive to all frequencies (Berman, 2000) (TNO Defensie en Veiligheid, 2010). So a 1000 Watt light emitting a broad spectrum light can illuminate less than an optimized 1000 Watt narrow-spectrum light. The exact frequency at which the human eye can perceive the most is dependent on the surrounding light levels (Berman, 2000) (TNO Defensie en Veiligheid, 2010). For typical public lighting levels (mesopic range) the eye is the most sensitive to blue/green (colder) lighting (NSVV, 2011). For typical daylight

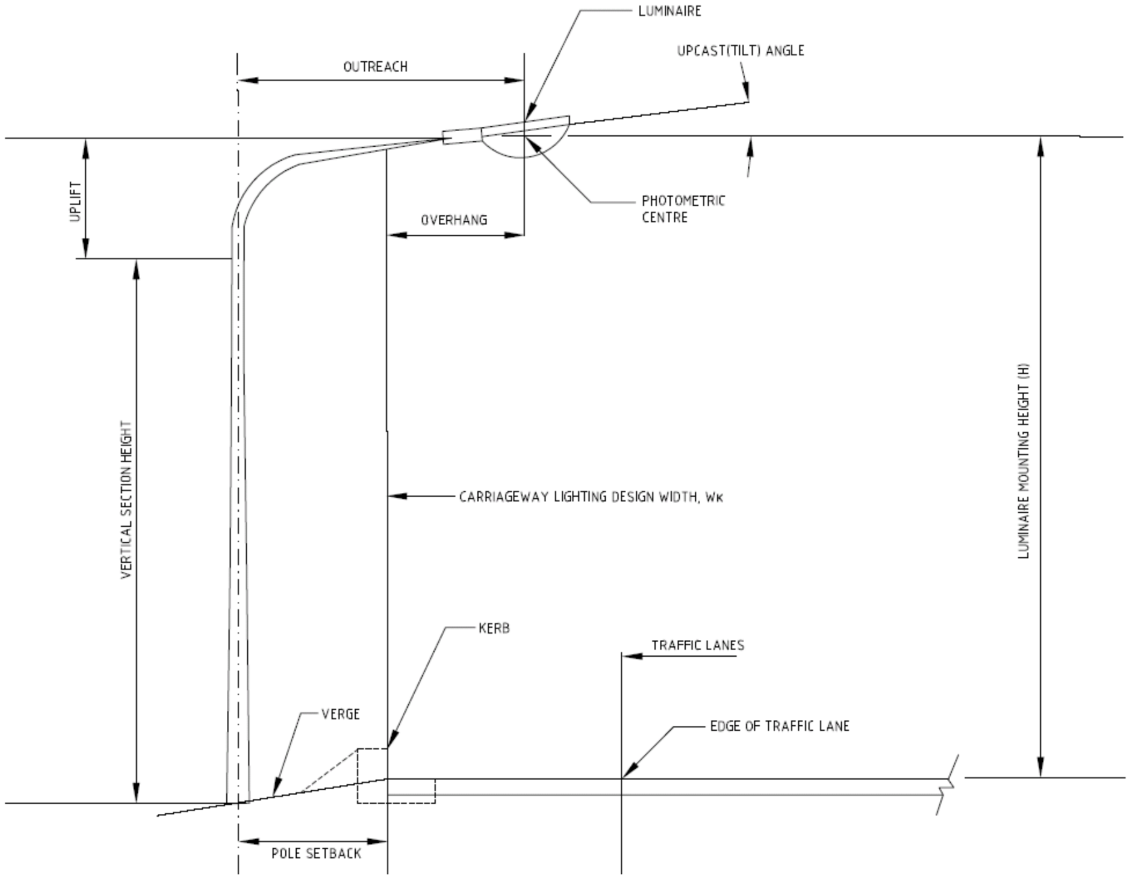

Figure E.1: Geometry and Terminology used in a typical public lighting installation (Energex, 2010)

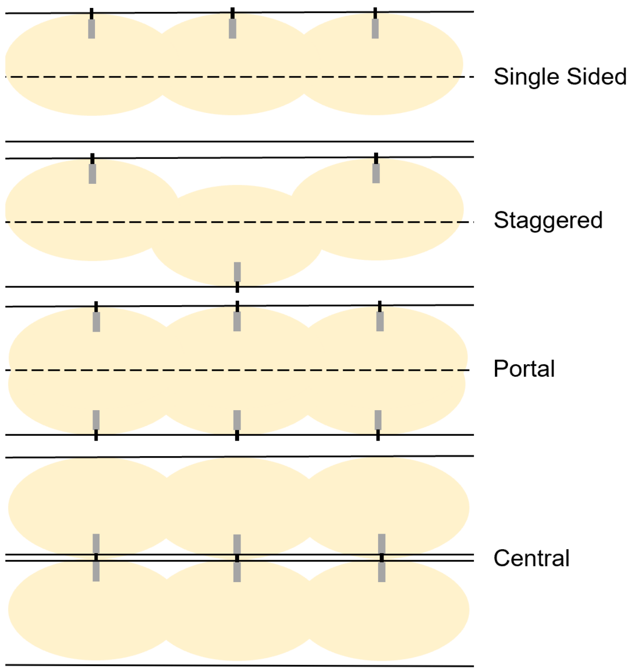

Figure E.2: Typical arrangements of public lighting (Energex, 2010)

levels of light, the eye is most sensitive to green/yellow (warmer) light (NSVV, 2011)

From a figure such as Figure E.3 the amount of lumen per watt (efficacy) can also be derived. This is important since it allows for calculating the power usage of a given light source for a certain amount of light. If the effect of the different sensitivities to certain colors is to be included, however, the lumen output of a light source needs to be multiplied with the certain S/P factor (Berman, 2000). Whether or not and how to include this effect in public lighting is however still debated (NSVV, 2011), (Berman, 2000). This debate is caused by the fact that a high SP factor only increases peripheral vision (NSVV, 2011). Furthermore, the effect is also dependent on the surface that is illuminated (Uchida & Ohno, 2016), and the age of the observer (TNO Defensie en Veiligheid, 2010). In Table E.1, examples of S/P factors are given for different light sources. Please note that in this table the color temperature is also given. Color temperature is a measure of light color based on the color of a black body radiator that is heated to a certain amount of Kelvin. So for every other light source, it does not define the spectral energy distribution and is, therefore, not relevant aside from indicating the perceived color. Another such quantity is the color rendering index (CRI).

Aside from the amount of light produced, the (spatial) distribution of light is also important. This is typically the responsibility of the fixture in combination with the height of the fixture. How the light is distributed can usually be seen in an I table (Energex, 2010). In such a table the light is given for every combination of γ and C angles. (See Figure E.4 for the definitions of the angles). The amount of light emitted at every interval is defined as the amount of candela per lumen emitted by the light source. One candela (cd) is equal to one lumen per steradian.

