Public street lighting for Rotterdam

Developing sustainable public lighting for residential streets

Master Thesis | Integrated Product Design | Nine Klaassen
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November, 2013

Delft University of Technology
Faculty of Industrial Design Engineering

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Chair: Dr. ir. S.J.F. (Bas) Flipsen
Mentor: Ir. A.E. (Arno) Scheepens

Company mentor: Ir. L.F. (Leon) Dijk
This thesis is the result of my study Industrial Design Engineering, with the master specification Integrated Product Design. I want to design products that matter, products that make the world a better place to be. I like to keep solutions realistic without compromising on creativity.

“Creativity is making the unthinkable thinkable.”

“Designing is making the unrealistic realistic.”

The assignment for this thesis, about public street lighting and urban nature, gave me the opportunity to design a meaningful product from which many stakeholders in the urban environment could benefit.

I believe I succeeded in this mission and I am happy with this project being the final result of my study.

This report will tell and show, with many visuals, the process I went through in the past six months. Enjoy reading about my process and finding out gradually what the final design will be!

Nine Klaassen,

November 2013
Acknowledgments

Before starting to tell the story of this thesis I would like to thank several people who helped me during my process.

First of all I would like to thank my supervisory team, Bas Flipsen and Arno Schepens from the TU Delft and Leon Dijk from the municipality of Rotterdam for the inspiration, motivation and guidance of my process.

Furthermore I would like to thank several residents in Rotterdam for giving their opinion on public street lighting and on my concepts and final design: Martine, Ellen, Birgit, Peter, Jan-Willem, Ernst, Daan, Michel, Loes, Thea and Tjebebe, thanks for your time.

From the municipality of Rotterdam I would like to thank Richard and Joep for helping me start up this project. For the interviews I conducted I would like to thank Ruud, Gerda, Marc, Jan, Inge, Tony, Peter, Onnie Bart, Erwin, Willem, Charl and Ben, Gerard and Ramon, your input was very valuable for me.

For the creative input I would like to thank, Erica, Olaf and Marijn from the municipality and Robert, Walter and Anke from Spark design & innovation. The creative session you all gave input for helped me to create the final concept. From the TU Delft I would like to thank Ernst-Jan for helping to prepare this creative session.

The refreshing moments at Heijplaat gave a nice touch to my working environment, for the pleasant working atmosphere and the walking tours at Heijplaat I would like to thank Carina and all other people I met during the days I worked in de Kas.

Next to the help from the municipality I got help from several companies, John from Schréder, Alwin and Amit from Tvilight and Leon from Solsolutions, with your help I was able to make the prototype.

The mental support came from my friends at the faculty and my roommates. Thanks Anne and Kimberly for listening, drinking coke and the motivation, I missed you during the last few weeks. Luckily Hester, Marit and Kim joined me on the second floor! Also, thanks to Geert for making the pictures of my prototype. And thanks to my roommates for the support and understanding, from now on I have time for baking pies again.

And last but not least the people who are closest to me. Thanks to my parents and brother for all the phone calls and mental support I got. And of course Peter, thanks for the feedback on my report and thanks for listening, it helped a lot for structuring my thoughts.
**Abstract**

Public street lighting has a major influence on safety, perception of safety and atmosphere perception. The municipality of Rotterdam has the obligation to provide the city with public street lighting. Also, they have the desire to create a pleasant atmosphere in the city during both day and night. A user study performed for this project has helped determine what a pleasant atmosphere means; clean streets (no litter), knowing your neighbors, enough urban nature and seeing in the dark. This thesis focuses on the last two points, because they seemed to be conflicting each other. A hypothesis was formulated, suggesting that urban nature and street lighting conflict each other above and underground. Above ground, trees reduce the light output of the street lighting when they grow close to a lighting point. Below ground, the roots of the trees get strangled between the power cables.

This conflict seemed to be enhanced by the fact that space is limited in the urban environment, especially in residential areas. A certain distance is needed between lampposts and trees, because of street lay-outs (side streets, parking spots, cables under ground) the options for are limited for placing a satisfying amount of trees in between the lighting points. However, the living quality of residential areas benefits from more urban nature.

The hypothesis was researched with observation and nine interviews. It was revealed that trees blocking light is solved easily by placing trees and lighting point correct. Correctly distancing trees and lighting points, both in height and horizontal spacing.

Trees can be allowed to block the light a little bit, because it creates a dynamic shadow on the road. For high speed roads (from 50 km/h) these shadows would become a problem for safety reasons. However, in residential streets it is not.

The underground conflict between tree roots and power cables can be solved in two different ways: find other ways to create residential green or redesign public street lighting. Within the first direction many solutions were found, however within the second direction there were not. Since 1800 the lamppost has looked the same: a light source on a pole. Other forms such as hanging street lighting and facade lighting solve some problems above ground (space consumption) but not underground. And these forms of public street lighting bring new problems with them (convincing building owners to allow this way of mounting).

With this analysis the assignment for this thesis was formulated:

*Solve the conflict between urban nature and public street lighting by designing a new street lighting system.*

Rotterdam has the goal to reduce CO$_2$ emission with 50% in 2020 (compared to 1990). To help reach this goal the CO$_2$ emission of the solution should be lower then the CO$_2$ emission of the current public street lighting. In order to do this the environmental aspects of public street lighting were researched for every step in the life cycle. This was done together with the (financial) value for every life cycle step. Together this results in an Eco-costs Value Ratio (EVR). The manufacturing and energy consumption turned out to be the most harmful steps for the environment. Maintenance and administration and energy consumption are the most expensive steps.

Reducing the energy consumption is beneficial in both environmental and financial terms. Reducing eco-costs in the manufacturing phase, together with reducing costs for maintenance and administration would make the design more valuable for the municipality.

This results in a list of requirements:

1. create a better atmosphere
2. create a safer feeling
3. create more space for urban nature
4. reduce CO$_2$ emission of Rotterdam
5. reduce energy costs
6. reduce maintenance costs
7. reduce administration costs
8. reduce eco-costs of the manufacturing phase

The assignment and list of requirements resulted in a new design for public street lighting, mounted on top of the roof of a house, the system is connected to the grid of the house. During night the light uses energy from the house. During the day one or two solar panels
This design offers a sustainable solution to the municipality: an innovative public street lighting product service system from which all involved stakeholders will benefit.

generates energy to compensate this use. The solar panel generates more than only what the light is using. This overcapacity is delivered free of charge to the resident. He or she gets a discount on the energy bill (up to € 50 euro per year per resident). The resident is not the building owner in many situations. A housing cooperation can be owner as well. Their benefit is the increasing value of a building with solar panels.

For the municipality the new concept means no energy costs, no digging, no separate grid and it is easier to convince the resident and building owner to cooperate. Because of these benefits the new design is cheaper than the current system, even with addition of the relatively expensive solar panels. The initial investment is a little bit higher, but the running costs (maintenance, administration and electricity) are much lower. With one solar panel the payback time is 9 years, with two solar panels the payback time is 36 years. The lifetime is at least 40 years.

Because of the energy production of the solar panels the new design has reduced the eco-costs and CO₂ emission to negative values. This means the environmental burden, caused by manufacturing and energy consumption, is largely compensated. The environmental benefits can get up to 2300 kg CO₂ equivalent per street per year.
<table>
<thead>
<tr>
<th><strong>Glossary</strong></th>
<th></th>
</tr>
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<tbody>
<tr>
<td><strong>Administration management</strong></td>
<td>Desk work, inspections</td>
</tr>
<tr>
<td><strong>CT</strong></td>
<td>Color Temperature in Kelvin, colors close to white light</td>
</tr>
<tr>
<td><strong>Diffuse light</strong></td>
<td>Large area that emits light</td>
</tr>
<tr>
<td><strong>Directional light</strong></td>
<td>Point light</td>
</tr>
<tr>
<td><strong>EVR</strong></td>
<td>Eco-costs Value Ratio</td>
</tr>
<tr>
<td><strong>Glare</strong></td>
<td>The luminance within the visual field that is larger than the luminance to which the eyes are adapted, this results in loss in visibility.</td>
</tr>
<tr>
<td><strong>ICOR</strong></td>
<td>Improvement Center Openbare Ruimte</td>
</tr>
<tr>
<td><strong>Illuminance</strong></td>
<td>Light that travels towards a surface, measured in Lux or Lumen/m²</td>
</tr>
<tr>
<td><strong>Intensity</strong></td>
<td>Amount of light</td>
</tr>
<tr>
<td><strong>LCA</strong></td>
<td>Life Cycle Analysis</td>
</tr>
<tr>
<td><strong>Luminance</strong></td>
<td>Luminance is the measure of luminous intensity per area in a given direction (cd/m²). It can also be described as light that is reflected from a surface (light source), measured in Lux or Lumen/m²</td>
</tr>
<tr>
<td><strong>MRO</strong></td>
<td>Milieu en Ruimtelijke Ontwikkeling, department for Environmental and Spacial development</td>
</tr>
<tr>
<td><strong>OBU</strong></td>
<td>Onderhoud BUitenruimte, department for outdoor maintenance</td>
</tr>
<tr>
<td><strong>PM&amp;E</strong></td>
<td>Department for Project management &amp; Engineering</td>
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<tr>
<td><strong>PV panel</strong></td>
<td>Photo Voltaic panel or solar panel</td>
</tr>
<tr>
<td><strong>Residential green</strong></td>
<td>A form of urban nature</td>
</tr>
<tr>
<td><strong>SB</strong></td>
<td>StadsBeheer, cluster for city maintenance</td>
</tr>
<tr>
<td><strong>SO</strong></td>
<td>StadsOntwikkeling, former dienst Stedenbouw en Volkshuisvesting, cluster for City development</td>
</tr>
<tr>
<td><strong>Spill light</strong></td>
<td>Strooilicht</td>
</tr>
<tr>
<td><strong>Stedin</strong></td>
<td>The grid manager, responsible for the electricity cables underground</td>
</tr>
<tr>
<td><strong>Technical management</strong></td>
<td>Maintenance</td>
</tr>
<tr>
<td><strong>TF-signal</strong></td>
<td>Tune-frequency signal</td>
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<td><strong>ICOR</strong></td>
<td>Improvement Center Openbare Ruimte</td>
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INTRODUCTION
1. The project

This project is carried out for the municipality of Rotterdam, with more than 600,000 residents, the second largest city of the Netherlands. In this thesis the conflict between urban nature and public street lighting is addressed.

First, the project will be introduced with a short explanation of the project its context, the initial problem definition and the assignment.

This introduction is followed by an extensive analysis phase on public street lighting and urban nature. A context and stakeholder analysis on both these subjects has been carried out and the Eco-costs Value Ratio (EVR) of public street lighting was calculated. After the analysis the original assignment was re-written in the form of a design brief. From there, the idea and concept generation was started. The concepts were evaluated with the stakeholders and with the EVR model. One concept was chosen and detailed in the design phase. The final design was then evaluated with the EVR model. A prototype was made and several tests were done. The thesis will end with an evaluation based on the list of requirements and recommendations for further research.

1.1. Context

The city of Rotterdam has the goal of becoming the most sustainable harbor city of Western Europe (Rotterdam Climate Initiative, 2013). This is described as becoming a clean, green and healthy city. (Gemeente Rotterdam, 2013b). The Climate Initiative Program needs to take care of this ambition by reducing the CO₂ emission of...
the city with 50% by 2025, compared to 1990. Also, they strive for improvement on air quality and noise reduction. One of the projects that contributes to this program is the Improvement Center Openbare Ruimte (ICOR). Within the ICOR project, sustainable public facilities, such as benches, vertical green, interactive trashcans, lampposts and multi-functional pavements, will be tested. ICOR is a test case, where Small and Medium sized Enterprises (SME’s) can install, test and show their products (the showcase is located at Heijplaat, Figure 1). Products at this showcase make public space a more pleasant place to be by making it greener, cleaner and healthier. The ambition of the ICOR project is to stimulate innovations that fits the following criteria (Urban2020, 2012):

- Deliver energy such as electricity or heat
- Compensate for harmful emissions such as CO$_2$
- Filter or clean the air or water
- Communicate with its users by advertisement or information

ICOR has a vision for the future, which is a multifunctional street with integrated sustainable solutions (Figure 2). This project will contribute to this vision.

1.2. **Problem definition**

Residential streets have an important role in a dense city such as Rotterdam. They are the daily environment of the citizens. Therefore, it is important to make streets a pleasant place to be: clean, green and healthy. In other words the perceived living quality of the street has to be increased. Many factors can influence this perception, such as:

- Accessibility of green (van Herzele, Wiedemann, 2002; van Hoorn, 2011)
- Street lighting and light color (Smeets, 2012)
- Noise (Smeets, 2012)
- Smell (Dietz, 2010)

How residents perceive and experience their street has been researched by Van Hoorn (2011) in terms of sustainability and future desires of the residents. In this research the residents indicated that they would like to have more green, more art, less parked cars and enough waste bins and street lighting. For this thesis it is too much to find solutions for all those needs. During an interview with an employer from the municipality two problem were selected (Ruijtenbeek, 2013): residential green (with a focus on trees) and lighting. These problems were selected because at this moment conflicts exist between those two: both above ground (leaves blocking the light, Figure 3) and underground (tree roots and cables, Figure 4).

1.3. **Assignment**

From this problem definition the assignment was formulated which fits in the ICOR context:

“Solve the conflict between urban nature and street lighting by designing a new street lighting concept that fits with the ICOR ambitions.”

Figure 3. Tree reduces the light intensity at street level

Figure 4. The problem underground
1.4. Research question
Before the design process can start an understanding of the current situation is needed. This includes a context analyses, literature review, stakeholder analysis (including user study) and competitor analyses. For these analysis research questions are set up.

1. **What does the current situation look like and which problems occur in this situation?** (Context analysis)
   1.1. What is described by law?
   1.2. What are the eco-costs and costs of public street lighting? (EVR)
   1.3. What are other solutions that solve (part) of the problem? (Competitor analysis)

2. **What are the requirements for residential street lighting?** (Stakeholder analysis)
   2.1. Who are the stakeholders in the street lighting system of Rotterdam, and what are their tasks and responsibilities in this system?
   2.2. What are their wishes/requirements?

3. **How do people experience light in relation to environmental atmosphere?** (Literature review and user study)
   3.1. What kind of atmosphere do they prefer?
   3.2. What do they expect from public street lighting?

1.5. Approach
Several methods were used during this thesis, for the first research question observations, interviews and an internet research was done. The Eco-costs Value Ratio model (explained on the next page) was used for answering subquestion 1.2. The answer to the second question was found by interviewing several stakeholders. Also, the conclusions of the result of the context analysis was incorporated in the requirements. For the third research question a literature and user study was done. With the results of these studies the list of requirements was finalized.

With the gathered information from the analyses phase a detailed design brief was written which was used as starting point for the design phase.

**Nature inspired design**

In the design phase Nature Inspired Design (NID) was used for inspirational purposes in the ideation and conceptualization phase. NID means learning from nature. Nature has developed itself for over 3.8 billion years, it knows what works and what lasts. Nature is extremely efficient and does not know about waste (closed material loops). This wisdom is something we can learn from and we can mimic in order to make efficient and innovative designs. Many examples exist, one of them is the design of a high speed train (Figure 5) (Biomimicry Institute, 2013). The initial design of this train had a problem: when entering a tunnel air would be compressed in front of the train, when leaving the tunnel the air would expand and create a sound explosion. A Japanese engineer happened to be a bird watcher, he noticed that the Kingfisher was able to dive into water without a splash, without turbulence. He analyzed the form of the beak and mimicked this on the train.
Eco-costs Value Ratio

The Eco-costs Value Ratio or EVR model uses a Life Cycle Analysis (LCA) to determine the eco-costs of every step of the life cycle. Next to this the value of all steps of the life cycle will be calculated. The ratio between these two numbers is the EVR:

$$EVR_{total} = \frac{\sum eco\text{-}costs_n}{value_{total}}$$

The ratio shows the sustainable efficiency of a product and/or service design, in a certain phase of the life cycle. By analyzing these aspects it can be determined where improvements can be made, increasing value or decreasing eco-costs (green arrows in Graph 1).

The value is expressed in euros, value can be different things: costs, selling price or Customer Perceived Value (CPV). In this thesis the price the municipality pays for public street lighting is used to determine the value of the different life cycle steps. For the municipality costs and price are the same (red dotted lines in Figure 6), because they do not sell a product to a second party and do not have the goal of making profit. More about value calculation can be found in appendix 8.2.

The eco-costs are also expressed in euros, it is based on the cost difference for choosing an alternative that does not harm the environment. Data is used from two databases, Idemat 2012 and Eco-invent. The eco-costs are ‘virtual’ costs, since they are not (yet) directly reflected in the price of a product (apples from Greece can be sold cheaper in our supermarkets then apples from Holland, even though the eco-costs for these Greek apples are higher due to transport). More about how the eco-costs are determined can be found in appendix 8.

Ideally the eco-costs will be low and the gained value during a life cycle step will be high. EVR can be used as evaluation tool in the design process. With the EVR different solution can be evaluated to determine which one is most efficient in terms of eco-costs and gained value.

In this thesis, EVR was used three times. First the current situation was analyzed, the benchmark, to find the life cycle steps where most improvements can be made. During the concept phase the EVR model was used to make a decision. The final design was evaluated with EVR and compared to the benchmark from the first analyses. This assures a realistic sustainable innovation because the value is in balance with the gained sustainability improvement.

The eco-costs are also expressed in euros, it is based on the cost difference for choosing an alternative that does not harm the environment. Data is used from two databases, Idemat 2012 and Eco-invent. The eco-costs are ‘virtual’ costs, since they are not (yet) directly reflected in the price of a product (apples from Greece can be sold cheaper in our supermarkets then apples from Holland, even though the eco-costs for these Greek apples are higher due to transport). More about how the eco-costs are determined can be found in appendix 8.
2. Part 1: context analysis

This first chapter of the analysis phase is about the context of the assignment. The research question that will be answered:

- What does the current situation look like and which problems occur in this situation?

The current situation will be described, followed by describing the problems that occur. The last part of the context analysis will be a description of the solutions that are currently found in Rotterdam and on the market in general.

2.1. Current situation

A visualization of the current situation (above- and underground) is seen in Figure 7. This is only one example. From observation it is concluded that this is a typical residential street for Rotterdam; parking on both sides, lighting and trees placed in an alternate pattern. When the street is small trees are placed near crossings or on small squares in the street (Figure 9). Light point heights are mostly 4 or 6 meter. Sometimes hanging street lighting is seen with a light point height of 10 m. Dimensions of several parts of a residential street vary between:

- sidewalks from 1 to 6 meters
- a car lane from 4 (one way) to 12 meter (one way or two way, and parking spots on one or both sides)
- light point height can be 4, 6, 8 and 10 meter
- building heights from 5 to 20 meter
- light point height between 4 and 10 m

Other examples for street lay-outs can be found in appendix 6.

Figure 7. Context assignment

Figure 8. Coolsestraat in Rotterdam, alternate pattern

Figure 9. Gouvernestraat in Rotterdam, trees on a small square in the street
2.2. Urban nature

“The amount and quality of green spaces affect citizens’ patterns of activities, the modes and frequencies of every day recreation and the opportunities to relax of daily stress.” (van Herzele, Wiedemann, 2002)

Urban nature is important for our well-being (A. van Herzele, de Vries, 2012). It contributes to the living quality of the city. Besides its social impact, urban nature brings more benefits such as noise reduction, temperature regulation and increasing air quality (Carles, 1992). It solves many problems the urban environment suffers from. Therefore the main function of urban nature can be described as follows: improving peoples well-being because it makes the urban environment cleaner and healthier. This main function can be split up in physical well-being (cleaner and healthier) and emotional well-being (healthier):

**Physical well-being**
- Filtering the air
- Noise reduction
- Temperature reduction
- Water management

**Emotional well-being**
- Atmosphere perception

**Types of urban nature**
Residential green is a form of urban nature, other types are quarter green (small parks) and district green (large parks) and urban forest for example (Figure 10). Residential green exists out of trees, planters, ivy, facade gardens and many forms. Trees are most robust, to weather changes and vandalism, and do not need much maintenance compared to other types of residential green. Other types, seen in Figure 11 till Figure 16, need more maintenance (nutrition and water) and are more vulnerable to weather changes and vandalism. A benefit is that they need less space underground compared to trees. A mix between trees and other types is the best option.

**Trees**

To check how green Rotterdam is, data about the amount of trees is compared with other cities. Rotterdam has 0.25 urban trees per head of the population, and more than one tree per head if het Kralingsebos is included in the calculation. Compared to other cities of the same size, 0.25 is not much. Rotterdam wants to increase the amount of trees, they have written the

<table>
<thead>
<tr>
<th>City</th>
<th>Population</th>
<th>Urban trees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utrecht (Gemeente Utrecht, 2013)</td>
<td>320.000</td>
<td>145.000 (0.45)</td>
</tr>
<tr>
<td>Den Haag (Gemeente Den Haag, 2008)</td>
<td>500.000</td>
<td>110.000 (0.22)</td>
</tr>
<tr>
<td>Rotterdam (Gemeente Rotterdam, 2013a)</td>
<td>600.000</td>
<td>148.000 (0.25)</td>
</tr>
<tr>
<td>Amsterdam (Parool, 2007)</td>
<td>800.000</td>
<td>450.000 (0.56)</td>
</tr>
</tbody>
</table>

Figure 10. Types of urban nature, focus of this thesis is on residential green
Bomenstructuurvisie for this purpose however they do not have enough financial resources to execute this vision.

Maintenance
From all sorts of residential green, trees need the least maintenance. They need to be pruned down every few years but they do not need extra nutrition. Planters do need water during dry summers. This is labor intensive and expensive, especially when planters are situated on difficult to reach locations (Figure 14).

Residential green
As stated in the problem definition the focus of this thesis is on residential areas. Residential streets have an important role in a dense city such as Rotterdam. They are the daily environment of the citizen. Therefore it is important to make streets a pleasant place to be. One of the factors that influences this is the accessibility of green. The thesis of van Hoorn (2012) indicated the need for more urban nature.

The parks in Rotterdam are used more and more these days for recreation. This trend indicates the need for green outdoor space. (Interview with Marc Verheijen). In this thesis this need will be fulfilled on residential area level. According to Kleis (2012) residential green is evenly important as parks. Therefore more residential green would increase the living quality of the street. An affordable solution should be found to create the opportunity for more residential green.

Maintenance
From all sorts of residential green, trees need the least maintenance. They need to be pruned down every few years but they do not need extra nutrition. Planters do need water during dry summers. This is labor intensive and expensive, especially when planters are situated on difficult to reach locations (Figure 14).
Figure 15. Fake residential green, picture of tree in Oude Westen

Figure 16. Vertical green in the Afrikaanderwijk

Figure 17. Zijdewinestraat in Rotterdam, without any residential green

Figure 18. Facade gardens in the Couwaelstraat, does not have much influence on the perception of the street being green
2.3. Public street lighting

“Light is crucial for the experience of safety, mystery and wellbeing in a physical and psychological way” (Stidsen, 2009)

“Research shows that light has an effect on, for instance, visibility, task performance, health, well-being and mood.” (Boyce, 2003; I. Vogels, Bronckers, X., 2009)

Street lighting has a major influence on safety (Stidsen, 2009), perception of safety and perception of atmosphere in general. Main function of (street) lighting: increase visibility during the night. But the question then is, why do people want this?

- Recognizing objects, persons and colors
- Orientation

Types of public street lighting

Public street lighting occurs in many forms, different types of mounting are shown in Figure 9. The type that is seen most is lighting points mounted on a pole. Different poles (Figure 23) and different luminaires (Figure 26) exist for these mounting types. One of the most used pole and luminaire combinations (Graph 2) is visualized schematically in Figure 19. With this configuration as an example it will be further elaborated how public street lighting works.

How does it work?

TF-signal

Public street lighting is connected to its own grid, during the day the grid is not provided from power, during night it is. With a TF-relay, or Tune Frequency relays it is switch on and off. A signal is send through the power line, which changes the state of the relay. The signal is sent by the grid manager when several luminous intensity measurements indicate a level below 40 lux (de Hooge, 2013).

Grid connection

The grid connection is the point where responsibility changes, the connection point and cable to the central switching point is managed and maintained by the grid manager.

Figure 19. A lighting pole, luminaire connected to the grid under ground

Figure 20. Luminaire mounting types
(Stedin), the cable towards and inside the mast is management and maintained by the chosen contractor for public space (this can differ every four years, at the moment of writing this thesis, in Rotterdam the contractor is CityTec).

**Fusebox**
The fusebox is installed for safety reasons, the pole may never be energized because high voltages (230 V) are applied. This would be dangerous for residents. The fusebox is located inside the pole (Figure 23), when a fuse breaks, it is easily replaced.

**Reflectors and Lenses**
A light bulb has a certain output angle, most of them have a spherical output, and reflectors or lenses in the luminaire shape the beam to a smaller angle. LED’s have integrated lenses which make them a light source with small beam angle. Still secondary optics (a second lens or reflector) are used to create a beam that is suitable for public street lighting. Optics that create oval, rectangular and asymmetric outputs are possible.

**Ballast**
The ballast is located inside the luminaire. It is taking care of the power supply of the light bulb. The newest ballast designs have different power output settings for dimming. Static dimming based on time schedules is seen most, dynamic dimming based on input data like weather, surrounding light and amount of traffic is being developed at the moment of writing this thesis.

**Light bulb**
Light bulbs that are used in public street lighting nowadays are seen in Table 2. Recently LED was added to this list. LED is not the most efficient in terms of Lm/W however the lifetime is very long, this increases the material efficiency. For one LED light bulb, more than four PL lights are needed.

In Figure 24 and Figure 25 different light source colors are shown. The use of a light source, which emits white light, increases color recognition compared to a monochromatic light source.

### Table 2. Different light bulbs

<table>
<thead>
<tr>
<th>Light bulb type</th>
<th>CT [K]</th>
<th>Efficiency [Lm/W]</th>
<th>Start up time [min]</th>
<th>Bulb lifetime [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pressure Sodium Vapor Light (SOX)</td>
<td>1800 (orange)</td>
<td>160</td>
<td>-</td>
<td>6000</td>
</tr>
<tr>
<td>High pressure Sodium Vapor Light (SON)</td>
<td>1950 (yellow)</td>
<td>100</td>
<td>4</td>
<td>28000</td>
</tr>
<tr>
<td>Metal halide lamps (CDM and CPO)</td>
<td>2800 warm white</td>
<td>100</td>
<td>5</td>
<td>6000</td>
</tr>
<tr>
<td>Mercury-vapor lamps</td>
<td>3600 cool white</td>
<td>20</td>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td>Compact fluorescent lamps (PL and PLL)</td>
<td>2700 warm white</td>
<td>80</td>
<td>-</td>
<td>10000</td>
</tr>
<tr>
<td>Light Emitting Diode (LED)</td>
<td>2700 warm white</td>
<td>60</td>
<td>-</td>
<td>45000</td>
</tr>
</tbody>
</table>
Luminaires

Rotterdam has guidelines for luminaire poles, their shape should be conical and not stepped (NPK, 2011). The material is steel and the finish galvanized and powder coated, in three colors: dark gray and light gray and a gray/blue color (Gemeente Rotterdam, 2012). These poles are seen in Rotterdam but much more designs as well. Older poles are stepped, poles without powder coating are seen and other color then the proposed once in the style guide. Of course poles that indicate crossings and traffic lights are seen in Rotterdam as well. Examples are seen in Figure 23.

When looking at the data about street lighting in Rotterdam the variety in luminaires is confirmed. About 300 types in 650 different configurations exist in Rotterdam (Gemeente Rotterdam, 2013d). 75% Of all lighting points (110.000) are lit with only 10 types of luminaires. Within these 10, still 80 different configurations exist:

- Light bulb type (influencing light color and power consumption)
- Light bulb settings (location inside luminaire)
- Light point height (depending on chosen pole)
- Dimming or no dimming

In Graph 2 the top 10 of luminaire designs, and the total amount of LED luminaires is shown. The first two luminaires are mainly used in residential streets. The Altra on top of a 6 meter pole and the Kegeltop on a 4 m pole.

To reduce the variety in luminaire designs a style
A guide was written in 2011. Materials, colors and forms of luminaires and poles are prescribed in this document. Because the lifetime of luminaires is 20 years, it will take a while before more coherence is seen in public space.

As pole material it is decided to use powder coated steel. The color of the coating is fixed as well, dark gray (RAL0003500) and light gray (50% RAL2605005 and 50% RAL0005000) and a gray/blue color (RAL2602005). For luminaire designs the preference is luminaires without small details, straight lines and continuous forms. (NPK, 2011) Style guidelines are set up for luminaires on top of a pole and for luminaires on an outrigger. These guidelines will be used during the design phase.

<table>
<thead>
<tr>
<th>Luminaires in Rotterdam</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED</td>
</tr>
<tr>
<td>SRS</td>
</tr>
<tr>
<td>FGS</td>
</tr>
<tr>
<td>Airtrace</td>
</tr>
<tr>
<td>Iris</td>
</tr>
<tr>
<td>SRM</td>
</tr>
<tr>
<td>SGS</td>
</tr>
<tr>
<td>Saffier</td>
</tr>
<tr>
<td>Kegeltop</td>
</tr>
<tr>
<td>Altra</td>
</tr>
</tbody>
</table>

Graph 2. Top 10 luminaires and LED luminaires
General light properties
Light can be described with four characteristics: luminous intensity, color (hue, saturation and brightness) or Color Temperature (CT), direction and diffusion (Cortes, 2009).

Luminous intensity
The luminous intensity is the amount of light coming from a source, it is measured in Candela (cd), also Lumen per Steradian (lm/sr). Next to luminous intensity of a light source also luminance and illuminance are used much as terms in the field of lighting. Luminance is the measure of luminous intensity per area in a given direction in cd/m². Illuminance is the amount of light reflected by a surface. Illuminance is measured in Lux, also lm/m², also cd*sr/m². Examples of illuminance can be found in Table 3.

Color
The color of light can be described with: hue, saturation and brightness (Figure 27). For white an other system exist, since many different forms of white light exists. It is described with a temperature in Kelvin (Figure 28).

Direction and diffusion
Diffuse light is light coming from a large area, direct light has a point light as source. The sun gives direct light, when the sky is cloudy the light is diffuse. Difference can be seen in the way shadows appear (Figure 29).