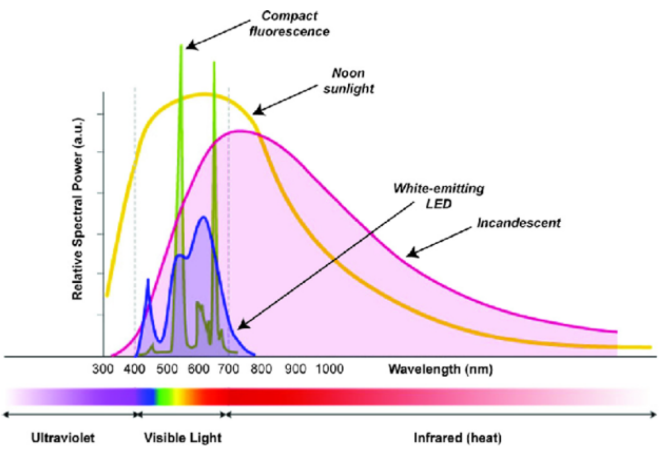

Figure E.3: Spectral energy distribution for different light-emitting sources (McKittrick & Shea-Rohwer, 2014)

Table E.1: Some representative S/P ratios (Lighting Industry Association, 2013)

Light source	S/P Ratio
Incandescent	1.36
Fluorescent (FL) (3500K)	1.36
FL (5000K)	1.97
High Pressure Sodium (HPS)	0.65
Low Pressure Sodium (LPS)	0.25
Light Emitting Diode (LED) (3500K)	1.39
LED (6000K)	2.18

E.2 Average (il)luminance

Depending on the situation a certain amount of light is required/desired (Energex, 2010), (van der Lugt, 2008). Depending on the situation, different quantities are used to measure the amount of light. For road sections between intersections (conflict areas) the average

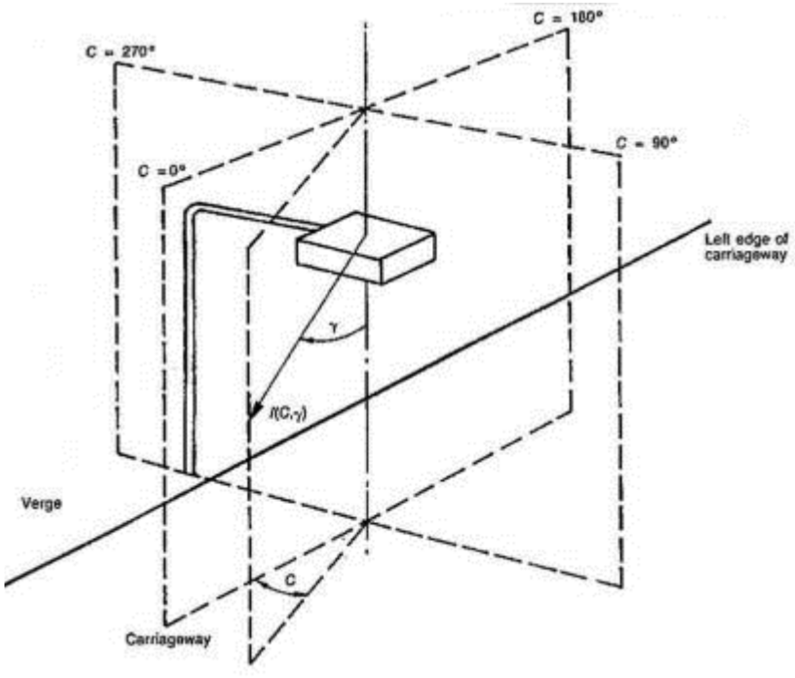

Figure E.4: Light Distribution Parameters (C and γ angles) (Energex, 2010)

luminance (L_{GEM}) is used (Energex, 2010), (NSVV, 2011), for conflict areas the average horizontal illuminance (E_{GEM}) is used (Energex, 2010), (NSVV, 2011), and for residential areas or other areas where pedestrian visibility and facial recognition is important the average vertical illumination (E_V) is used (Energex, 2010), (NSVV, 2011). The averages are used since that way an area can be evaluated instead of just one small spot. Minima are also used for pedestrian and conflict areas to assess the uniformity of the lighting. The divide in lighting measurements is present due to the different functions of lighting in those situations as well as differing computational complexity for different situations (Energex, 2010).

First, the concept of illuminance is explained. Illuminance is the amount of light that falls onto a surface and is measured in lux (lx) (lumen per square meter). The illuminance can be calculated with Equation E.1, in which E is the illuminance in lux, d the distance from the source to the point (in meters), Θ the angle of the light from the normal of the light ($\gamma = 0$), I_Θ the intensity of the source in the direction Θ (in candela) as per the I-table.

$$E = cos(\Theta)\frac{I_\Theta}{d^2} \tag{E.1}$$

The illuminance for one point can then be computed by adding the values from all relevant light sources. The average horizontal illuminance (U_h) is then calculated by calculating the average over all points on the road surface (NSVV, 2011). The average vertical illuminance U_V is calculated on an imaginary non-transparent vertical surface at 1.5m height in the travel direction (NSVV, 2011).

The luminance of an area (on the road) is defined as the perceived amount of light that the area emits, it is defined in candela per square meter (cd/m^2). Luminance is a function of the illuminance, the reflectivity of the road, and the (relative) location of the observer (CIE, 2000). The average luminance of is calculated for the area of the road between 60 and 170 meters in front of the driver (CIE, 2000). This is done since this is where a driver is usually looking when driving on a road (van der Lugt, 2008). CIE (2000) states the calculations required for calculating the average luminance in an area. Due to a large number of data points present and calculations required, these calculations (as well as the illuminance) calculations are usually done using specialized software (van der Lugt, 2008).

E.3 Uniformity of the lighting

Aside from the average lighting level, the uniformity of the lighting is also of importance. Uniformity is important since bright spots can blind road users and thereby hide obstacles in dimmer spots (van der Lugt, 2008). Both the absolute uniformity ratio (U_o) as well as the horizontal uniformity ratio U_h are defined as the lowest (il)luminance divided by the average (il)luminance, (Energex, 2010), (NSVV, 2011). The transverse uniformity U_l is defined as the minimum luminance divided by the maximum luminance along an imaginary line on the center of a driving lane.

In the case that not only the road needs to be illuminated, but also sidewalks or bicycle paths the Surround Ratio (SR) is of importance (NSVV, 2011). The Surround Ratio is a measure of the illumination of a verge. This is calculated using Equation E.2. In this equation, E_{avgr} is the average illumination in the 5 meters of road directly adjacent to the verge, and E_{avgv} is the average illumination in the 5 meters of verge directly adjacent to the road NSVV (2011).

$$SR = \frac{E_{avgr}}{E_{avgv}} \tag{E.2}$$

E.4 Glare

Glare can be described as a shine in the eye with an uncomfortably bright light. While this may be perceived as uncomfortable, it can also directly impede vision. Threshold increment (TI) is a measure of this impedance (NSVV, 2011), (van der Lugt, 2008). It can be calculated using Equation E.3. In this Equation, k is a constant (that can vary depending on the age of the observer, typically 650), E_e is the total light from the light source(s) illumination the eye, L_{AV} is the average luminance of the road surface, and Θ is the angle in degrees of the arc between the line of sight and the center of each/the luminaire (CIE, 2000).

$$TI = \frac{k}{L_{AV}^{0.8}} \cdot \sum \frac{\cdot E_e}{\Theta^2} (\%) \tag{E.3}$$

Appendix F

Lighting profiles

In this appendix, the lighting profiles are given. A lighting profile gives the light output percentage of a light for any given time during a day. The lighting profile without dimming can be found in Table F.1. This profile is based on the times that the sun comes up and goes down in the Netherlands (Simons, 2021). In Table F.2, the statically dimmed profile can be seen. This profile is dimmed according the Gerwen/Nederwetten dimming schedule found in Nuenen. In the profile without dimming light is on full power 54.3% of the year, with static dimming this is reduced to 29.8%.

Table F.1: Lighting profile without dimming

Month\Time	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00	22:30	23:00	23:30
Jan	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Feb	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Mrt	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Apr	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%
Mei	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%
Jun	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%
Jul	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%
Aug	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Sep	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Okt	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Nov	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Dec	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Month\Time	**00:00**	**00:30**	**01:00**	**01:30**	**02:00**	**02:30**	**03:00**	**03:30**	**04:00**	**04:30**	**05:00**	**05:30**	**06:00**	**06:30**	**07:00**	**07:30**	**08:00**	**08:30**	**09:00**	**09:30**	**10:00**	**10:30**	**11:00**	**11:30**
Jan	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%
Feb	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%
Mrt	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Apr	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mei	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Jun	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Jul	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Aug	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Sep	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%
Okt	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%
Nov	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%
Dec	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%

Table F.2: Static dimming lighting profile

Month\Time	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00	22:30	23:00	23:30
Jan	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Feb	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Mrt	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Apr	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	60%	60%	60%	60%
Mei	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	60%	60%	60%	60%
Jun	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	60%	60%	60%	60%
Jul	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	60%	60%	60%	60%
Aug	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Sep	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Okt	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Nov	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Dec	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	60%	60%	60%
Month\Time	**00:00**	**00:30**	**01:00**	**01:30**	**02:00**	**02:30**	**03:00**	**03:30**	**04:00**	**04:30**	**05:00**	**05:30**	**06:00**	**06:30**	**07:00**	**07:30**	**08:00**	**08:30**	**09:00**	**09:30**	**10:00**	**10:30**	**11:00**	**11:30**
Jan	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%
Feb	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%
Mrt	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Apr	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mei	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Jun	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Jul	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Aug	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Sep	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%
Okt	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%
Nov	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%
Dec	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	60%	60%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%

Appendix G

Traffic profiles

To calculate the power usage with intelligent dimming, information about the traffic profile is required. In this appendix, that information is given and the method for calculating the power usage with intelligent dimming is given. Additionally, the case assumptions are varied to study the effects they have.

G.1 Information and calculation

A traffic profile gives the distribution of traffic. Using this the percentage of traffic occurring on a certain day during a certain (half) hour can be calculated. To calculate the traffic profile, two sources are used. The first one is used to model the hourly traffic pattern. The work by Regehr et al. (2015) is used for this. In Table G.1, the half-hourly traffic profiles for weekdays and weekends can be seen. However, traffic is not the same every day. Therefore, another source of information is required. Stern et al. (2010) state that on weekends 14% of traffic occurs and on weekdays 86% of traffic occurs.

Now, if the total traffic is known of an area, an estimation of the hourly traffic can be made using the provided information. If then, it is assumed that the traffic is distributed evenly within every half hour, the time between traffic participants can be calculated. Based on the time that a light is to be on for a traffic participant, the fraction of time that a light is on (and thus energy usage) can be calculated.

Table G.1: Daily traffic per hour (Regehr et al., 2015)

	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30
mon-fri	2.73%	2.73%	2.73%	2.86%	2.98%	3.48%	3.98%	4.22%	4.47%	4.22%	3.98%	3.60%
sat-sun	3.87%	3.87%	3.87%	3.87%	3.87%	4.00%	4.13%	4.00%	3.87%	3.74%	3.62%	3.49%
	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00	22:30	23:00	23:30
mon-fri	3.23%	2.86%	2.49%	2.24%	1.99%	1.86%	1.74%	1.62%	1.49%	1.24%	0.99%	0.75%
sat-sun	3.36%	2.97%	2.58%	2.32%	2.07%	1.94%	1.81%	1.68%	1.55%	1.29%	1.03%	1.03%
	00:00	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00	05:30
mon-fri	0.50%	0.37%	0.25%	0.20%	0.15%	0.15%	0.15%	0.20%	0.25%	0.37%	0.50%	0.99%
sat-sun	1.03%	0.90%	0.77%	0.65%	0.52%	0.46%	0.41%	0.34%	0.26%	0.26%	0.26%	0.39%
	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30
mon-fri	1.49%	2.49%	3.48%	3.23%	2.98%	2.61%	2.24%	2.36%	2.49%	2.61%	2.73%	2.73%
sat-sun	0.52%	0.65%	0.77%	1.16%	1.55%	1.81%	2.07%	2.45%	2.84%	3.10%	3.36%	3.62%

G.2 Intelligent lighting dependencies

In this section, the traffic, as well as the case assumptions, are changed to illustrate the effects they have on intelligent dimming electricity usage.

In Nuenen a dimming profile as provided in Table F.2 is used as the basis for intelligent dimming. On top of this, intelligent dimming rules are set as can be seen in Table 4.2. Together with the traffic, they define the amount of time that an area is lit. In Table G.2 and G.3, the assumptions from Table 4.2 are changed together with the traffic amount. As can be seen, the energy usage is quite dependent on the traffic as well as the time that a light point is on for one traffic participant. Furthermore, the influence of different intelligent dimming rules can be seen between the two tables. It should be noted that static dimming according to the profile as seen in Table F.2 results in lights being on full power 29.8% of the time. No dimming (Table F.1) results in lights being on full power 54.3% of the time. In conclusion, it can be said that the effectiveness of intelligent dimming profiles is highly dependent on the parameters used and the situation. Therefore, it is not a one size fits all solution.