Table 3. Illuminance

<table>
<thead>
<tr>
<th>Illuminance (lux)</th>
<th>Surfaces illuminated by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>Moonless clear night (Schlyter, 2006)</td>
</tr>
<tr>
<td>0.27 – 1.0</td>
<td>Full moon clear night (Schlyter, 2006)</td>
</tr>
<tr>
<td>3.4</td>
<td>Twilight (Photonis.com)</td>
</tr>
<tr>
<td>3 – 5</td>
<td>Residential street lighting (NEN, 2004)</td>
</tr>
<tr>
<td>10</td>
<td>Public street lighting for highways (NEN, 2004)</td>
</tr>
<tr>
<td>50</td>
<td>Family living room lights (NEN, 2004; Pears, 1998)</td>
</tr>
<tr>
<td>100</td>
<td>Very dark overcast day (Schlyter, 2006)</td>
</tr>
<tr>
<td>320 – 500</td>
<td>Office lighting (European Standard, 2011)</td>
</tr>
<tr>
<td>10000 – 2500</td>
<td>Full daylight (Schlyter, 2006)</td>
</tr>
</tbody>
</table>

Public street lighting properties
These general light properties are manipulated to create a desired lighting solution. Besides these properties of light, for public street lighting other elements have to be taken into account: Light point height, uniformity, glare, blinding and light pollution.

Light point height
When lighting points are positioned high they can light a large area. This way, less lighting points are needed, compared to low lighting points. However, higher lighting points are more easily obscured by trees, lower lighting points can be positioned below the crown of a tree (Figure 7). Lower lighting points are perceived....
more friendly then higher points (de Hooge, 2013). Both options have positive and negative points.

**Uniformity**
The uniformity rate is determined by minimum light level/mean light level, with higher lighting points a more uniform light pattern can be created. A high uniformity feels more safe for residents. It means the mean intensity can be lowered. (de Hooge, 2013). The minimum and mean light level are influenced by the light beam angle and the distance between the light points. This distance creates less or more overlap in the light pattern (Figure 7). Figure 30 shows examples of a low uniform light design and a design with a high uniformity.

**Glare**
The amount of non-visible space around a lighting point (Figure 30). If the amount of around a light source is too high it disturbs the visibility of the environment.

**Blinding**
Blinding is caused when the light directly shines into your eyes. Higher intensities cause more problems. Blinding can be reduced by smaller output angles and higher lighting points.

**Light pollution and spill light**
Light pollution (Figure 31) is caused when light is shining towards locations where it is not wanted (the sky or inside houses). With a high amount of spill light (Figure 32) more light pollution is present. LED has less amount of spill light and is easy to direct so this will solve some problems.

![Figure 30. Non uniform versus uniform lighting (CityTec, 2013) and glare around light source](image)

![Figure 31. Ligh pollution (ASC GCA, 2013)](image)

![Figure 32. Spill light from PL source (left), LED (right)](image)
2.4. Eco-costs Value Ratio of public street lighting

The research question that will be answered in this paragraph:

- What are the costs and eco-costs of public street lighting?

In order to answer this question the EVR model is used (check page 15 for explanation of this model). The chosen lamppost for this analysis is the Kegeltop, on a 4 m steel pole. This luminaire is one of the most used ones in residential streets and it is a well-known design. The results of this analysis will be described in this paragraph. The complete analysis report, including the data set, can be found in appendix 8.

Rotterdam uses Total Costs of Ownership (TCO) to compare different luminaires, for a tender for example. The analysis is carried out with the same Functional Unit (FU) as the TCO data uses, for one street (1200*20 m) for one year with a light level according to regulations (minimum of 3 lux at street level and a uniformity rate of at least 25%).

**Figure 33. Kegeltop manufactured by Indal**

### Costs

**Manufacturing and installing costs**
These costs include the purchasing costs of the pole and luminaire and the working hours and administration costs of the installation process. Creating a grid connection, digging for cables and the pole are expensive: about 55% of the installing costs. Purchasing the pole and luminaire is the other 45%.

**Technical management**
This is mainly related to maintenance work, such as:

- process residential notifications of failures
- replace light bulbs
- repair electronics and cable failures and after accidents
- prevent cable failures
- number poles
- clean luminaires
- monitor expenses

**Administrative management**
These costs are related to desk work. Examples are:

- file management
- keep the monitoring system up to date (numbering poles)
- office expenses and taxes
- safety inspections and processing of the inspection reports
- set-up documents for the next tender
- outdoor inspection of luminaires

**Energy consumption**
This is based on the most used light source for residential streets: a 36 W PL light bulb. The yearly operating time of a single light bulb is 4200 hours. Also some taxes are included in the energy consumption costs.

**End of life**
These are the costs for the removal tax of a pole and luminaire, and the removal costs of the current grid connection.

*Graph 3. Costs for lighting one street for one year*
**Eco-costs**

The eco-costs of lighting can be seen in Graph 3 (right). Not all phases have relevant eco-costs, administration and technical management consist out of labor. Maintenance does require some car kilometers to be driven, but this has almost no influence on the eco-costs. The eco-costs of the energy consumption are highest. However, also the manufacturing phase has a high influence on the eco-costs. The eco-costs of the End of Life phase are negative since the material of the pole (steel) is recycled by the contractor.

Graph 5. Eco-costs costs for lighting one street for one year

<table>
<thead>
<tr>
<th></th>
<th>Current situation</th>
<th>Total: € 531</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing light</td>
<td>295</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td>276</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy consumption</td>
<td>-40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Graph 4. Eco-costs Value Ratio

<table>
<thead>
<tr>
<th></th>
<th>Current scenario</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs [€/street/year]</td>
<td>Eco-costs [€/street/year]</td>
<td>EVR</td>
</tr>
<tr>
<td>Manufacturing lighting</td>
<td>1418</td>
<td>276</td>
</tr>
<tr>
<td>Installation</td>
<td>3280</td>
<td>276</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>6219</td>
<td>572</td>
</tr>
<tr>
<td>Technical and administration management</td>
<td>11051</td>
<td>572</td>
</tr>
<tr>
<td>End of Life</td>
<td>11056</td>
<td>532</td>
</tr>
</tbody>
</table>
EVR
In Graph 4 the costs, which represent the value, and eco-costs are plotted against each other. The graphs show which life cycle steps are most harmful for the environment and which steps are most expensive. The ratio is highest after the manufacturing phase followed by the energy consumption, installation phase and technical and administration management.

From this graph it can be distracted where improvements should be made. The manufacturing and energy consumption phase cause a rise in eco-costs, reducing or compensating these eco-costs should be taken into account in the design process. Costs can be saved in all phases, however a focus on manufacturing, energy consumptions and technical and administration management is advised. Since these add most costs, most savings can be accomplished in these phases.

2.5. What is described by law?
Several norms exist, which contain guidelines for street lighting. Light intensity levels for several types of streets are prescribed, even as uniformity and light color. Light intensity and uniformity are prescribed in NEN norms, light color is described in the light vision of Rotterdam. The color temperature of the light source should be 3000 K as stated in the light vision (Lightvision, 2011). The 36 Watt PL light in the Kegel has a temperature of 3000 K. (Indal, 2013). Which part of the NEN norm should be applied to residential streets is also prescribed in the light vision: Class ME4b for lower speed car lanes and S5 for pedestrian or cyclist areas. (Lightvision, 2011) (CEN, 2003)

The uniformity is one of the most important parameters according to the light architect. Because it influences the perception of safety and the perception of spaciousness of a street. (Veitch, 1998). With a higher uniformity a lower mean light level can be used. Where the norm strives for 20% as the uniformity rate, Rotterdam prefers at least 25%. This could mean placing lamppost closer to each other (more overlap in light pattern) or using hanging street lighting because they can create a more uniform light.

These regulations have to be kept in mind, mainly for safety issues. However a critical note is required: society changes and technology improves. With these changes the opinion regarding lighting of urban space changes. With LED lighting a lower light level could be chosen than with monochromatic light sources for example (Akerboom, 2013). Regulations take time to develop, causing them to be behind on trends and innovations. When a new lighting concept is designed it has to be judged whether the regulations are still relevant or not.

Table 5. Overview of lighting classes according to regulations (CEN, 2003)

<table>
<thead>
<tr>
<th>ME-Class</th>
<th>Minimum light level</th>
<th>Mean light level</th>
<th>Uniformity rate (minimum/mean light intensity)</th>
<th>Threshold Increment*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME4b (lower speed vehicle area, &lt;30km/h)</td>
<td>0.3 cd/m2 (3.8 lux with hemispherical light source)</td>
<td>0.75 cd/m2 (9.4 lux with hemispherical light source)</td>
<td>0.4</td>
<td>15 %</td>
</tr>
<tr>
<td>S5 (pedestrian and cyclist area)</td>
<td>0.6 lux</td>
<td>3 lux</td>
<td>0.2</td>
<td>-</td>
</tr>
</tbody>
</table>

*The TI value is the loss of visibility caused by glare.
2.6. Problems and conflicts
Until now different types and characteristics of urban nature and public street lighting were discussed. This chapter will pay attention to the problems that occur and the conflicts between urban nature and public street lighting.

Urban nature problems

Limited space
The facts say that Rotterdam has a satisfying amount of trees however they are not evenly spread through the city and that makes that Rotterdam is not perceived as a green city. The municipality has some plans for planting more trees, the Bomenstructuurvisie however not enough money is available to realize this plan. Planting more trees is one solution but other options could be explored as well. The examples in Figure 11 till Figure 16 show other options; vertical green, planters, shrubs and ivy. These types of green need less space above- and underground.

Maintenance
From all sorts of residential green, trees need the least maintenance when they are fully grown. When they are young they need some extra nutrition. The urban environment mainly exists out of dense and hard pavement such as concrete tiles and asphalt. This prevents air, water and nutrition from falling leaves, during autumn season, to be inserted in the ground. Therefore extra nutrition is needed. Planters need even more maintenance since they are more vulnerable to weather conditions and the use of a city (football hooligans for example).

Night view
During the day trees create a cozy atmosphere, during this is different in some situations. In Figure 34 dark spots in the view are seen. This is not beneficial for the atmosphere.

Public street lighting problems

Lack of space
The urban environment is busy and can be chaotic, many actsives are carried out at the same time by multiple people in a small area. Sometimes this goes wrong as can be seen in Figure 36.
Light pollution
Light does not only bring advantages during the night. Problems such as light pollutions, blinding and glare are common. In Figure 7, it could be seen that light is shining into houses, this light pollution is indicated as a problem by several the residents. On the other hand the façade is lighted as well this gives a more spacious feeling according to de Hooge (summary of interview in appendix 1.2) and that is beneficial for the perception of safety.

Multifunctional use
Rotterdam has the ambition to use poles for multiple purposes, such as combining poles for tram power lines with lighting poles and traffic signs. Only this is not always working out as desired. Multiple reasons are given:

- The RET (Rotterdamse Elektrische Tram, the company that takes care of public transport by tram in Rotterdam) does not allow it with some of their poles
- The RET poles are not on the drawing when the landscape architect starts designing and the landscape architect does not pay enough attention when visiting the area.
- The contractor can make mistakes, sometimes they put extra poles where the contract says it should be combined.
- Figure 40 and Figure 37 show examples of where functions are combined and of where it went wrong.

Using a pole as bike stand is also an example of multi-functional use, convenient for the bike owner, less convenient for others since it gives a messy street view, the pole can get damaged and the door in the pole is blocked.

Wiring
Lighting a tree with Christmas lights is nice when it is dark, during the day it looks less appealing (Figure 40). Atmosphere lights complicate maintenance of the tree. The lights first have to be removed before branches can be pruned, this consumes time and that costs money. Trees with Christmas lights are mainly located at squares, boulevards and parkways and less in residential streets. Since this thesis focuses on residential streets it is out of the scope of the project.

Maintenance and administration
The technical management (maintenance) and administration management costs are the most expensive parts of public street lighting. Mainly because it is labor intensive.
Conflicts

Under ground
One of the problems stated in the initial problem definition, tree roots and cables, is confirmed by the analysis. Trees need a lot of space underground and underground also cables are located as could be seen in Figure 4 and Figure 7. Tree roots will get damaged when digging for installing new cable or for repairing cables. This damage reduced the lifetime of the tree, also digging becomes more difficult since the tree roots are obstacles (Figure 41).

Above ground
The other problem stated in the initial problem definition was trees blocking light. This is partly confirmed by the information found during the analysis phase. Mainly on high speed roads it is a problem since it causes unexpected shadows that could be dangerous. Every three to five years trees are inspected and pruned down to avoid these problems (Kors, 2013). In residential streets this problem does not cause safety issues. The shadows that are created reduce the uniformity rate however this is not taken into account during the design process, the light architects calculates the uniformity rate without any elements in the street (de Hooge, 2013). Trees blocking the light reduces blinding and light pollution in houses and that is a positive effect. It also gives a natural light pattern on the street and the tree itself is lit. The advantage of lighted trees is shown in Figure 43.
2.7. Existing solutions

Solutions found in Rotterdam

Conflict under ground
For the problem of tree roots and cables underground, solutions are found in the documents available at the municipality. Guidelines are set-up with several solutions, such as: changing the location of cables, putting the cables inside a concrete containers, planting smaller trees (Figure 44) or increasing floor level. These solutions would solve many problems. However, in current situations it is too expensive to apply these solutions, in the future problems can be prevented, but for now the situation is as it is.

The municipality has maps of all components placed underground: cables, wires, drainage pipes, gas-pipes, metro tubes, even bombs from the second world war, are on this map. When digging is required, it is obligatory to consult these maps. This helps to prevent problems such as damaging tree roots or gas pipes. Unfortunately the maps are not always up to date so this is not a perfect solution.

Conflict above ground
This problem turned out to be less relevant in residential areas. However, it should be taken into account when designing the urban plan and lighting plan. A light should not be completely blocked by a tree. This would reduce the light output too much which reduces the light intensity at street level, creating an unsafe feeling. The solution is found in the lay-out of trees and lighting points. One solution that is seen to avoid the problem is placing trees on one side of the road and lighting points on the other side (Figure 46). Another is placing lights and trees alternately.

Maintenance of urban nature
A nice solution where the municipality does not need to perform maintenance of residential green, can be found in the Hondiusstraat in Rotterdam. The residents planted their own flower bulbs and they maintain them (this example of urban nature was shown in Figure 11).
**Limited space**
The Hondiusstraat has space for such residential initiatives but not all streets are suitable for this. Such as the Zijdewindestraat, a street with small sidewalks, parking on both sides a no residential green which was shown in Figure 17. A solution is to offer parking spaces in order to create space for residential green. Another option that does not consume much space would be vertical green. In the Couwaelstraat, which was shown in Figure 18, some residents have facade gardens however, this does not have a very large impact on the perception of the street being green.

The multifunctional use of lighting poles is a solution for the fact that space is limited in the urban environment. Applying this more can be done by communicating in time with the right people. However such communication is out of the scope of this project. Using the environment in a multifunctional way is inspiring and coherent with nature inspired design approach: researching what the environment can contribute.

**Night view**
Lighting trees during the night will solve the problem of them becoming dark spots in the view. This can be done with ground spots (Figure 46). Or from a larger distance since the tree is more equally lit. This idea of lighting trees is also mentioned in the interview with Jan van den Enk. He suggests to light trees with green light, to accentuate their color.

**Light pollution**
Light pollution can be avoided by placing shield in the luminaire which directs the light better. This decreases efficiency but does reduce light pollution. Painting a part of the luminaire black is a solution that is performed by some residents themselves, off course this is not allowed since the light intensity at street level may not meet the norm requirements anymore. LED light bulbs offer a solution as well with smaller beam angles and less spill light.

**Maintenance and administration**
Digitalization of several performed tasks can be a solution for reducing both costs. Several wireless management systems are on the market which can monitor public street lighting. Rotterdam is doing a pilot project with a system of Philips at the moment. Also, applying LED technology will reduce costs. LED’s have a longer lifetime and therefore have to be replaced less often.
Solutions on the market
The presented solutions are all solutions that are already found in Rotterdam. Looking a bit further to what the market is offering, brings other solutions. In this paragraph these solutions are discussed.

FreeStreet, hanging street lighting, Eindhoven (Philips lighting)
In this obstacle free design the lighting and power cable are integrated in the hanging wire, all-in-one design. This is efficient material use and the design is small and will not be in the way of the line of sight. The light output is limited (1600 lm) and therefore this design is only suitable for heights until 3.5 m.

Bahnhofstrasse Zürich, 3d lighting (Artemide and North Light)
A different way of lighting a square: many small lighting points, mimicking a sky full of stars. This creates a nice view during the night when it is dark however, during day the a feeling of a closed space with a ceiling is created.

Greenspotlight, Eindhoven (BYTR)
A combination of a planter and a hanging lighting point. The goal of the design is to create a more efficient use of space. This design replaces mobile planters and lighting points on the ground. Unfortunately most people are not looking upwards, and will not notice and enjoy this kind of urban nature. Maintenance is a big issue as well, the ivy needs enough minerals and water to keep healthy. Also, wind is a problem here, it will make the luminaire swing and that does create a pleasant constant light design. The wind increases force applied to the walls this design is hanging from and it causes vibrations.

StreetSun, self-supporting (Voltastream bvba)
This design includes a battery, which provides power for 45h of lighting (12 W, 1200 lm). The battery has a lifetime of 5 to 6 years and thus it needs replacement during the lifetime of the luminaire.

Biolamp, algea lighting and air filter, Hungary (Peter Horvath)
A conceptual design which not only lights the street but also filters the air (the main function of the algae).
Patagonia self-supporting with dynamic dimming (FlexSolutions)
This high-end lighting pole is a modular system with PV panels on the surface of the pole and a battery inside the pole. The focus is the south European market and areas around the equator where the sun is providing much more power than in Holland.

Mira, self-supporting with dynamic dimming, (Voltastream bvba)
In this design the battery is integrated in the pole. To create enough battery capacity for a stable system the pole has a diameter of 180mm, twice as much as a normal lighting pole.

Broken light, Atjehstraat, Rotterdam (Daglicht & vorm)
This lighting project in Rotterdam is lighting the facade and sidewalks with nicely designed random patterns. The facade lighting creates an open spacious and safe atmosphere and the character of the street is highlighted. Also the light is not shining through windows. Residents react positive on this design. One disadvantage is that much more light is needed compared to other streets, also the luminaire design is custom made and therefore very expensive.
Lunar-resonant lighting, reacts on moonlight (Civil Twilight)
This lighting design measures light coming from the surrounding and adapts it light output to this value. They claim energy savings of 90%.

Citytouch, remote controlled dimming with radio frequency (Philips lighting)
Digitalizing of our society is a trend that is visible in public street lighting as well. Wireless control systems, wireless dimming and communication saves time and money the administration management.

CitySense, intelligent dimmer, (Tvilight)
Tvilight designed a wireless control system that can be incorporated with different kind of luminaires. They also have a motion sensor that can be installed on various lighting poles to reduce light pollution and energy consumption.

Solar panels on top of residential roof, Public/private cooperation (municipality of Landgraaf)
An example of what can be expected in the future: private-public cooperations that improve sustainability of a city. In this case the municipality is doing the investments and residents pay off every year so they do not have to spend that much money in one time. The municipality benefits in terms of sustainability: they provide enough solar panels to neutralize the energy needed for public street lighting. In this case the municipality does not benefit in terms of money, they still pay for the energy use of lighting.
2.8. Conclusion

Problems

One of the initial conflicts is confirmed: between tree roots and cables. The other conflict: trees blocking light is considered more relevant on high speed road ways. In residential areas this problem also has some benefits (less light pollution, natural light pattern). Other problems were found during the analysis phase as well:

1. Rotterdam is not perceived as a green city.
2. The amount of space urban nature needs under ground.
3. Space is limited in the urban environment this causes problems when multiple objects want to make use of this space (a tree, a lighting point, a planter or a parking space?).
4. Spill light and light pollution inside houses is bothering residents.
5. Maintenance and administration costs of public street lighting are high.
6. Eco-costs and energy costs of public street lighting are too high.
7. The enormous variety in luminaires is causing problems with stock control.

Solutions

The first problem could be solved by creating more layers in the vegetation; by placing planters, planting ivy and vertical green. This kind of vegetation does not have the disadvantages that trees have both above ground and underground. However, they are more vulnerable to the city climate and its users (e.g. football hooligans) compared to trees. Therefore, the maintenance costs are higher compared to trees. A solution for this is to let residents take care of urban nature themselves.

Choosing the right type and right location of urban nature can solve problems 2 and 3. Problem 3 could also be solved by choosing obstacle free lighting (from buildings for examples).

Solutions found on the market can solve problem 4, 5 and 6. Because LED can be directed much better without the use of reflectors and has less spill light. Also, LED lighting has a much longer lifetime which will reduce the maintenance and administration costs.

Solution for reduction the administration costs are found in the overview of existing solutions: wireless communication to automate administration management.

In the overview of solutions that can be found in the market, solutions for problem 6 are found: self supporting or semi-self supporting designs are already on the market. Mostly in combination with dynamic dimming (based on time of the day and season, motion and surrounding light) and interactive dimming (based motion detection). This reduced energy consumption which makes self-supporting designs more realistic.

The enormous variety in luminaires is a problem that is difficult to solve, since the lifetime of a luminaire is 20 years and the supplier is changed every 4 years. It takes a while to reduce the amount of different designs. This problem is not further addressed in this thesis, because it is a problem caused by how a governmental organization works. That is not something that could be changed easily.

LED and solar panels are interesting trends to follow. Fully self-supporting lighting points are judged as unsuitable for the Dutch market, because the power of the sun is not constant enough. Semi self supporting designs are worth researching.

Requirements

Requirements for the design phase that were found during this part of the analysis:

1. Use LED technology as light source
2. Use a color temperature of 2700 to 3000 K
3. Create a uniformity rate of minimum of 25% percent, preferably higher.
4. Use a low light level of 3 lux
5. The facade should be lighted to increases the feeling of spaciousness
6. Design a semi-self supporting system
3. Part 2: Stakeholder analysis

The goals of the stakeholder analysis is to answer the following research question:

- What are the requirements for residential street lighting? (Stakeholder analysis)

In order to answer this question, sub-questions need to be answered first:
- Who are the stakeholders in the street lighting system of Rotterdam, and what are their task and responsibilities in this system?
- What are their wishes/requirements?

The stakeholder analysis is mainly done with interviews. The interviews resulted in an understanding of everyone's responsibilities and the communication lines. First all stakeholders are shortly introduced, followed by an overview in Figure 59. The chapter will end with an overview of the requirements per stakeholder.

Stadsontwikkeling (SO)

Stadsontwikkeling or SO, is the cluster for urban planning. They initiate projects and manage them. Part of the project is executed by employees from the cluster itself, other tasks are outsourced to other sectors or departments. Regarding public space, they make the Urban Plan (UP) this includes, routing, pavement, street furniture, vegetation and lighting. For making this plan several experts within different sectors and departments are consulted. In the design plan that SO creates, safety and aesthetics are important.

They want to create a public space that contributes to the living quality of the city. Orientation during day and night is important.

Landscape architect (Onnie Tjia)
The landscape architect is the designer of urban space. He decides how the space is divided and which kind of function it should have. This includes where and what kind of objects are installed.

Line of sight, overview, safety and coherence in aesthetic are important for the landscape architect. When the environment is suitable, the landscape architect prefers obstacle free lighting.

Urban nature expert (Jan van den Enk)
The landscape architect consults this expert with information about soil, surface, location and surrounding. This expert can then decide on the kind or green that could be placed at the specific location, urban nature that will survive its environment.

Variety in urban nature is important. The small trees a landscape architect desire, that are not obstructing line of sight and public street lighting, are not preferred by the urban nature expert. Creating shadow and regulating the temperature in the city is an important effect of urban nature.

Lighting expert (Willem Adriaanse)
The lighting expert is responsible for special lighting projects. Where standard solutions are not suitable he will make a specific design for that situation.

The lighting expert is convinced of LED technology and likes to integrate lighting in its surrounding. Facade lighting of special architectural buildings can be done nicely with LED technology according to him.

Stadsbeheer (SB)

Stadsbeheer or SB is responsible for project execution and maintenance (keeping the situation as it is). Projects can be initiated by SO, PM&E, the resident or the Gemeente Werven.

For this cluster up to date administration is important, with an up to data database of lighting points they can execute their job faster and with better result.

Administration manager (Arno Struik)
The team manager is responsible for keeping the administration of public lighting up to date and acting upon what is registered (giving maintenance orders to executing parties). The administration manager gives orders to the light architect, operator and maintenance manager.

For the administration manager it is important to receive correct data about the performed tasks. When luminaires and light bulbs are replaced for examples. When this data is correct, tasks and the need for financial resources in the future can be better predicted. At the moment the system is not up to date, this sector is working hard to fix this problem.
Light architect (Ben Festen en Charl de Hooge)
The light architect works closely together with the landscape architect. He decides what kind of light bulb, mirrors, lenses, shields and diffusers are needed. He decides which components are placed inside the luminaire. (The landscape architect decides about the outside design of the luminaire.). The light architect does not particularly likes obstacle free lighting, it can create a better light design but the paperwork needed for applying this costs a lot of time. Also involved building owners are not always cooperating.

Consultant lighting and sustainability (Gerda Velthoen)
The consultant advises on sustainability issues and general lighting aspects. She gives advise on reducing energy consumption and reducing maintenance costs. She is also doing research to new technologies and solutions in public space.

The consultant likes innovative concept, but on they other hand she wants proven technology for public street lighting. Because it should last for 20 to 40 years, technology should be reliable.

Operator lighting (Peter Holswilder en Peter de Graag)
The operator is responsible for installing and maintain projects in the outdoor environment. They hire contractors and give them their tasks. When problems occur during projects they solve them together with the other employees from this sector.

The operator wants reliable solutions, that are low in maintenance. An easy installation process, without the delay and expenses caused by the grid manager is preferred too.

Technical maintenance manager (Ruud Timmers)
Managing the technical maintenance is done at sector level, Onderhoud BUitenruimte, or OBU. This sector is the executing party of the municipality. The manager of this sector explains what their job is: "When a street needs to be refurnished, we get drawings from the landscape architect and we start looking for the right parties to do the job, via tenders or known contractors. We also check if the design can be realized in public space. We visit the street and check whether the design fits (above and underground). Cable are never at the exact location they should be, trees are not always on a drawing etc. Together with the landscape architect we adapt the Urban Plan when needed. When a project is finished we give feedback about what was changed to the situation, the management department puts this knowledge in a computer-management system. From then on we are responsible for keeping the situation as it is.”

Problems underground are mentioned by the maintenance manager, no digging would ease their job and cause less need for adapting the Urban Plan.

The technical maintenance manager points out a risk of public street lighting, the risk of electric shock, when the isolation of a wire or a connection is damaged. The pole can be energized, especially for children this is dangerous.

Executor maintenance urban nature (Bart Kors)
The executor of urban nature maintenance is responsible for pruning down trees, irrigation and nutrition of urban nature.

Pruning down trees is much more work with Christmas lights attached to it. The executor understands the appealing atmosphere it creates unfortunately it makes his job difficult. An other labor intensive job is the irrigation of planters. However, the benefits urban nature bring to the city are worth these investment according the executer.

Executor maintenance lighting (Erwin Verkic)
The executor of lighting maintenance needs to take care that 98% of all lighting points in Rotterdam are working correctly. That means he is responsible for changing light bulbs on time, maintain cable connections and poles and clean luminaires etcetera.

When a luminaire needs to be cleaned or when a light bulb needs to be replaced. The construction workers finds (dead and alive) wasps and spiders inside the luminaire. They make the luminaire dirty and the wasps can be dangerous when they are disturbed.
Figure 59. Overview of involved stakeholders within the organizational structure of the municipality with communication lines and cooperation lines.
Collaboration with the grid manager is a problem the executor is familiar with. The grid managing company reacts slow on repair orders. The 98% is reached most of the time. However, his job would become easier when this problem is eliminated.

**External**

**Stedin, grid manager**

Stedin is owner and of the cables and connections below the street. They execute projects and maintain the current situation. Public street lighting is only a few percent of their annual turnover, therefore it does not have priority. This frustrating for the municipality.

**CityTec, executor maintenance**

CityTec installs and maintains public space. They are the contractor for smaller, singular projects, they have a contract with the municipality for 4 years. Next year a new tender is written so other parties can enroll for the job for 4 years as well.

CityTec is develops solutions themselves as well, they have designed a lighting pole and luminaire and they are working on a wireless management system. LED and digitalization of certain tasks is a trend they want to follow.

**Green choice, energy company**

Green choice delivers energy to the municipality for their offices, street lighting, city advertisement, traffic lights etc. Green choice delivers green energy from several sources: 30% wind energy, 35% biomass, 35% energy from water. They want to decentralize the production of energy, cooperation with consumers that generate energy is one example. Their mission is formulated on their website: “Our wish is that our clients generate as much energy as they use.” (Greenchoice, 2013)

**Resident**

The resident is the actual user of the lighting and urban nature. They live with it and it needs to support their well-being. Their opinion and ideas regarding their street and street lighting will be discussed in the next chapter about the user study.

<table>
<thead>
<tr>
<th>Table 6. Requirements per stakeholder</th>
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<tr>
<td><strong>Stakeholder</strong></td>
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<tr>
<td>Landscape architect</td>
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<tr>
<td>Urban nature expert</td>
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<td></td>
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<tr>
<td>Lighting expert</td>
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<tr>
<td>Administration expert</td>
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<td>Light architect</td>
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<td>Consultant</td>
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<td>Operator lighting</td>
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<td>Technical maintenance manager</td>
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<tr>
<td>Green choice</td>
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</tbody>
</table>
3.1. Conclusion

The main findings in this research are that most stakeholders see a future in wireless controlled luminaires. Rotterdam is experimenting with it, but it has not yet been incorporated on a large scale. Next to this is obstacle free lighting that is desired by the landscape architect. Unfortunately the light architect does not support this desire. Because it is difficult to realize (paperwork). This is something to keep in mind. Furthermore the reachability of the luminaire is important for different parties.

Requirements

Requirements that were confirmed and found during this part of the analysis

1. Use LED technology as light source
2. Create a uniformity rate of minimum of 25% percent, preferably higher.
3. Use a low light level of 3 lux
4. The facade should be lighted to increases the feeling of spaciousness
5. Design lighting that does not consume space on the ground (obstacle free lighting)
6. Reduce administration costs (distracted from the wish for distant controlled lighting)
4. Part 3: user study

This part of the analysis will focus on the people using the street, the residents. The research question that will be answered:

- How do people experience light in relation to environmental atmosphere?
- What kind of environment do they prefer?
- What do they expect of public street lighting?

In order to answer these questions first a literature study was done on the perception of lighting. Followed by consulting the residents themselves.

4.1. Literature

Most research about experience of light in relation to atmosphere perception is done for indoor environments. However research of Cortes and Paramo does focus on urban lighting. Their research is about describe the connection between emotions and lighting parameter (intensity, color, direction and diffusion). Intensity is connected to fear, affection and uncertainty. Color and direction are related to unpleasant surprise, pleasant surprise, amusement and fascination. Diffusion is related to inspiration and contempt and disappointment (Cortes, 2009).