Table G.2: intelligent dimming with 20% min. brightness, 75% dimming, 30% min. traffic brightness

Seconds lit\Weekly traffic	2500	5000	7500
20	22.9%	28.7%	30.1%
30	26.7%	30.1%	30.9%
40	28.7%	30.7%	31.2%

Table G.3: intelligent dimming with 10% min. brightness, 75% dimming, 20% min. traffic brightness

Seconds lit\Weekly traffic	2500	5000	7500
20	20.0%	26.1%	27.6%
30	23.9%	27.6%	28.4%
40	26.1%	28.2%	28.7%

Appendix H

Finding studies containing effects to include in the DSS

To investigate what effects should be taken into account aside from the effects stated in municipal policy documents and already found documents a literature search was conducted using a custom query in the TU/e variant of WorldCat Discovery. The query can be seen below.

(ti:("Street") OR ti:("Public")) AND ti:("Lighting") AND (ti:("Effects") OR ti:("Effect") OR ti:("Result") OR ti:("Results"))

For this query, there are 46 peer-reviewed results through 2020 (including some doubles). Of these, 18 were deemed relevant. These works were subdivided among the topics of road safety, crime, safety perception, impressions of the environment, animals, human health, the environment, mobility, and economic effects.

Appendix I

Risk analyses ranges

In Table I.1 the knowledge-uncertainty quantity ranges can be seen.

Table I.1: Knowledge-uncertainty quantity ranges

What	**Range**	**Worst case**	**Best case**
Perceived safety			
- Individuals WTP	10%-1000%	0.1	10
Economy			
- Increase in nightly activity social gain	10%-1000%	0.1	10
Impressions of the environment			
- Decrease in ALAN WTP	10%-1000%	10	0.1
- Prevent increase in ALAN WTP	10%-1000%	0.1	10
Mobility			
- Motor vehicle mobility social cost Perceived safety	50%-150%	0.5	1.5
- Motor vehicle mobility social cost Economic activity	10%-1000%	10	0.1
- Congestion social cost Perceived safety	50%-150%	0.5	1.5
- Congestion social cost Economic activity	10%-1000%	10	0.1
- Congestion social cost Installation	50%-150%	1.5	0.5
- Congestion social cost Maintenance	50%-150%	1.5	0.5
Road safety			
- Accidents social cost Perceived safety	50%-150%	0.5	1.5
- Accidents social cost Economic activity	10%-1000%	10	0.1
- Accidents social cost Installation	50%-150%	1.5	0.5
- Accidents social cost Maintenance	50%-150%	1.5	0.5
Animals			
- Food pollination decrease social cost (food supply decrease)	10%-1000%	10	0.1
- Biodiversity WTP	10%-1000%	10	0.1
- Animal well being WTP	10%-1000%	10	0.1
Human Health			
- Melatonin production social cost	10%-1000%	10	0.1
- Increase in foot mobility social cost Perceived mobility	50%-150%	0.5	1.5
- Increase in foot mobility social cost Economic activity	10%-1000%	0.1	10
Environment			
- Car mobility pollution social cost perceived safety	50%-150%	0.5	1.5
- Mobility pollution social cost installation	50%-150%	1.5	0.5
- Mobility pollution social cost maintenance	50%-150%	1.5	0.5
- Mobility pollution social cost economic activity	10%-1000%	10	0.1
- Electricity generation pollution social cost	50%-150%	1.5	0.5
- FL light mercury pollution social cost	50%-150%	1.5	0.5
- luminaire production pollution social cost	50%-150%	1.5	0.5
- Pole production pollution social cost	50%-150%	1.5	0.5

Appendix J

DSS results for the areas

In this appendix, the results as seen in the DSS, for the areas as seen in Section 7.1, are presented. The Decision Support System (DSS) will be run with a selection of settings. The first setting is to run the Social Cost-Benefit Analysis (SCBA) for global costs and benefits and global lighting policy (EGG). The second setting is to run the SCBA for global costs and benefits with a local lighting policy (bound to the area) (EGL). Third, the boundaries of the SCBA costs and benefits will be set to local (municipal boundaries) (ELL). Fourth, all effects will be disabled, thus creating a Cost-Based Analysis (CBA) (for municipal cost boundaries) (CLL).

J.1 Case results: Eeneind-Oost

As already mentioned in Section 7.1, the Eeneind-Oost area is a residential area where Light Emitting Diodes (LEDs) (placed in 2011) are used for public lighting.

J.1.1 Global costs and benefits and global illumination policy

The results with global costs and benefits and global illumination policy found by the DSS can be seen in Table J.1. The found configurations for these results can be seen in Table J.2.

As can be seen in Table J.1, the base-case has a negative Net Present Value (NPV) while the maximum NPV case does not. This means that public lighting is viable in this location according to the DSS. However, the configuration for that optimal situation is quite peculiar. As can be seen in Table J.2, the optimum lighting scenario uses a Low Pressure Sodium (LPS) based lighting system. Looking at the costs and effects, this can, however, be explained. The cost for LPS systems is quite low. The effect that its production has on the environment is also low. Both offset the increase in the energy cost. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.2, the poles should also be replaced later than in the base-case to maximize the NPV.

Table J.1: Eeneind-Oost global costs and benefits and global illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	0	-44	-7054	-3261	-7054
- New investment	€	-17368	-13144	-39568	-29807	-40626
OPEX						
- Electricity	€	-4866	-11193	-7334	-16374	-4731
- Maintenance	€	-6769	-9348	-4033	-7926	-6334
Effects						
- Perceived safety	€	19418	19418	19418	19418	19418
- Economy	€	200572	200572	200572	200572	200572
- Impressions of the environment	€	-6039	-6039	-6039	-6039	-6039
- Mobility	€	21776	20415	21762	20951	21762
- Road safety	€	2410	2245	2408	2310	2408
- Animals (incl. food)	€	-101634	-101634	-101634	-101634	-101634
- Human health	€	-3852	-3852	-3852	-3852	-3852
- Environment	€	-112785	-16446	-140836	-31988	-118186
Total						
- Total NPV	€	-9137	80950	-66191	42370	-44297
- Power usage	kWh	142293	409585	236608	642552	126496

Table J.2: Eeneind-Oost global costs and benefits and global illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Aluminium	Steel	Steel
- Type of new luminairies		LED Static	LPS	LED Intelligent	HPS	LED Intelligent
- Dimming profile used new lights?		Static	No dimming	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2036	2039	2033	2039	2033
- Replacement year of existing lights	year	2036	2039	2033	2039	2033
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	4	23	9	23
- Luminaire cleaning interval new lights	years	6	5	7	7	5
- Replacement year of existing poles	year	2061	2095	2033	2039	2033
- Replacement interval of new poles	years	50	84	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	24.8	36.1	27.5	63.4	23.5
- New lights power	W	24.8	36.1	27.5	63.4	23.5

J.1.2 Global costs and benefits and local illumination policy

The results with global costs and benefits and local illumination policy found by the DSS can be seen in Table J.3. The found configurations for these results can be seen in Table J.4.

As can be seen in Table J.3, the base-case has a negative NPV while the maximum NPV case does not. This means that public lighting is viable in this location according to the DSS. However, the configuration for that optimal situation is quite peculiar. As can be seen in Table J.4, the optimum lighting scenario uses a LPS based lighting system. Looking at the costs and monetized effects, this can, however, be explained. The cost for LPS systems is quite low. The effect that its production has on the environment is also low. Both offset the increase in the energy cost. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.4, the poles should again be replaced later than the base-case to maximize the NPV. While the replacement interval after the first replacement seems to be only 28 years, this value is not tested because the calculation only runs until 2070 and the pole is replaced after 2070. It should, therefore, be ignored.

Table J.3: Eeneind-Oost global costs and benefits and local illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	0	-44	-7054	-3261	-7054
- New investment	€	-17368	-13144	-39568	-29807	-40626
OPEX						
- Electricity	€	-4866	-11193	-7334	-16374	-4731
- Maintenance	€	-6769	-9348	-4033	-7926	-6334
Effects						
- Perceived safety	€	19418	19418	19418	19418	19418
- Economy	€	200572	200572	200572	200572	200572
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	21776	20415	21762	20951	21762
- Road safety	€	2410	2245	2408	2310	2408
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	-3852	-3852	-3852	-3852	-3852
- Environment	€	-112785	-16446	-140836	-31988	-118186
Total						
- Total NPV	€	98536	188623	41482	150043	63376
- Power usage	kWh	142293	409585	236608	642552	126496

Table J.4: Eeneind-Oost global costs and benefits and local illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Aluminium	Steel	Steel
- Type of new luminairies		LED Static	LPS	LED Intelligent	HPS	LED Intelligent
- Dimming profile used new lights?		Static	No dimming	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2036	2039	2033	2039	2033
- Replacement year of existing lights	year	2036	2039	2033	2039	2033
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	4	23	9	23
- Luminaire cleaning interval new lights	years	6	5	7	7	5
- Replacement year of existing poles	year	2061	2095	2033	2039	2033
- Replacement interval of new poles	years	50	28	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	24.8	36.1	27.5	63.4	23.5
- New lights power	W	24.8	36.1	27.5	63.4	23.5

J.1.3 Local costs and benefits and local illumination policy

The results with local costs and benefits and local illumination policy found by the DSS can be seen in Table J.5. The found configurations for these results can be seen in Table J.6.

As can be seen in Table J.5, both the base-case and the maximum NPV case have large positive NPVs. This means that public lighting is viable in this location according to the DSS. Because the harm Light Emitting Diode (LED) production causes to the environment is now not taken into account as much, LED lighting with static dimming is the best lighting solution. Despite more efficient LEDs finally winning the tradeoff between the purchase price, energy usage, and pollution during production, intelligent LEDs are still not worth their additional cost. The energy savings are not substantial enough to offset the purchasing cost increase. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.6, the poles should again be replaced later than the base-case to maximize the NPV.

Table J.5: Eeneind-Oost local costs and benefits and local illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	0	-44	-7054	-3261	-7054
- New investment	€	-17368	-9574	-39594	-29807	-40626
OPEX						
- Electricity	€	-14034	-13822	-61417	-53159	-13574
- Maintenance	€	-6769	-6957	-7647	-7926	-6334
Effects						
- Perceived safety	€	19418	19418	19418	19418	19418
- Economy	€	200572	200572	200572	200572	200572
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	17862	17882	16774	17036	17848
- Road safety	€	2410	2412	2278	2310	2408
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	-3852	-3852	-3852	-3852	-3852
- Environment	€	66	114	-56	-30	-35
Total						
- Total NPV	€	198305	206149	119422	141302	168770
- Power usage	kWh	142293	149918	627755	642552	126496

Table J.6: Eeneind-Oost local costs and benefits and local illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Steel	Steel	Steel
- Type of new luminairies		LED Static	LED Static	HPS Static	HPS	LED Intelligent
- Dimming profile used new lights?		Static	Static	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2036	2039	2033	2039	2033
- Replacement year of existing lights	year	2036	2039	2033	2039	2033
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	28	9	9	23
- Luminaire cleaning interval new lights	years	6	5	7	7	5
- Replacement year of existing poles	year	2061	2095	2033	2039	2033
- Replacement interval of new poles	years	50	84	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	24.8	24.0	63.4	63.4	23.5
- New lights power	W	24.8	24.0	63.4	63.4	23.5

J.1.4 Local CBA

The results with a local CBA found by the DSS can be seen in Table J.7. The found configurations for these results can be seen in Table J.8.

As can be seen in Table J.7, both the base-case and the maximum NPV case have large negative NPVs. This means that public lighting is viable in this location according to the DSS. This is also logical since only cost is taken into account. Because the harm LED production causes to the environment is now not taken into account, LED lighting with static dimming is the best lighting solution. Despite more efficient LEDs finally winning the tradeoff between the purchase price, energy usage, and pollution during production, intelligent LEDs are still not worth their additional cost. The energy savings are not substantial enough to offset the purchasing cost increase. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.8, the poles should again be replaced later than the base-case to maximize the NPV.

Table J.7: Eeneind-Oost local CBA found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	0	-44	-7054	-3261	-7054
- New investment	€	-17368	-9574	-39594	-29807	-40626
OPEX						
- Electricity	€	-14034	-13822	-61417	-53159	-13574
- Maintenance	€	-6769	-6957	-7647	-7926	-6334
Effects						
- Perceived safety	€	0	0	0	0	0
- Economy	€	0	0	0	0	0
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	0	0	0	0	0
- Road safety	€	0	0	0	0	0
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	0	0	0	0	0
- Environment	€	0	0	0	0	0
Total						
- Total NPV	€	-38171	-30398	-115712	-94152	-67589
- Power usage	kWh	142293	149918	627755	642552	126496

Table J.8: Eeneind-Oost local CBA found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Steel	Steel	Steel
- Type of new luminairies		LED Static	LED Static	Hps Static	HPS	LED Intelligent
- Dimming profile used new lights?		Static	Static	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2036	2039	2033	2039	2033
- Replacement year of existing lights	year	2036	2039	2033	2039	2033
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	28	9	9	23
- Luminaire cleaning interval new lights	years	6	5	7	7	5
- Replacement year of existing poles	year	2061	2095	2033	2039	2033
- Replacement interval of new poles	years	50	84	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	24.8	24.0	63.4	63.4	23.5
- New lights power	W	24.8	24.0	63.4	63.4	23.5

J.2 Case results: Pastoorsmast

As already mentioned in Section 7.1, the Pastoorsmast area is a residential area where HPS lighting (placed in 2008) is used for public lighting.

J.2.1 Global costs and benefits and global illumination policy

The results with global costs and benefits and global illumination policy found by the DSS can be seen in Table J.9. The found configurations for these results can be seen in Table J.10.