How these characteristics are connected to the several emotions is not stated in their conference paper. In an email conversation with Berenice Cortes the following assumptions (based on observation and interviews done during the context and stakeholder analysis) are confirmed:

- Higher intensity results in less fear (till a certain point)
- Lower intensities lead to more affection (till a certain point)
- Decreasing intensity leads to increased uncertainty which leads to anxiety
- A directed light (small beam) source gives unpleasant surprise
- Multiple, colored lights in a street are amusing and fascinating
- Diffuse light results in a contempt feeling
- Diffuse light is disappointing because it creates a dull atmosphere

More general research about environmental perception is done by Vogels (2008). She found 38 words in 4 categories (coziness, liveliness, tenseness, detachment) that can describe an atmosphere (Table 2 and Table 3 in appendix 2). Van Erp (2008) researched if certain light characteristics could be linked to those words (Table 1 in appendix 2). He showed a preference for certain light settings: positive words are related to diffuse warm white light and direct light. Warm white, diffuse light is more suitable for functional tasks while direct light is more suitable for social activities.

This is confirmed by Mahnke, in his book he states that a good balance between variety (in intensity and color) and unity is necessary to create a favorable atmosphere. (Mahnke, 1996). Examples of combining these different light settings is seen around Christmas when small direct lights are put in trees to create a cozy atmosphere. These lights are combined with more diffuse public street lighting. Another example is found in the Atjehstraat in Rotterdam, different light settings are used to create a functional light level and on top of that a cozy atmosphere is created with extra light sources. Next to this balance the uniformity is an important parameter. Because it influences the perception of safety and the perception of spaciousness of a street. With a higher uniformity a lower mean light level can be used. (Veitch, 1998).

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Color and direction</th>
<th>Diffusion</th>
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<tbody>
<tr>
<td>Fear</td>
<td>Unpleasant and pleasant surprise</td>
<td>Contempt Disappointment</td>
</tr>
<tr>
<td>Affection</td>
<td>Amusement Fascination</td>
<td></td>
</tr>
<tr>
<td>Uncertainty</td>
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4.2. User research

The hypothesis for the user research, based on the previous literature study is: “that a combination of diffuse and direct, warm white (low CT) is preferred”.

In order to get to know the atmosphere residents in Rotterdam prefer, a user research was carried out. Combining this research with the research of van Erp can confirm or reject the hypothesis and give an indication about the requirements for street lighting.

Participants

The user research was done with 11 residents (age range 20 to 62) living in several neighborhoods in Rotterdam (Figure 60).

Method

The residents were given a booklet which they could take home. The booklet contained 6 questions, for which they needed to observe the street lighting to answer the questions:

1. Make a picture of your street during day and evening/night.
2. What do you do in your street, what would you like to do (and why)?
3. In which situations that you would like to do does street lighting play a role and how?
4. Can you describe the atmosphere in your street during the day and during the evening? (here the 38 words are given to choose from). Explain what you like and dislike about the atmosphere
5. Can you describe the light in your street?
6. What is your future vision on street lighting?

Results

The results to all six questions can be found in appendix 3. The results which were directly relevant for answering the research question, about atmosphere perception, will be discussed in discussed in this section. In Table 8 and Table 9 the answers to what people do and want to do in their street are summarized.

Going from A to B is the activity they do most, next to that chatting with neighbors is mentioned a lot in both tables this desire mentioned. This means functional and social use of the street. The atmosphere that they want for these purposes can be extracted from question 4. The answers can be found in Table 10. Most positive words are from the category cozy (bold words). This means that people want a cozy atmosphere. The research of van Erp showed that cozy light settings correspond with diffuse warm white and direct light.

The interview with de Hooge and Velthoen (appendix 1.2) suggested that people want
De Hooge mentioned that a street should invite people to walk into. This corresponds with the user saying a street should be accessible. Tranquility (rustgevend) as well as peaceful/quiet (rustig, stil, rust) is mentioned as a desired atmosphere. Tranquility, peace and quietness, can be stated as desired atmosphere because it is mentioned frequently and since the opposite, noise (herrie from hangjongeren, dreigende passanten and vrachtwagens) is mentioned as undesirable. A tranquil, peaceful and quiet atmosphere corresponds with warm white light.

The extra words in Table 10 that are used by the participants indicate that public space is a multidisciplinary space, this is not surprising. But it shows that it is important to keep in mind that public street lighting and urban nature are not the only factors influencing the atmosphere perception. Litter and parked cars are mentioned as important problems as well. However, these indirect influences are problems that are out of the scope of this project.
4.3. Conclusion
The research of van Erp (2008) shows a preference for certain light settings, based on the 38 atmosphere words that are found by Vogels (2008). Combined with functional activities people associate with certain light settings, an indication for preferred outdoor lighting can be given:

- Diffuse warm white light with high intensity is suitable for functional tasks.
- Direct light is more suitable for social activities.
- A low light intensity is described as tranquil and relaxed, a higher intensity as friendly.

This means that the stated hypothesis (combination of diffuse and direct, warm white (low CT) is preferred) was right, a balance between direct and diffuse light to make the street suitable for functional and social activities.

The importance of the uniformity rate is found in the literature as well, which is coherent with the wishes of the light architect.

Furthermore, the opinion of the resident, regarding their street, was found. They think the light and luminaire design are boring, they would prefer custom design for each neighborhood. What they also mentioned is that they suffer from light pollution, street lighting is shining into their houses.

Requirements
Requirements that were found and confirmed during this part of the analysis:

1. Use LED technology as light source
2. Use a color temperature of 2700 to 3000 K
3. Create a uniformity rate of minimum of 25% percent, preferably higher.
4. Use a low light level of 3 lux
5. The facade should be lighted to increase the feeling of spaciousness
6. Design lighting that does not consume space on the ground (obstacle free lighting)
7. Reduce administration costs
8. Combine direct and diffuse light to create a cozy atmosphere
### Context

**Problems related to urban nature and the conflict with lighting**
- Spiders and wasps living inside the luminaire
- Space is rare in urban environment versus Trees need a lot of space
- Dense and hard pavement is not beneficial for trees because it blocks nutrition (water, air and minerals)
- Tree leaves blocking light
- Sun does not provide enough constant power, for applying self-supporting lighting points
- Roots get damaged when a street needs to be opened
- City is not perceived as green because urban nature is not evenly spread through the city

**Problems related to human activities in the urban environment**
- Unexpected and varying light sources from shop windows reduce the uniformity rate
- Dark facades are perceived as scary
- Darkness can be calming
- Light level is not judged as sufficient
- Bike resting against pole
- Car clashes

### Design

**Problems related to public street lighting design**
- Light pollution
- Blinding
- Dangerous since light is provided with 230 V
- Holes in a wall, needed for hanging street lighting damage a building.
- Poles are not used as multifunctional as they could be
- Public street lighting is perceived as boring
- Poles can disturb the view and they need space

**Not yet fulfilled needs**
- Residents want light to evoke liveliness and hospitality
- Obstacle free design
- Paperwork that is needed for obstacle free designs
- Residents want that light increases safety and stimulates small interaction
- Residents want cozy light
- Residents do not want the same luminaires and poles in every neighborhood versus variety in luminaires and stock control

### Life cycle

**Manufacturing and installation phase**
- Grid connection is expensive
- Digging is expensive and annoying for residents

**Use phase**
- The energy consumption of public street lighting is most harmful for the environment
- Energy consumption is expensive

**Technical management**
- Sphere lighting is difficult to maintain
- Hanging luminaires are difficult to reach
- The municipality is dependent of Stedin (grid manager)

**Administration management**
- The monitoring system is not up to date
- For hanging street lighting difficult juridical procedures have to be executed
- The paperwork needed for hanging and facade lighting costs time and money

**End of Life**
- The municipality does not benefit from recycling (money).
5. Design brief

The design brief includes an extended problem definition and a list of requirements. Both are based on the conclusions from the analyses phase. This brief will be used as start for the design phase.

5.1. Problem definition

Municipality perspective
The main problems regarding public street lighting were found by looking at the situation from the perspective of the municipality. The problems are the entanglement of cables and tree roots under ground, the costs of the grid connection, the maintenance costs, energy consumption costs, eco-costs of energy consumption and eco-costs of manufacturing.

Residential perspective
From the residential perspective problems and needs were found as well:

- Residents want more than the basic lighting for safety. They want social lighting: light that creates a cozy atmosphere. Residents also want light that is not shining into their houses.
- Rotterdam is not perceived as green, because urban nature is not evenly spread through the city. Some streets do not have space for trees, because space is limited in the urban environment.

With these problems the assignment was rewritten as:

*Solve the conflict between urban nature and public street lighting by designing a new street lighting product service system that creates more space for urban nature.*

5.2. List or Requirements

The assignments is completed with a list of requirements the final design should fulfill:

**Costs**
1. The design should reduce energy consumption costs
2. The design should reduce technical management costs
3. The design should reduce administration management costs
4. The design should ease the installation process

**Environment**
5. The amount space for urban nature should be increased
6. The eco-costs of energy consumption should be reduced
7. The eco-costs of the manufacturing phase should be reduced
8. Tree roots may not be damaged during installation of the system
9. Air or water should be filtered
10. Materials should be as less harming to the environment as possible
11. Used materials should be recyclable

**Aesthetics**
12. The design should be integrated in the environment
13. The design should fit the Rotterdamse Stijl
14. The design should not consume space at floor level (obstacle free)

**Light and luminaire**
15. LED technology should be applied as light source
16. The light intensity at street level should be 3 lux
17. The uniformity rate should be 25%
18. The LED light color should be between 2700 K and 3000 K
19. Light pollution inside houses should be reduced
20. The light may not be blinding for the resident
21. The luminaire should be low in maintenance
22. The design should be vandalism proof
23. A wide range of residential streets should be covered.
24. As much work as possible should be done in Rotterdam (social return)

**Atmosphere perception**
25. Light should create a cozy atmosphere to stimulate small social interactions
26. The design should create a safe feeling
6. Ideation

During this project ideas are generated constantly. From the beginning on small sketches were made with ideas. All these sketches are gathered on idea-cards. These ideas were complemented and evaluated during a creative session with 4 students and a creative Biomimicry-session (the results of this session can be found in appendix 4.1).

The sketches drawn during the whole project and the creative session with students resulted in about 60 ideas. The Biomimicry session added another 12. These ideas were filtered based on the assignment written in chapter 5.2 on page 40. Added to this list was the requirement that the solution should be suitable for residential street. When an idea was not fulfilling three of the mentioned points it was filtered out. After this selection process, about 40 ideas were left. The remaining were clustered into four categories, energy, light, connection and functionality. An overview of the ideas can be found in a morphological chart, within the four categories subcategories can found.

Figure 61. Sketches created during the ideation phase

Figure 62. proces.ai
Figure 63. Morphological chart with partial solutions on the main subjects
7. Conceptualization

In this chapter the combination of features that was selected in the ideation phase will be designed into concepts. The process that was followed during the conceptualization will be discussed first, then all concepts will be shown and explained with posters and an overview will be given. The chapter will be finalized with deciding which concept to continue with, based on several evaluation methods: a stakeholder evaluation and EVR in combination with the Datum method.

7.1. Process

First conceptualization round
From the morphological chart in Figure 63, four different combinations were selected. First a selection of connection methods was made based on the wishes from the municipality (more space for urban nature, obstacle free design, reduce energy consumption, reduce CO2 emission, reduce technical management and administration costs). With this selection, interesting combination were made with parts from the other categories and subcategories. Wishes from the resident for a better atmosphere are taken into account when finding these interesting combinations.

First evaluation
The four concepts were evaluated with several interviews and email conversations. During these conversations the best features from the four concepts were found. Talking through and getting feedback on the concepts gave new inspiration. This resulted in a fifth concept.

Second conceptualization round
Parts of this fifth concept were already found in the first four concepts. However a different and realistic way of connecting the luminaire to its surrounding is presented in this fifth one.

Final evaluation
All five concepts, were scored on the list of requirements, in comparison to the current situation. These scores are processed coherent with the EVR model. The graphs show which concept is best to continue with, seen from EVR perspective: a realistic sustainable solution.
Connection
This obstacle free concept takes shape in two mounting options:
• Wall mounting
• Gutter mounting
With the gutter mounting the building is not damaged and the light is fully integrated in its environment. The gutter can function as heat sink for example. The wall mounted version does damage the building a little bit. However it has benefits for atmosphere perception.

Atmosphere
This concept creates more space in the street since no poles are needed. The resident can buy an add-on for wall mounted luminaire, a light string, to create a nice atmosphere in the street. Also helping to create a atmosphere is the possibility for lighting the facade. Further more the light is directed towards the street and will not shining into houses. The gutter mounted option with high lighting point can light the facade as well, and it creates a high uniformity rate which increases the perception of safety.

Power
The light will be connected to the power grid of the building. No extra grid connection is needed and no digging, this saves time and money. Since the resident benefit from this design they are likely to allow a connection to their grid. The municipality should compensate the resident for the energy consumption of the luminaire. This can be done by paying a fee to the resident or by integrating a solar panel in the design. This way the design generates its own energy. In this case energy costs will be zero for the municipality.
Connection
The Arc light can be seen as a horizontal lighting pole, it does not consume surface space. The material of the arch should be flexible and long lasting, bamboo might be very suitable for this purpose. The arch is applying pressure force to the facade because this will damage the facade less than the tension force of hanging street lighting. In the design several options exist:
- a luminaire with integrated solar panel
- a luminaire with lights on the side, to light the facade
- extra solar panels that could be attached to the arch

Atmosphere
The design creates more space at the sidewalks and an open view. Different types of lenses take care that light is not shining into houses and that it is only lighting the facade there where no windows are situated. The arch highlights the transition of ‘your’ street and the rest of the city. This will create a welcome feeling when entering the street.

Power
The light and solar panels can be connected to the power grid of the house. Because of solar panel integration the design can generate electricity for the residents and that could save them money. This benefit will make it easy to convince them to allow the municipality to install this design. The municipality will not have energy costs anymore. With LED as light source maintenance and administration costs and energy consumption will be reduced. By making use of dynamic dimming and motion detection even more energy can be saved. During night the light will be dimmed to 60%, when motion is detected, two lights on both sides of the moving objects will increase their intensity to 100%. Since this design is located in the center of the street, it is suitable for measuring the light coming from the surrounding (moon, cloud reflection), this will also be included in the dimming variables. The 100% will differ per day by making use of the available light from the surrounding.
The Bamboo concept is using local grown bamboo fiber in combination with a biological resin as material for the lighting pole. Bamboo is the fastest growing plant on earth and produces 35% more oxygen than trees of the same height. Bamboo does not need much space underground can grow in the urban environment, this concept increase the availability of urban nature directly.

Atmosphere
The battery that is included into this design will be shaped like a bench. This will create more possibilities for the resident to have a small chat with their neighbor. Another benefit for the resident is the lighting of the facade, different lenses can be installed on the luminaire. This way the light is directed to the facade and not to windows.

Power
The luminaire includes a solar panel that stores energy in a battery. The battery is integrated in the environment and has a double function, it is also street furniture, therefore not seen as an obstacle. To decrease the battery size energy consumption should be reduced as much as possible, LED technology with dynamic dimming will take care of this desire. During night the light will be dimmed to 60%, when motion is detected, two lights on both sides of the moving objects will increase their intensity to 100%. The 100% will differ per day by making use of the available light from the surrounding (moon, cloud reflection). A light sensor measures the environmental light level and send a signal to the dimming device which changes the 100%.
Connection
In this design trees are used as support, this makes the design nicely integrated in its environment. The connection to the tree is flexible and is stretched with the growth of the tree. This way the tree will not get damaged. Large trees can be used as support for the lighting directly. Smaller trees are not strong enough, they have wooden support themselves. This support can be redesigned to be combined with lighting. It could also be integrated with the nutrition system a young tree needs.