As can be seen in Table J.9, both the base-case and the maximum NPV case have large negative NPVs. This means that public lighting is not viable in this location according to the DSS. The difference in viability for these DSS settings between this area and the other areas is caused by the fact that the Pastoorsmast does not have any inhabitants. This changes the outcome since many effects are calculated for every inhabitant of a street. Note that the configuration for that optimal situation is once again quite peculiar. As can be seen in Table J.10, the optimum lighting scenario uses a LPS based lighting system. The energy savings of LEDs are not substantial enough to offset the purchasing and manufacturing (social) cost. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.10, the poles should also be replaced later than the base-case to maximize the NPV.

Table J.9: Pastoorsmast global costs and benefits and global illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	-110	0	-2255	-1552	-2255
- New investment	€	-7305	-5402	-15543	-13186	-15902
OPEX						
- Electricity	€	-2865	-5818	-3765	-8162	-2642
- Maintenance	€	-3628	-4981	-1822	-3999	-3401
Effects						
- Perceived safety	€	0	0	0	0	0
- Economy	€	0	0	0	0	0
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	-452	-1004	-433	-798	-433
- Road safety	€	-55	-122	-52	-97	-52
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	0	0	0	0	0
- Environment	€	-47830	-7258	-58781	-14153	-48915
Total						
- Total NPV	€	75065	182809	109421	274359	66294
- Power usage	kWh	71240	79327	254438	267592	57109

Table J.10: Pastoorsmast global costs and benefits and global illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Steel	Aluminium	Steel	Steel
- Type of new luminairies		LED Static	LPS	LED Intelligent	HPS	LED Intelligent
- Dimming profile used new lights?		Static	No dimming	No dimming	No dimming	Static
Time						
- Replacement year of existing fixtures	year	2033	2035	2031	2035	2031
- Replacement year of existing lights	year	2023	2024	2022	2022	2022
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	4	23	9	23
- Luminaire cleaning interval new lights	years	4	3	5	5	3
- Replacement year of existing poles	year	2058	2091	2031	2035	2031
- Replacement interval of new poles	years	50	28	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	33.7	47.8	36.4	84.7	31.1
- New lights power	W	33.7	47.8	36.4	84.7	31.1

J.2.2 Global costs and benefits and local illumination policy

The results with global costs and benefits and local illumination policy found by the DSS can be seen in Table J.11. The found configurations for these results can be seen in Table J.12.

As can be seen in Table J.11, both the base-case and the maximum NPV case have large negative NPVs. This means that public lighting is not viable in this location according to the DSS. The difference in viability for these DSS settings between this area and the other areas is caused by the fact that the Pastoorsmast does not have any inhabitants as already mentioned. This changes the outcome since many effects are calculated for every inhabitant of a street. Note that the configuration for the optimal situation is once again quite peculiar. As can be seen in Table J.12, the optimum lighting scenario uses a LPS based lighting system. The energy savings of LEDs are not substantial enough to offset the purchasing and manufacturing (social) cost. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.12, the poles should again be replaced later than the base-case to maximize the NPV. While the replacement interval after the first replacement seems to be only 28 years, this value is not tested because the calculation only runs until 2070 and the pole is replaced after 2070. It should, therefore, be ignored.

Table J.11: Pastoorsmast global costs and benefits and local illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	-110	0	-2255	-1552	-2255
- New investment	€	-7305	-5402	-15543	-13186	-15902
OPEX						
- Electricity	€	-2865	-5818	-3765	-8162	-2642
- Maintenance	€	-3628	-4981	-1822	-3999	-3401
Effects						
- Perceived safety	€	0	0	0	0	0
- Economy	€	0	0	0	0	0
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	-452	-1004	-433	-798	-433
- Road safety	€	-55	-122	-52	-97	-52
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	0	0	0	0	0
- Environment	€	-47830	-7258	-58781	-14153	-48915
Total						
- Total NPV	€	-62245	-24585	-82651	-41947	-73600
- Power usage	kWh	75065	182809	109421	274359	66294

Table J.12: Pastoorsmast global costs and benefits and local illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Steel	Aluminium	Steel	Steel
- Type of new luminairies		LED Static	LPS	LED Intelligent	HPS	LED Intelligent
- Dimming profile used new lights?		Static	No dimming	No dimming	No dimming	Static
Time						
- Replacement year of existing fixtures	year	2033	2035	2031	2035	2031
- Replacement year of existing lights	year	2023	2024	2022	2022	2022
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	4	23	9	23
- Luminaire cleaning interval new lights	years	4	3	5	5	3
- Replacement year of existing poles	year	2058	2091	2031	2035	2031
- Replacement interval of new poles	years	50	28	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	33.7	47.8	36.4	84.7	31.1
- New lights power	W	33.7	47.8	36.4	84.7	31.1

J.2.3 Local costs and benefits and local illumination policy

The results with local costs and benefits and local illumination policy found by the DSS can be seen in Table J.13. The found configurations for these results can be seen in Table J.14.

As can be seen in Table J.13, both the base-case and the maximum NPV case have large negative NPVs. This means that public lighting is not viable in this location according to the

DSS. The difference in viability for these DSS settings between this area and the other areas is again caused by the fact that the Pastoorsmast does not have any inhabitants. Because the harm LED production causes to the environment is now not taken into account as much, LED lighting with static dimming is the best lighting solution. Due to the relatively high traffic load, static LEDs are also the most efficient. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is earlier than in the base case. This means that the energy savings are substantial enough to offset the increase in purchasing and manufacturing environmental social cost. As can be seen in Table J.14, the poles should again be replaced later than the base-case to maximize the NPV. While the replacement interval after the first replacement seems to be only 23 years, this value is not tested because the calculation only runs until 2070 and the pole is replaced after 2070. It should, therefore, be ignored.

Table J.13: Pastoorsmast local costs and benefits and local illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	-110	-111	-2255	-1552	-2255
- New investment	€	-7305	-4527	-15792	-13186	-15902
OPEX						
- Electricity	€	-8993	-8407	-28140	-27005	-8237
- Maintenance	€	-3628	-3785	-3554	-3999	-3401
Effects						
- Perceived safety	€	0	0	0	0	0
- Economy	€	0	0	0	0	0
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	-452	-430	-778	-798	-433
- Road safety	€	-55	-52	-94	-97	-52
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	0	0	0	0	0
- Environment	€	-40	-8	-110	-101	-103
Total						
- Total NPV	€	-20583	-17320	-50725	-46737	-30383
- Power usage	kWh	75065	68208	263131	274359	66294

Table J.14: Pastoorsmast local costs and benefits and local illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Steel	Steel	Steel
- Type of new luminairies		LED Static	LED Static	HPS dimming	HPS	LED Intelligent
- Dimming profile used new lights?		Static	Static	No dimming	No dimming	Static
Time						
- Replacement year of existing fixtures	year	2033	2031	2031	2035	2031
- Replacement year of existing lights	year	2023	2024	2022	2022	2022
- Replacement interval of new fixtures	years	25	23	23	23	23
- Replacement interval of new lights	years	25	23	9	9	23
- Luminaire cleaning interval new lights	years	4	4	5	5	3
- Replacement year of existing poles	year	2058	2077	2031	2035	2031
- Replacement interval of new poles	years	50	69	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	32.7	32.5	83.7	83.7	31.1
- New lights power	W	32.7	32.5	83.7	83.7	31.1

J.2.4 Local CBA

The results with a local CBA found by the DSS can be seen in Table J.15. The found configurations for these results can be seen in Table J.16.