Atmosphere
The luminaire is located parallel to the road, both the sidewalk and the road can be lighted easily with such a configuration. With this design the facade can be lighted as well, to create a spacious feeling. The flexible structure for the facade lighting makes it easy to adjust to every facade design. This lighting is mounted quite low (3 to 4 m) and that creates a cozy atmosphere.

Power
A low lighting point needs less power for creating the desired light intensity. With LED as light source the energy consumption is reduced a lot. Motion detection is included and that will reduce the energy consumption even more. During night the light will be dimmed to 60%, when motion is detected, two lights on both sides of the moving objects will increase their intensity to 100%. These luminaires are located close to large trees therefore they need to be cleaned more then others. With coating of Titanium Dioxide this need will be reduced, with this coating dirt is washed away automatically with every rain shower.
Connection
The roof is the most ideal place for a solar panel in the residential environment. The connection of a solar panel on top of a roof is easy and strong. Using this connection for public street lighting is the basic idea behind this concept. The house is not damaged with this way of mounting for obstacle free lighting.

Atmosphere
A lighting point at a large height can light a large area. This is beneficial for the material use, since less luminaires are needed. A large height increases the feeling of safety since the uniformity rate is increased. A high lighting point is less cozy and therefore coziness should be created in another way. Lighting the facade can have this effect. It will create a spacious and cozy feeling in the street.

Power
for energy costs of the municipality. The solar panel can harvest more energy in one year than what is needed for the light. The user will have a lower energy bill. Since this luminaire and solar panel will be connected to the power grid of the house.

For the municipality this means that they do not have to pay for a grid connection. The light makes use of LED and that will reduce maintenance costs. A coating of Titanium Dioxide will reduce these costs even more, since dirt is washed away automatically with every rain shower.
### 7.2. Overview

This overview shows where the concepts make most improvements on eco-costs (compared to the current situation) and what value they add for the main stakeholder groups.

**Table 11. Overview, the first four from the first concept round, the fifth one after evaluating the first four with the stakeholders**

<table>
<thead>
<tr>
<th>Eco-costs</th>
<th>Value for the municipality</th>
<th>Value for the resident</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Saves space and material (pole is eliminated)</td>
<td>- Energy costs (LED and dimming)</td>
<td>- Light is not shining into houses</td>
</tr>
<tr>
<td>- Saves energy (LED)</td>
<td>- Maintenance costs (LED and coating)</td>
<td>- Facade can be lighted, this creates a more safe feeling</td>
</tr>
<tr>
<td>- Local materials</td>
<td>- Obstacle free design</td>
<td>- Integrated in the environment</td>
</tr>
<tr>
<td>- Saves energy (LED and dimming)</td>
<td>- Bamboo produces more oxygen</td>
<td>- Users can influence the lighting design of their street</td>
</tr>
<tr>
<td>- Energy costs (LED and dimming)</td>
<td>- Social return</td>
<td>- Light is not shining into houses</td>
</tr>
<tr>
<td>- Maintenance costs (LED and coating)</td>
<td>- Producing energy</td>
<td>- Facade can be lighted, this creates a more safe feeling</td>
</tr>
<tr>
<td>- Obstacle free design</td>
<td></td>
<td>- More urban nature</td>
</tr>
<tr>
<td>- Producing energy</td>
<td></td>
<td>- Integrated in the environment</td>
</tr>
<tr>
<td>- Bamboo produces more oxygen</td>
<td></td>
<td>- Users can benefit from PV-panel, that generates energy for them</td>
</tr>
<tr>
<td>- Integrated in the environment</td>
<td></td>
<td>- Integrated in the environment</td>
</tr>
</tbody>
</table>

**Eco-costs**
- Saves space and material (pole is eliminated)
- Saves energy (LED)
- Local materials
- Saves energy (LED and dimming)
- Bamboo produces more oxygen

**Value for the municipality**
- Energy costs (LED and dimming)
- Maintenance costs (LED and coating)
- Obstacle free design
- Producing energy
- Social return
- Obstacle free design
- Producing energy

**Value for the resident**
- Light is not shining into houses
- Facade can be lighted, this creates a more safe feeling
- Integrated in the environment
- Users can benefit from PV-panel, that generates energy for them
- More urban nature
- Integrated in the environment
- Users can benefit from PV-panel, that generates energy for them
7.3. Comparison
To decide which concept to continue with the stakeholders at the municipality and the residents were consulted. After these interviews and email conversations, the fifth concept was introduced. All five concepts will be compared with EVR in combination with the Datum method (van Boeijen, 2013).

Stakeholder opinions
The employees at the municipality who were interviewed during the stakeholder analysis were asked to make a top 4 (Table 7) and give arguments (appendix 7) with it. The residents were asked by email what their opinion was, from the 11 residents that responded on the booklets, 5 responded on this follow up question.

The stakeholders have a preference for the surround light because it is obstacle free, can lit the facade and is not shining into houses. They think this way of mounting is most realistic. The light string should be eliminated from the concept, since it would make the street view messy, and responsibility issues will occur when private parties install products themselves in public space. Also, it should be something special for winter season.

The tree support scores worst from the perspective of the municipality, because most stakeholders do not believe the tree will not get damaged. Also maintenance and inspection will cost a lot of money. The stakeholders think that creating a coherent light design over time is not possible, since trees grown where they want. If they do not grow straight the luminaires will not hang in a nice line, this will create an unstructured view which is not beneficial for creating a pleasant atmosphere. Residents have a problem with the applicability, many residential streets do not have trees that could support this design.

The bamboo light scores second, extra urban nature is desired, but bamboo does not fit the urban environment. It is associated with other environments such as the jungle and third world countries. People are also worried about vandalism in this concept.

The arc light scores third, the solar panels are judged positive. The way of mounting, less. The arch could create a tunnel or ceiling effect. And that is not beneficial for the feeling of spaciousness.

The Rooftop concept is not in this comparison because it was designed later in the process. The opinion of the stakeholders is taken into account.

The urban nature expert sees a benefit in the fact that no underground cables are needed and sees possibilities in the creation of nice shadow patterns.

The consultant like the fact that the solar panels deliver energy to the grid and that energy costs are eliminated.

The light architect believes rooftop mounting could work, although the extra variable of building height makes designing a lighting plan more time consuming.

The technical maintenance manager likes the fact that Stedin is no stakeholder anymore and the fact that digging is not necessary.

Table 12. Stakeholder opinions, top 4

<table>
<thead>
<tr>
<th></th>
<th>Administration manager</th>
<th>Urban nature expert</th>
<th>Consultant</th>
<th>Light architect</th>
<th>Landscape architect</th>
<th>Technical maintenance manager</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surround</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Bamboo</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Arc light</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Tree support</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 13. Residential opinions, top 4

<table>
<thead>
<tr>
<th></th>
<th>Resident 1</th>
<th>Resident 2</th>
<th>Resident 3</th>
<th>Resident 4</th>
<th>Resident 5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surround</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Bamboo</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Arc light</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Tree support</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>
**EVR and Datum method**

The *Datum method* is a tool for comparing solutions with a *datum*: the current situation. Every new solution is compared on a set of requirements. Concepts can score better, equal or worse compared to the current situation. (van Boeijen, 2013)

In this thesis the Datum method is combined with EVR. This is done by splitting up in requirements, in requirements that have influence on value and requirements that influence the eco-costs.

Normally the date or current situation is scored zero on all requirements, that would not work in this case. Since the requirements are split up in two groups and the groups are divided by each other (Eco-costs/Value), the value cannot be zero. Therefore the current situation is scored ‘2’ on all requirements. A higher value or higher eco-costs scores 3, a lower value or lower eco-costs score 1. Note that a higher value is positive and a higher eco-cost negative. The goal of increasing value and reducing eco-costs has to be kept in mind. The complete list with scores can be found in appendix 5, the results will be discussed here.

In Graph 6 the virtual eco-costs and virtual value are plotted with the current situation as datum. It is clearly visible that all concepts score better than the current situation. The *Surround light* and *Rooftop* score best, followed by the *Tree support* and *Arc light*, last is the bamboo concept. This is partly coherent with what the stakeholders and residents are saying. The first choice is clear, the surround light. Then the evaluations differ. The stakeholders and residents like the bamboo concept while it scores lowest on value when looking at the requirements. One explanation for this might be the more traditional design of the bamboo concept looks familiar and trustworthy. The arc light and the tree support score very close on value and eco-costs however the residents and municipality like the arc light more. The main reason is that they do not believe the tree concept is realistic and that it is only possible in very few situation.

In Graph 6 the Rooftop scores very close to the Surround light. Since the rooftop concept is designed later in the process, this one likely to have the best outcome. To be sure weather this is true, a second comparison is made with the Rooftop as date (Graph 7). Now, a more clear difference can be seen between the Surround light and the Rooftop.

7.4. **Conclusion**

Based on the interviews with stakeholders, email conversation with residents and the two comparisons with the date method and EVR scores a concept can be chosen to continue with. At first the Bamboo, Arc light and Tree support can be eliminated. Since they score lowest looking at stakeholder and resident opinions. Also in the Graph 6 they both score low. The Surround light and the Rooftop are left, Graph 7 shows that the Rooftop has the best EVR score. Also since this design combines features of the others, the Rooftop concept can be chosen to continue with.
8. Final design

This chapter will explain about four groups of features of the concept:
- Light design
- Rooftop mounting
- Power system
- Features inside the luminaire and its design

A feasibility study for the lighting concept was done and a small research on the possibilities of including batteries in the power system. Specific knowledge had to be gathered about rooftops and how solar panels are connected to it. With this knowledge a luminaire connection could be designed. What kind of panel, inverter and other parts were needed for the power system is explained as well. The components inside the luminaire and its aesthetics are discussed as well. Those feasibility studies, experiments and researches, resulted in a new design for public street lighting.

8.1. Light design

First, the light design needs to be determined. Two kinds of light are distinguished: light creating a certain atmosphere and light creating a basic level of safety. Several options for atmosphere lighting, and how the desired atmosphere and safety is created (LED optics) will be described this paragraph.

Atmosphere lighting

Figure 65 shows the idea of lighting the facade with projected lines of light. Small experiments were carried out determine the feasibility of the idea.

Safety lighting

In the first experiment a LED strip is shielded with black paper with holes in it to create stripes (on small scale). Problems can be seen: the light stripes are diverging and fading quite fast. Also, LED strips have multiple light sources causing multiple lines to be created. With one light source, above the opening in the shielding, a straight line could be created. This is only possible right down from the luminaire. A few meters next to the luminaire is not possible with this way of shielding.

In the second experiment, creating a straight light line a few meters next to the luminaire is attempted. With a single light source (a 300W profile spot with knives and adjustable focus) from a large distance (2m) a single line of light is tried to be created. Figure 62 shows the result.

Figure 65 shows the test set ups. In the first experiment a LED strip is shielded with black paper with holes in it to create stripes (on small scale). Problems can be seen: the light stripes are diverging and fading quite fast. Also, LED strips have multiple light sources causing multiple lines to be created. With one light source, above the opening in the shielding, a straight line could be created. This is only possible right down from the luminaire. A few meters next to the luminaire is not possible with this way of shielding.

Creating a small line turned out to be difficult. An expert from Luxexcel (Meulblok, 2013), specialized in 3d printing of LED lenses, was consulted to determine if this idea could be created with their lenses. Their opinion was that straight lines should be possible, but sharp edges will be difficult. The development process of such a system requires a lot of knowledge about optics and some trial and error processes. It would not be feasible to develop such a design within the (time)boundaries of this thesis project. Therefore first the focus will be on the basic level of lighting. The extra layer of on the facade of houses will be left for further development.
The safety lighting should fulfill the norms as described in the analysis phase: a minimum, average light level of 3 lux with a uniformity rate of 25%. To accomplish a uniform light intensity across streets with fixtures at different heights, the light should dimmed according to height of the fixture (how this is done exactly is visualized in paragraph 8.4 about luminaire design). This extra variable in combination with different street widths gives the need for a variety in LED lenses. The width of most residential streets varies between 8 and 20 meter. The light point heights this design should be suitable for is set from 6 to 12 m. These are 2 and 4 story buildings which are seen a lot in Rotterdam. An advise about LED’s and lenses is given by Schréder, who did several calculations and selected three types of lenses for a 28 Watt LED array (Geerdink, 2013). The results are displayed in Table 15, which shows that a wide range of street lay-outs can be covered. However not all suggested width/height ratios are possible. The calculations are done with lenses available in their catalogue, developing other lenses might increase the streets that can be covered. An other option to increase the range, with the current available lenses, is increasing the power output of the LED’s or changing the mounting angle of the luminaire (Figure 68) and LED array. This is also beneficial against light pollution inside houses. Tests on this subject will be done with a prototype, the results will be described later in this report (chapter 12).

With the information about lenses, angles and power it is possible to visualize the desired lighting plan for different street lay-outs. For every street lay out a new lighting plan should be created, based on the building heights and street width. One example is given in Figure 69. More examples will be given in appendix 6.

Table 15. Results calculation Schréder (Geerdink, 2013)

<table>
<thead>
<tr>
<th>Street width [m]</th>
<th>Light Point Height [m]</th>
<th>Light Point Distance [m]</th>
<th>Angle luminaire [degrees]</th>
<th>Mean light intensity [lux]</th>
<th>Uniformity [%]</th>
<th>Lens advise (# Schréder)</th>
<th>Width/Height Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>12</td>
<td>23</td>
<td>0</td>
<td>3.0</td>
<td>25.2</td>
<td>5098</td>
<td>1.67</td>
</tr>
<tr>
<td>14</td>
<td>12</td>
<td>36</td>
<td>0</td>
<td>3.0</td>
<td>32.8</td>
<td>5102</td>
<td>1.17</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>42</td>
<td>0</td>
<td>3.0</td>
<td>51.6</td>
<td>5102</td>
<td>0.83</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>20</td>
<td>0</td>
<td>3.6</td>
<td>15.3</td>
<td>5098</td>
<td>2.00</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
<td>37</td>
<td>0</td>
<td>3.0</td>
<td>19.3</td>
<td>5102</td>
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<td>10</td>
<td>10</td>
<td>48</td>
<td>0</td>
<td>3.0</td>
<td>31.6</td>
<td>5102</td>
<td>1.00</td>
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<tr>
<td>20</td>
<td>8</td>
<td>29</td>
<td>0</td>
<td>3.0</td>
<td>26.4</td>
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<tr>
<td>14</td>
<td>8</td>
<td>27</td>
<td>0</td>
<td>3.5</td>
<td>25.1</td>
<td>5102</td>
<td>1.75</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>45</td>
<td>0</td>
<td>3.5</td>
<td>25.3</td>
<td>5068</td>
<td>1.67</td>
</tr>
<tr>
<td>20</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.33</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.33</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>32</td>
<td>0</td>
<td>3.5</td>
<td>25.3</td>
<td>5068</td>
<td>1.67</td>
</tr>
</tbody>
</table>
By mounting the lighting on the rooftop, close to the facade, the facade is lighted as well and atmosphere lighting is created automatically. The earlier proposed way of facade lighting might have a stronger influence than this way of lighting the facade. However, using the safety lighting as facade lighting too is much easier, it is a first step in the right direction of creating a pleasant and spacious atmosphere with facade lighting.

Lighting residential streets with a high lighting point and accentuating the facade is not common in Rotterdam. In the style guide for lighting, facade lighting is only used for special architectural buildings. If the effect in residential streets is as suggested (pleasant and spacious) could be researched with a pilot project. Research topics could be:

- Does the facade lighting overrule lighting from windows (if so the street might look less alive).
• What would happen when the facades are not appealing in terms of architectural style and maintenance (are these unappealing characteristics accentuated or reduced)?