As can be seen in Table J.15, both the base-case and the maximum NPV case have large negative NPVs. This means that public lighting is not viable in this location according to the DSS. This is also logical since only cost is taken into account. Because the harm LED production causes to the environment is now not taken into account, LED lighting with static dimming is the best lighting solution. Due to the relatively high traffic load, static LEDs are also the most efficient. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is earlier than in the base case. This means that the energy savings are substantial enough to offset the increase in purchasing cost. As can be seen in Table J.16, the poles should again be replaced later than the base-case to maximize the NPV. While the replacement interval after the first replacement seems to be only 28 years, this value is not tested since the calculation only runs until 2070 and the pole is replaced after 2070. It should, therefore, be ignored.

Table J.15: Pastoorsmast local CBA found results

What	**Unit**	**Base**	**Max. NPV**	**Min. NPV**	**Max. energy**	**Min. energy**
CAPEX						
- Lost capital	€	-110	-111	-2255	-1552	-2255
- New investment	€	-7305	-4527	-15792	-13186	-15902
OPEX						
- Electricity	€	-8993	-8407	-28140	-27005	-8237
- Maintenance	€	-3628	-3785	-3554	-3999	-3401
Effects						
- Perceived safety	€	0	0	0	0	0
- Economy	€	0	0	0	0	0
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	0	0	0	0	0
- Road safety	€	0	0	0	0	0
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	0	0	0	0	0
- Environment	€	0	0	0	0	0
Total						
- Total NPV	€	-20036	-16830	-49742	-45741	-29795
- Power usage	kWh	75065	68208	263131	274359	66294

Table J.16: Pastoorsmast local CBA found configurations

What	**Unit**	**Base**	**Max. NPV**	**Min. NPV**	**Max. energy**	**Min. energy**
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Steel	Steel	Steel
- Type of new luminairies		LED Static	LED Static	HPS dimming	HPS	LED Intelligent
- Dimming profile used new lights?		Static	Static	No dimming	No dimming	Static
Time						
- Replacement year of existing fixtures	year	2033	2031	2031	2035	2031
- Replacement year of existing lights	year	2023	2024	2022	2022	2022
- Replacement interval of new fixtures	years	25	23	23	23	23
- Replacement interval of new lights	years	25	23	9	9	23
- Luminaire cleaning interval new lights	years	4	4	5	5	3
- Replacement year of existing poles	year	2058	2077	2031	2035	2031
- Replacement interval of new poles	years	50	69	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	32.7	32.5	83.7	83.7	31.1
- New lights power	W	32.7	32.5	83.7	83.7	31.1

J.3 Case results: Larikslaan

As already mentioned in Section 7.1, the Larikslaan area is a residential area where FL lighting (placed in 2008) is used for public lighting.

J.3.1 Global costs and benefits and global illumination policy

The results with global costs and benefits and global illumination policy found by the DSS can be seen in Table J.17. The found configurations for these results can be seen in Table J.18.

As can be seen in Table J.17, the base-case has a negative NPV while the maximum NPV case does not. This means that public lighting is viable in this location according to the DSS. However, the configuration for the optimal situation is quite peculiar. As can be seen in Table J.18, the optimum lighting scenario uses a LPS based lighting system. Looking at the costs and effects, this can, however, be explained. The cost for LPS systems is quite low. The effect that its production has on the environment is also low. Both offset the increase in the energy cost. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.18, the poles should again be replaced later than the base-case to maximize the NPV. While the replacement interval after the first replacement seems to be only 28 years, this value is not tested because the calculation only runs until 2070 and the pole is replaced after 2070. It should, therefore, be ignored.

Table J.17: Larikslaan global costs and benefits and global illumination policy found results

What	**Unit**	**Base**	**Max. NPV**	**Min. NPV**	**Max. energy**	**Min. energy**
CAPEX						
- Lost capital	€	0	-140	-4092	-2793	-4092
- New investment	€	-12361	-9757	-27239	-22295	-28227
OPEX						
- Electricity	€	-2809	-5654	-3741	-7951	-2525
- Maintenance	€	-6956	-9796	-3589	-7841	-6751
Effects						
- Perceived safety	€	11243	11243	11243	11243	11243
- Economy	€	116129	116129	116129	116129	116129
- Impressions of the environment	€	-3497	-3497	-3497	-3497	-3497
- Mobility	€	12181	11127	12220	11538	12220
- Road safety	€	1343	1216	1348	1266	1348
- Animals (incl. food)	€	-58845	-58845	-58845	-58845	-58845
- Human health	€	-2230	-2230	-2230	-2230	-2230
- Environment	€	-46666	-6924	-59500	-13757	-47372
Total						
- Total NPV	€	7532	42871	-21793	20966	-12598
- Power usage	kWh	66855	171311	101635	261015	54916

Table J.18: Larikslaan global costs and benefits and global illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Aluminium	Steel	Steel
- Type of new luminairies		LED Static	LPS	LED Intelligent	HPS	LED Intelligent
- Dimming profile used new lights?		Static	No dimming	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2033	2035	2031	2035	2031
- Replacement year of existing lights	year	2021	2022	2021	2021	2021
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	4	23	9	23
- Luminaire cleaning interval new lights	years	4	3	5	5	3
- Replacement year of existing poles	year	2058	2091	2031	2035	2031
- Replacement interval of new poles	years	50	84	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	16.0	23.4	17.8	41.0	15.1
- New lights power	W	16.0	23.4	17.8	41.0	15.1

J.3.2 Global costs and benefits and local illumination policy

The results with global costs and benefits and local illumination policy found by the DSS can be seen in Table J.19. The found configurations for these results can be seen in Table J.20.

As can be seen in Table J.19, the base-case has a negative NPV while the maximum NPV case does not. This means that public lighting is viable in this location according to the DSS. However, the configuration for the optimal situation is quite peculiar. As can be seen in Table J.20, the optimum lighting scenario uses a LPS based lighting system. Looking at the costs and effects, this can, however, be explained. The cost for LPS systems is quite low. The effect that its production has on the environment is also low. Both offset the increase in the energy cost. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.20, the poles should again be replaced later than the base-case to maximize the NPV. While the replacement interval after the first replacement seems to be only 28 years, this value is not tested because the calculation only runs until 2070 and the pole is replaced after 2070. It should, therefore, be ignored.