A pilot project costs time (at least half a year) and money. So for now research has to be done with renderings. The program, Dialux is used for this purpose. This is an open source rendering program for light architects. Files of luminaires can be loaded into the program to visualize and calculate with realistic data. The examples in Figure 70, are created with data from Schréder and Indal. The first render in Figure 70 shows the difference between luminaires, the three lens types Schreder advised and the benchmark, the Kegel. LED lighting can have a smaller beam and a has a low amount of spill light causing more light to be directed towards the street. That makes LED lighting very suitable for public street lighting (no light is directed to the sky where it will cause light pollution). The second render shows light intensity with luminaire angle as variable. With a small angle more light is directed towards the back, this is not wanted since it will than shine into houses. With a large angle, the light is directed to the front.

The third render shows how the facade will be lighted, with different distances. The light pattern and light intensity on the facade is seen. Close to the facade gives a small intense light spot, further from the facade a large spot with low intensity. The last option is most pleasant for the resident because they will not be hindered with light inside the house. LED light has a small

Figure 70. Different luminaires and different settings
amount of spill light (de Hooge, 2013) and this reduces light pollution. The conclusion is an angle of 25 degrees and a distance of at least 0.75 meter is advised. This results a light design as shown in Figure 72 it can be compared to the current situation in Figure 73. The light is not shining into houses (in contrast to the current situation) and a high uniformity rate is reached (up to 45%, instead of 25% in the current situation). Note that these images are computer simulations and do not represent a very realistic light intensity. For comparing the two situation they can be used perfectly. Figure 76, Figure 77, and Figure 78 do show a realistic view of the old and new situation. Figure 77 is an experiment with tree locations, which give a nice pattern on the floor. However, more light is needed to have enough light on street level. Figure 78 shows the final result.

Table 16. Difference between the current and new situation

<table>
<thead>
<tr>
<th></th>
<th>Uniformity rate (minimum/mean light level)</th>
<th>Amount of lighting points</th>
<th>Power consumption [kWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>25 % (3.3/0.8)</td>
<td>8</td>
<td>1200</td>
</tr>
<tr>
<td>New</td>
<td>45 % (3.0/1.4)</td>
<td>6</td>
<td>380</td>
</tr>
</tbody>
</table>

Figure 71. Effect of the new light design on the uniformity colors represent light intensity in lux

Figure 72. High lighting points in the new situation, with light direction lines

Figure 73. Low lighting point in the current situation, with light direction lines
Figure 74. Current situation, light intensities

Figure 75. New situation, light intensities

Figure 76. Old situation with luminaires on a 4 meter pole

Figure 77. Experiment with the new situation, trees in front of luminaires
Figure 78. Final result of the new light design in a typical street of Rotterdam, trees and lighting points are placed alternately.
8.2. **Rooftop mounting**

For mounting public street lighting on top of a roof, it is important to know what kind of roofs are found in residential streets. Two main types of roofs are distinguished, flat rooftops (Figure 79) and pitched roofs. Most slopes of pitched roofs vary between, 20 to 45 degrees (WaterproofMagazine, 2013), slopes until 60 degrees are also seen, but less.

For pitched roofs two orientations exist in comparison with the street: the roof can be positioned parallel (Figure 81) or perpendicular (Figure 79). For all these rooftops a connection should be designed for the luminaire.

This design includes solar panels, therefore it was researched how they are connected to a rooftop: it is a strong connection and does not damage the house. For pitched roofs, an aluminum solar rail is mounted on the wooden construction of the roof with a steel bracket (Figure 82). Solar panels are mounted onto the rail with brackets and screws (Figure 88). For a flat roof, the construction is different. An extra triangular construction is needed to put the solar panel in the most efficient position. In the Netherlands this is 36 degrees, facing the south (Siderea, 2013). The efficiency based on angle and direction can be seen in Figure 80. Facing the north is only possible with a small angle. When a pitched roof is facing the north, it should be considered to place the solar panels on the other side of the house, or place the luminaires on the other side of the street.

![Figure 79. Flat roof (top) and perpendicular oriented roof (bottom)](image1)

![Figure 80. Efficiency of solar panels, angle and orientation](image2)

![Figure 81. Parallel roof](image3)

![Figure 82. Solar panel mounting on wooden roof construction](image4)
**Frame**

The frame is connected to the solar rail. The luminaire itself is to connected this frame with a ball joint. This makes that one frame can be used for several slopes. The parallel roof orientation and the flat roof can use the exact same frame for connecting the luminaire to the solar rail (Figure 83). The perpendicular roof orientation needs an other frame (Figure 84).

The ball joint has a maximum tilt angle of 20 degrees in all direction, this fits the needed angle range to cover most rooftops (Figure 85).

The frame is made out of aluminum to fit the style of the solar panels, it is black anodized because that fits the color of the solar panel and the colors set in the *Rotterdamse Stijl* (dark gray) most.

Examples of connections for the three different rooftops will be shown on the next pages.
Parallel roof orientation

Figure 86. Roof parallel to the street
Figure 87. Ball joint and power cable

Figure 88. Luminaire frame connection with solar rail and solar panels, for perpendicular roof orientation

Figure 89. Roof perpendicular to the street (evening)
This triangle needs extra ballast to be stable with a 4 kg luminaire hanging on to the frame. The distance from the center of gravity of the luminaire to the triangle varies between 0.6 an 1.4 m. The distance between the center of gravity of the ballast and the triangle is always 1.3 m. The arms are almost of equal length, that would mean that a ballast of the same weight as the luminaire would be sufficient. However wind will apply extra forces to the luminaire. To be safe a ballast of double the weight of the luminaire is advised.

**Flat roof**

![Figure 90. Section view, detail luminaire connection](image)

![Figure 91. Flat rooftop connection](image)
8.3. Power system

The power system is visualized schematically in Figure 90. Solar panels with a micro inverter and switch box are connected to an extra circuit breaker inside the house. The luminaire is connected to this circuit breaker as well. This is to reduce the risk of failure of the luminaire. The resident may not use this circuit breaker for other devices. A kWh meter is added which can show the resident how much overcapacity the solar panel(s) have.

Connecting the system to the grid of the house avoids digging and an extra and expensive grid connection underground. Stedin is no direct stakeholder anymore when this connection is applied. The overcapacity is delivered free of charge to the resident, this makes it easier to convince them to cooperate.

It was also researched if batteries would be a feasible solution to avoid the grid connection completely. In Graph 8 the generated power of several amounts of solar panels and the power used by the luminaire can be seen. With one panel the overcapacity per year is small (70 kWh). With two panels it is 260 kWh per year, or 50 euro. On monthly basis the panels do not generate enough power for compensating the electricity use of the luminaire. In November, December, January and March the luminaire uses more. From four large panels (6.3 m2), the solar panels will always generate enough power every month to compensate the energy use of the luminaire. With this scenario it is researched if a system with batteries can be considered.

For one night of lighting in January (16 hours) 0.45 kWh is needed. When the system is using low voltage, a battery of almost 40 Ah, 12 V is needed. To reduce risk of the batteries being empty, and the light going out (when it is snowing for example and the PV panels generate nothing for a few days), 120 Ah or even more is advised. Such a battery costs about 400 euro and weights 40 kg and has a lifetime of 1200 cycli (Conrad.com, 2013). Therefore the battery should be replaced once or twice every twenty years, this will become too expensive. Note that these calculation are true when four large panels are installed, with only one or two panels the batteries size will be much larger. For this reason it is decided to connect the system to the grid.

Solar panels

One or two solar panels will be installed on top of the roof (depending on the budget). With a small amount of solar panels the installation is more easy. No large inverter is needed a micro inverter can be installed with the panels on top of the roof. The municipality does not need to find a place inside the house to store an inverter. The solar panel should generate at least 120 kWh a year for compensating the energy use of the lighting. Overcapacity is needed to give the resident a convincing reason to cooperate. Therefore around 200 kWh should be generated every year. Solar panels that can generate these should have a maximum power output of about 220 Wp (Joint Research Centre, 2013).

The micro inverter that will be selected in the...
next paragraph is suitable for 60-cell solar panels. Doing internet research it is found out that most panels with around 200 Wp and 60-cell are Polycrystalline panels.

Two websites are used to select a solar panel. The website www.zonnepanelen.nl sells several certified solar panels (TÜV and CE), they also have requirements for labor conditions of the producers. Brands sold at this website are used to do the research. Selected options are found in Table 18.

Table 18. Solar panel options

<table>
<thead>
<tr>
<th>ZN Shine</th>
<th>Bisol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wp</td>
<td>220 and 240</td>
</tr>
<tr>
<td>Size</td>
<td>1640<em>990</em>30</td>
</tr>
<tr>
<td>Mass</td>
<td>19.5</td>
</tr>
<tr>
<td>Efficiency</td>
<td>15.3 and 16.6</td>
</tr>
</tbody>
</table>

**Micro inverter**

The system has quite a low power output and therefore a micro inverter can directly be connected to the power grid via a socket or fixed connection. Installing an extra circuit breakers makes the system ready for expending, if the resident wants to buy extra solar panels this is possible. (Therefore in the costs calculation installing an extra circuit breaker is included.)

The micro inverter has to be IP6X classified since it will be installed outside. A few options are found; Enecsys, Enphase and Omnik. The most suitable one is from Enecsys, one reason is that their inverter can be linked to two solar panels, this will save costs. Next to this, the inverters of Enecsys have special condensators (thin-film in stead of electrolytic), these have a longer lifetime. The inverter is IP65 classified and handle a maximum input of 480 Wp (DC) and a maximum output of, 450 W (AC). This inverter is suitable for 60-cell solar panels. The inverter has a wireless output options with Zigbee signal. A gateway will receive a signal from the inverter and sends the information to an interface on a computer or phone. The micro inverter can be connected to the rail of the solar panel, it will be hidden under the solar panel itself to protect it from dirt.

---

**Table 17. Solar panel options**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>225</td>
<td>450</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Warentee period</td>
<td>25</td>
<td>25</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Price</td>
<td>170</td>
<td>260</td>
<td>180</td>
<td>135</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Gateway + zigbee</td>
<td>Gateway + zigbee</td>
<td>Wifi or GPRS, usb,</td>
<td>Gateway + wifi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ethernet</td>
<td></td>
</tr>
</tbody>
</table>

---

![Figure 93. Enecsys micro inverter for two PV panels](image)

Graph 8. Energy consumption light and PV panels
8.4. **Luminaire design**

The function of the luminaire housing is cooling the LED’s (this will increase their lifetime) and housing the electronics. Also the luminaire helps with creating the desired light design. After a test and some experiments with the prototype (chapter 12) it was decided to place the LED plate (Figure 95) under an angle, this makes that the luminaire protects the light from shining into the house. When in the future more efficient LED’s will be available the LED plate can be easily replaced, by removing the protection glass, this makes the design future proof.

*Figure 94. Inside luminaire*

*Figure 95. Aluminum LED plate with LED array of 6*4 LED’s and lenses*
Dimming

The light output has to be dimmed according to the mounting height. This is done once by the contractor during installation. The building height can be measured with an infrared distance meter and then a button is turned to the right position. This button is a potentiometer (resistor) which change the dimming input from 0 to 10 Volt. With this input the driver will take care of the right light output. Since the light intensity has a quadratic relation with distance, the angle the button has to be turned is different for every extra meter of height.

Dynamic dimming (e.g. based on time, weather conditions, light pollution, season or amount of activity) is seen more often in public street lighting. Reducing energy costs is the main reason, less light pollution an other. For residential streets this kind of dimming is considered an option only when motion detection is included. When people are using the street it should be lit according to the regulation. The estimation is that this could save 30% extra energy (Binsbergen, 2013). With a light output of 28 W the saving could be 8 W. Adding motion detection is expensive and complex. Since luminaires need to communicate with each other (multiple luminaires should go on, when one detects motion). An interview was done with Binsbergen (2013), from Twilight (a company specialized in adding motion detecting to existing street lighting). This interview gave insight in the costs for adding motion detection. It turned out to be more expensive then the savings on energy costs it could bring. Therefore dynamic dimming is not integrated in the design.

An other way of dimming was proposed in the concept as well, dimming based on light pollution from glass houses or on available moonlight. It turns out that the moon has a maximum light intensity of 1 lux (1 day a month during full moon) and light pollution from glass houses and other light sources such as industry, will have a maximum light intensity of 0.1 lux (Sotto le Stelle, 2008). These light sources will not create the need for dimming.
**LED module and lenses**
The LED module and lens selection is based on calculation done by Schréder. (Geerdink, 2013). Schréder is specialized in lens manufacturing and the company produces luminaires. The results from the calculation can be seen in Table 10. The selected LED module contains 24 LED’s, these LED’s can be combined with different lenses for different street lay-outs. The needed power is 28 Watt to light a street with 3 lux. Schréder has a luminaire with this LED module and with the different lenses. This luminaire is suitable for implemented in the design directly. However it does not completely fit the *Rotterdamse Stijl*. Later in the report an advise will be given on the desired aesthetics for Rotterdam.

**Driver**
The driver takes care of power supply, this is variable since the luminaire can be dimmed. The driver translates input to the right amount of power. The driver for this design is from Schréder as well, since they supply LED’s and lenses as well. They supply complete packages that are completely compatible.

**Control system and management software**
The control system is capable of doing several things: sensors could be connected for example e.g. motion detection or a light sensor. This data is used for dynamic dimming or telling if the light output is correct. The control system can monitor energy consumption and store data about the luminaire. Furthermore the control system can set up a wireless connection with other luminaires and a central device (Figure 33). Several management and control systems could be used, Owlet used by Schréder, CityTouch from Philips and CitySense from Tvilight are examples. As said before, dynamic dimming is not included in this design (onlye dimming based on building height). Only failure prediction and switching might be reasons to choose for a management system. However LED’s breaks down much less then PL lighting, therefore it is not worth the investments. For switching the light on and off another solution should be found.

**Switching on and off**
The luminaire will be connected to the grid of the house, therefore traditional on/off switching is not possible (TF-signal). Other options for switching are a

<table>
<thead>
<tr>
<th>Table 19. Management software available on the market</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Node communication</strong></td>
</tr>
<tr>
<td><strong>Back-office/gateway communication</strong></td>
</tr>
<tr>
<td><strong>Node:Gateway ratio</strong></td>
</tr>
<tr>
<td><strong>Dimming options</strong></td>
</tr>
<tr>
<td><strong>Functionality</strong></td>
</tr>
<tr>
<td><strong>Driver connection</strong></td>
</tr>
<tr>
<td><strong>Extra’s</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 20. Overview, switching options</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TF signal</strong></td>
</tr>
<tr>
<td><strong>+</strong></td>
</tr>
<tr>
<td><strong>+</strong></td>
</tr>
<tr>
<td><strong>-</strong></td>
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<td><strong>-</strong></td>
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</tbody>
</table>
build in clock, a light sensor or switching based on wireless signal input (Table 20). The wireless signal input itself can be based on several sources, such as time, surrounding light intensity and the weather (measured at a central spot). A complete communication network has to be set up for this, when combined with a management system it might be an interesting solution. Since it is decided not to use a management system, wireless switching is not profitable.

An astronomic clock is an accurate switching option, only during installation it has to be programmed based on its location on earth, and every luminaire needs an extra part.

The street lights should turn on almost at the same time, therefore a small light sensor is excluded as well. Multiple light sensors might solve this problem, or increasing the measuring area of the light sensor. This could mean using the solar panel as light sensor. This is expected to be the most simple solution that needs the least extra parts.