Table J.19: Larikslaan global costs and benefits and local illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	0	-140	-4092	-2793	-4092
- New investment	€	-12361	-9757	-27239	-22295	-28227
OPEX						
- Electricity	€	-2809	-5654	-3741	-7951	-2525
- Maintenance	€	-6956	-9796	-3589	-7841	-6751
Effects						
- Perceived safety	€	11243	11243	11243	11243	11243
- Economy	€	116129	116129	116129	116129	116129
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	12181	11127	12220	11538	12220
- Road safety	€	1343	1216	1348	1266	1348
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	-2230	-2230	-2230	-2230	-2230
- Environment	€	-46666	-6924	-59500	-13757	-47372
Total						
- Total NPV	€	69873	105212	40549	83307	49743
- Power usage	kWh	66855	171311	101635	261015	54916

Table J.20: Larikslaan global costs and benefits and local illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Aluminium	Steel	Steel
- Type of new luminairies		LED Static	LPS	LED Intelligent	HPS	LED Intelligent
- Dimming profile used new lights?		Static	No dimming	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2033	2035	2031	2035	2031
- Replacement year of existing lights	year	2021	2022	2021	2021	2021
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	4	23	9	23
- Luminaire cleaning interval new lights	years	4	3	5	5	3
- Replacement year of existing poles	year	2058	2091	2031	2035	2031
- Replacement interval of new poles	years	50	84	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	16.0	23.4	17.8	41.0	15.1
- New lights power	W	16.0	23.4	17.8	41.0	15.1

J.3.3 Local costs and benefits and local illumination policy

The results with local costs and benefits and local illumination policy found by the DSS can be seen in Table J.21. The found configurations for these results can be seen in Table J.22.

As can be seen in Table J.21, both the base-case and the maximum NPV case have large positive NPVs. This means that public lighting is viable in this location according to the DSS. Because the harm LED production causes to the environment is now not taken into account as much, LED lighting with static dimming is the best lighting solution. Despite more efficient LEDs finally winning the trade-off between the purchase price, energy usage, and pollution during production, intelligent LEDs are still not worth their additional cost. The energy savings are not substantial enough to offset the purchasing cost increase. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is earlier than in the base case. This means that the energy savings are substantial enough to offset the increase in purchasing and manufacturing environmental social cost. As can be seen in Table J.22, the poles should again be replaced later than the base-case to maximize the NPV.

Table J.21: Larikslaan local costs and benefits and local illumination policy found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	0	0	-4092	-2793	-4092
- New investment	€	-12361	-7216	-27246	-22295	-28227
OPEX						
- Electricity	€	-8057	-8291	-26987	-25541	-7091
- Maintenance	€	-6956	-7234	-7048	-7841	-6751
Effects						
- Perceived safety	€	11243	11243	11243	11243	11243
- Economy	€	116129	116129	116129	116129	116129
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	9915	9920	9263	9271	9954
- Road safety	€	1343	1344	1265	1266	1348
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	-2230	-2230	-2230	-2230	-2230
- Environment	€	-4	58	-144	-126	-131
Total						
- Total NPV	€	109021	113722	70152	77082	90151
- Power usage	kWh	66855	70557	252245	261015	54916

Table J.22: Larikslaan local costs and benefits and local illumination policy found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Steel	Steel	Steel
- Type of new luminairies		LED Static	LED Static	HPS dimming	HPS	LED Intelligent
- Dimming profile used new lights?		Static	Static	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2033	2033	2031	2035	2031
- Replacement year of existing lights	year	2021	2022	2021	2021	2021
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	28	9	9	23
- Luminaire cleaning interval new lights	years	4	5	5	5	3
- Replacement year of existing poles	year	2058	2089	2031	2035	2031
- Replacement interval of new poles	years	50	84	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	16.0	16.9	41.0	41.0	15.1
- New lights power	W	16.0	16.9	41.0	41.0	15.1

J.3.4 Local CBA

The results with a local CBA found by the DSS can be seen in Table J.23. The found configurations for these results can be seen in Table J.24.

As can be seen in Table J.23, both the base-case and the maximum NPV case have large negative NPVs. This means that public lighting is not viable in this location according to the DSS. This is also logical since only cost is taken into account. Because the harm LED production causes to the environment is now not taken into account, LED lighting with static dimming is the best lighting solution.Despite more efficient LEDs winning the trade-off between the purchase price, energy usage, and pollution during production, intelligent LEDs are still not worth their additional cost. The energy savings are not substantial enough to offset the purchasing cost increase. Furthermore, it can be seen that the replacement date for the optimal NPV scenario is later than in the base case. As can be seen in Table J.24, the poles should again be replaced later than the base-case to maximize the NPV. While the replacement interval after the first replacement seems to be only 28 years, this value is not tested since the calculation only runs until 2070 and the pole is replaced after 2070. It should, therefore, be ignored.

Table J.23: Larikslaan local CBA found results

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
CAPEX						
- Lost capital	€	0	0	-4092	-2793	-4092
- New investment	€	-12361	-7216	-27246	-22295	-28227
OPEX						
- Electricity	€	-8057	-8291	-26987	-25541	-7091
- Maintenance	€	-6956	-7234	-7048	-7841	-6751
Effects						
- Perceived safety	€	0	0	0	0	0
- Economy	€	0	0	0	0	0
- Impressions of the environment	€	0	0	0	0	0
- Mobility	€	0	0	0	0	0
- Road safety	€	0	0	0	0	0
- Animals (incl. food)	€	0	0	0	0	0
- Human health	€	0	0	0	0	0
- Environment	€	0	0	0	0	0
Total						
- Total NPV	€	-27374	-22741	-65372	-58470	-46160
- Power usage	kWh	66855	70557	252245	261015	54916

Table J.24: Larikslaan local CBA found configurations

What	Unit	Base	Max. NPV	Min. NPV	Max. energy	Min. energy
Type of lighting used as replacement						
- Type of new poles		Steel	Composite	Steel	Steel	Steel
- Type of new luminairies		LED Static	LED Static	HPS dimming	HPS	LED Intelligent
- Dimming profile used new lights?		Static	Static	No dimming	No dimming	Intelligent
Time						
- Replacement year of existing fixtures	year	2033	2033	2031	2035	2031
- Replacement year of existing lights	year	2021	2022	2021	2021	2021
- Replacement interval of new fixtures	years	25	28	23	23	23
- Replacement interval of new lights	years	25	28	9	9	23
- Luminaire cleaning interval new lights	years	4	5	5	5	3
- Replacement year of existing poles	year	2058	2089	2031	2035	2031
- Replacement interval of new poles	years	50	84	23	23	23
Lighting replacement specifications						
- Number of lights per fixture		1	1	1	1	1
- New fixture power	W	16.0	16.9	41.0	41.0	15.1
- New lights power	W	16.0	16.9	41.0	41.0	15.1