The current output of the solar panel will be measured based on advise of the company Eternalsun (Roest, 2013). A micro-controller or the driver directly will read this input and send a signal to a relays, who will allow power to flow to the light. The proposed circuit is seen in Figure 98.

Figure 98. Electronic circuit
**Luminaire design**

How the final design of the luminaire evolved, and why it looks like it does now, is shown in this chapter.

In Rotterdam a style guide is written, which defines the *Rotterdamse Stijl* (RS), for products in public space, their color, materials and main shapes are defined in this document. The preference is luminaires without small details, straight lines and continuous forms, Figure 100 (NPK, 2011). Words such as robust, timeless and sustainable are mentioned as well. Style guidelines are set up for luminaires on top of a pole and for luminaires on an outrigger. The last one is most suitable to be applied to the situation in the new design. Since the luminaire is placed on an outrigger from a roof. However the house is the main element and not the pole or outrigger, therefore some elements from the style guideline are not applied.

The variable that are considered are the form of the luminaire and position compared to the facade of the house.

First several luminaire designs are shown in Figure 101. The designs are based designs of Schréder. Their luminaires are tested on heat flow, strength, vibrations and water tightness. An extra function this luminaire needs to have, compared to current luminaires, is an adjustable angle in three directions because of different rooftops. Next to this integrating sheets against spill light are desired.

In the first option these sheets are not fully integrated, also the angle can only be adjusted in one direction. In the second option both luminaires can be adjusted in angle two directions. Here the design for flat roof an pitched roof are different. In order to reduce complexity during installation, reduce parts that the contractor should have, one system for all situation is desired. In the third option this is done with a ball joint.

On the next page, several examples of basic shapes are shown from a view the residents will see the luminaire.

The first, square, and second, triangular, shape are fitting the RS most. However with the house as main element the second design does not look natural and consistent with its surrounding. The first option is better and looks more robust.

The third option has natural shape and a circular light form, however a circular form is less efficient since all components that need to fit in are square forms. Also the RS does prefer straight lines. The last form is most consistent with the shape and lines of the house. The straight lines, robust and timeless form are suitable for the RS. Figure 106 shows what the resident would see when looking up to the luminaire during the day. A light that is guarding the street and the people living their.
Figure 102. Square form, straight lines are preferred by the RS and the square form fits with the rectangular form of a building.

Figure 103. Circular form, looks friendly but is not preferred by the RS.

Figure 104. Triangular form, fits the RS but fits less with the square form from a building

Figure 105. Square form, straight lines are preferred by the RS and the rectangular form fits with the rectangular form of a building.
Figure 106. Day view from the perspective of the resident, the light is watches out over the people living in the street.
9. **Eco-costs Value Ratio**

The EVR of the new design will be explained in this chapter. The EVR of the current system was already discussed in chapter 2.4 on page 28. Three new scenario’s will be used to explain the effects of several system lay-outs of the new design, in terms of costs and eco-costs.

Because the municipality does not have the goal of making profit, costs and price are the same. (Figure 107). Therefore, in this EVR analyses cost and price have the same value. Next to this, surplus value is not taken into account in the calculations. Because most surplus value of this system can be accounted for by other stakeholders besides the municipality. Such as the resident: light that is not shining into houses, obstacle free, generating energy and increasing building value. Plotting costs on the Y-axis means that the direction of improvement is changed, in Graph 9 the first green arrow points to the direction of reducing costs.

<table>
<thead>
<tr>
<th>Surplus value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
</tr>
<tr>
<td>Price</td>
</tr>
<tr>
<td>Customer Perceived Value</td>
</tr>
</tbody>
</table>

Figure 107. Costs, price and Customer Perceived Value (CPV) for governmental organizations

9.1. **Scenarios**

The new design has impact outside the boundaries of the current system. More stakeholders are involved in the new situation. Therefore several scenarios will be described next to the current situation;

1. The new situation with the same boundaries (this would mean no solar panels)
2. A scenario with extended boundaries with one solar pane
3. A scenario with extended boundaries and an additional solar panel, to see what the influence would be of extending the system with extra panels.

The EVR scores of all three scenario’s will be compared with the current situation and will be shown in Graph 11 until Graph 15 and Table 25 and Table 26. First the value (costs) and eco-costs will be treated separately.

**Assumptions**

To gather all the data several assumptions are made. Most are discussed during the analysis phase, where the costs and eco-costs of the current situation are discussed (chapter 2.4 on page 28). Some extra assumptions had to be made when gathering data about the three scenario’s.

- Price of solar panel, inverter and LED unit are constant. They are likely to become lower in the future but the uncertainty, about how much prices will decrease, is too high. It would influence the business case in a positive way.
- Energy price is constant, on the short term the prices are likely to become lower, on the long run they might grow. Since the rate is an unclear factor it is not taken into account.

<table>
<thead>
<tr>
<th>Table 21. Overview scenario’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminaires per street</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Power supply</td>
</tr>
<tr>
<td>Light point height</td>
</tr>
</tbody>
</table>
The cost calculation of all scenarios is based on data about Total Costs of Ownership that is available at the municipality. The differences between the current and new design will be explained here.

1 Manufacturing lighting
This step is the manufacturing of the luminaire and pole or rooftop mounting materials. Luminaire costs of LED luminaires are provided by Schréder, 30% discount when ordering large amounts is included as well, a LED luminaire will then cost 350 euro (a traditional luminaire costs about 200 euro). Manufacturing of a lighting pole of 4 meter costs about 150 euro, a rooftop connection is set at 50 euro (it is an integrated part of the solar panel connection). Lifetime of the luminaire is 20 years, the connection system lasts for 40 years. Therefore two luminaires are needed over the total lifetime of the system.

2 Manufacturing solar
A combination of a solar panel and inverter were selected before. Adding an extra solar panel will not double the price since the same inverter can be used for one and two panels. Lifetime of the solar panels and inverter is estimated to be 20 years (Groene Courant, 2013).

3 Installation
The installation costs are less expensive in the new situation, since no extra grid connection fee has to be paid to Stedin. In the new situation removing the current grid connections is included in the installation costs. These
connection are not needed anymore and for safety reasons they should be cut-off or completely removed. Costs for this removal are more than half of the installation costs in the new situation. Installation costs for the solar panels, a micro inverter and an extra circuit breaker are included in scenario three and four. The estimation of these costs (200 euro) is based on a phone call with Eric van Doorn from Enerpro (Enerpro, 2013).

4 Energy consumption
Individuals pay a higher price for energy than the large organizations therefore in the current scenario an energy price of 0.12 €/kWh is used an in the new scenario’s a price of 0.20 kWh. Still a saving on energy costs occur since the LED luminaires need much less power. Energy costs will be lower of even negative in the new scenario since the luminaire needs less power. In the third and fourth scenario total energy costs are negative since the solar panels produce more then the luminaires uses.

5 Maintenance and administration
Technical and administration management costs (maintenance and desk work) are almost in every scenario reduced because LED lighting will save on maintenance costs. Because digging is not necessary anymore even more costs are reduced. Total savings are estimated to be 20%. This assumption is based on the budget list of 2013 and 2014, costs that will not occur in the new design. Only in the first scenario administration costs are higher, this is because of administration needed for compensating residents for the energy consumption.

6 End of Life
At this moment Rotterdam is not accounting for valuable materials during the End of Life, if they will do this in the future it could bring them some financial benefits. However it is very small as can be seen in Graph 10.

7 Solar energy produced for lighting
Energy is produced by the solar panels, a part of this production is meant as compensation for the energy use of the lighting.

8 Overcapacity
The overcapacity of the solar panels is delivered free of charge to the resident. For the resident this energy has value since they get a discount on their energy bill.

Eco-costs

1 Manufacturing lighting
The eco-costs for manufacturing (materials and production) of the luminaires and pole or rooftop connection is the first blue square. The eco-costs reduction is due to the difference of mounting. A lighting pole needs a lot more material then the rooftop connection. The steel pole accounts for half of the eco-costs of this manufacturing phase.

2 Manufacturing solar
The solar panels are 60-cell polycrystalline panels since those are the best combination with the chosen inverter. They have a lower eco-costs per m² compared to monocrystalline panels. The inverter is also taken into account in this step.

3 Installation
The eco-costs are very low since this it is mainly transport and that has a small influence.

4 Energy consumption
The eco-costs of energy consumption are based in green energy in the current situation and the situation without solar panels. In the new situation energy eco-costs are based on roof mounted solar panels.

5 Maintenance and administration
The eco-costs technical and administration management are almost zero, since it exists out of some kilometers driven with a van and the impact of these kilometers is quite low.
6 End of Life
Mainly recycling of aluminum will bring some eco-costs benefits at the end of life.

7 Solar energy produced for lighting
Eco-costs of energy production of the solar panels compensate for the energy consumption in step 4.

8 Overcapacity
The solar panels produce more energy than the lighting used, therefore extra environmental benefits are gained. The resident is using less energy from the grid.

Graph 11. Eco-costs for the current and new scenarios
Eco-costs and Value

When combining the costs and eco-costs into one graph, from every step in the lifecycle (not in chronological order) it can be seen what their contribution is.

**Scenario one, no solar panels**

Graph 12 shows the current situation and the first new scenario that is most similar to the current situation, since power is supplied by the grid. This graph shows the impact of basic idea of the new concept; rooftop mounting and connection to the power grid of a house. Every step in the graph is explained below.

The production phase (including materials) and the energy use have a large impact on the eco-costs. The technical and administration management has most effect on the costs. The end-of-life does not influence the system much.

The energy price per kWh in the new scenario is higher and the energy consumption lower. Although the difference is small the slope of step 4 in both graphs differs.

In every step of the new design both financial and environmental benefits are gained with the new situation. Per street the total financial benefits are € 1540, the eco-costs are reduced with more than € 300 per street.

| Table 22. EVR score scenario one, € per year per street |
|--------------|-----------------|--------|
| Costs        | Eco-costs       | EVR    |
| Current      | € 11056         | € 532  | 0.048 |
| First        | € 9513          | € 212  | 0.022 |

Graph 12. Scenario without solar panels compared to the current situation
**Scenario two, one solar panels**

Graph 13 shows the current situation and the scenario with one solar panel.

The production of the solar panels is visualized separately from the production of lighting to show what its impact on the EVR is. The solar panel compensates, during the day, for the energy consumption, during the night, of the light. Thus step 4 and 7 are identical but in opposite direction.

The total amount of financial project benefits can not be accounted for by the municipality alone. The overcapacity of the solar panel is delivered free of charge to the grid of the resident, therefore the resident is also prescribed for a part of the project benefits.

In every step of this scenario both financial and environmental benefits are gained with the new situation. Per street per year the total financial benefits are € 3280, from which € 2130 is for the municipality and € 1150 for 80 residents (80 lighting points per street, so 80 residents will be involved). The eco-costs are reduced with more than € 570 per street.

<table>
<thead>
<tr>
<th>Table 23. EVR score scenario two, € per year per street</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Second</td>
</tr>
</tbody>
</table>

Graph 13. Scenario with one solar panel compared to the current situation
**Scenario three, two solar panels**

Graph 14 shows the current situation and the scenario with two solar panels.

The first and second solar panel are visualized separately and put at the end of the graph to show what an extra panel would do with the system. Step 2a includes one solar panel and mounting materials, step 2b is an additional panel and the needed additional mounting materials. Step 2b can be repeated for every additional panel.

The installation of an extra panel has a small influence on the installation (eco-)costs and is therefore not visualized separately.

The first solar panel generates energy to compensate for the energy used by the luminaire (step 7). The overcapacity of the first solar panel (8a) and the total energy production of the second solar panel (8b) are delivered free of charge to the grid of the resident. With two solar panels the residents benefit from more overcapacity.

The total financial benefits here are € 4670 per year per street. If the municipality pays for the second solar panel the resident will benefit with € 4200 per year per street (with 80 residents, € 50 per year). The municipality benefits with € 470 per street per year. Eco-costs are saved with almost € 900 per year per street.

| Table 24. EVR score scenario three, € per year per street |
|-----------------|-----------------|-----------------|
| **Costs**       | **Eco-costs**   | **EVR**         |
| Current         | € 11056         | € 532           | 0.048           |
| Third           | € 6380          | €-362           | -0.057          |

Graph 14. Scenario with two solar panels compared to the current situation
Conclusion

The EVR in the third new scenario, with two solar panels has the best EVR score as can be seen in Table 25 and more in detail in Table 26, with every additional solar panel the EVR score will be reduced further.

The municipality cannot account for all financial project benefits, since part of it (the overcapacity of the solar panel) will be for the resident. Therefore the advise for the municipality is to choose the scenario with one solar panel, this scenario has the best rate between financial and environmental benefits looking from the perspective of the municipality.

Adding additional solar panels might be interesting when the municipality is more healthy financially seen. An other option is to ask the resident or housing cooperation if they would be interested in financing extra panels. The installation will be paid by the municipality and therefore it is cheaper to buy extra panels for other parties.

Table 25. EVR score scenario two, euro per year per street

<table>
<thead>
<tr>
<th>Costs</th>
<th>Eco-costs</th>
<th>EVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>€11056</td>
<td>€532</td>
</tr>
<tr>
<td>First</td>
<td>€9513</td>
<td>€212</td>
</tr>
<tr>
<td>Second</td>
<td>€7773</td>
<td>-42</td>
</tr>
<tr>
<td>Third</td>
<td>€6380</td>
<td>-362</td>
</tr>
</tbody>
</table>

The EVR in the third new scenario, with two solar panels has the best EVR score as can be seen in Table 25 and more in detail in Table 26, with every additional solar panel the EVR score will be reduced further.

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### Table 26. Cumulative data EVR

<table>
<thead>
<tr>
<th></th>
<th>Current Costs</th>
<th>Current Eco-costs</th>
<th>Current EVR</th>
<th>New, no solar Costs</th>
<th>New, no solar Eco-costs</th>
<th>New, no solar EVR</th>
<th>New, one solar panel Costs</th>
<th>New, one solar panel Eco-costs</th>
<th>New, one solar panel EVR</th>
<th>New, two solar panels Costs</th>
<th>New, two solar panels Eco-costs</th>
<th>New, two solar panels EVR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing lighting</td>
<td>14.18</td>
<td>2.76</td>
<td>0.195</td>
<td>17.00</td>
<td>0.66</td>
<td>0.039</td>
<td>15.00</td>
<td>0.66</td>
<td>0.044</td>
<td>15.00</td>
<td>0.66</td>
<td>0.044</td>
</tr>
<tr>
<td>Manufacturing first PV panel</td>
<td>14.18</td>
<td>2.76</td>
<td>0.195</td>
<td>17.00</td>
<td>0.66</td>
<td>0.039</td>
<td>34.00</td>
<td>1.54</td>
<td>0.045</td>
<td>34.00</td>
<td>1.54</td>
<td>0.045</td>
</tr>
<tr>
<td>Installing</td>
<td>32.80</td>
<td>2.76</td>
<td>0.084</td>
<td>31.50</td>
<td>0.66</td>
<td>0.021</td>
<td>51.00</td>
<td>1.54</td>
<td>0.030</td>
<td>53.50</td>
<td>1.54</td>
<td>0.029</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>62.19</td>
<td>5.72</td>
<td>0.092</td>
<td>51.32</td>
<td>2.50</td>
<td>0.049</td>
<td>70.82</td>
<td>3.69</td>
<td>0.052</td>
<td>73.32</td>
<td>3.69</td>
<td>0.050</td>
</tr>
<tr>
<td>Technical and administration management</td>
<td>110.51</td>
<td>5.72</td>
<td>0.052</td>
<td>95.38</td>
<td>2.50</td>
<td>0.026</td>
<td>108.38</td>
<td>3.69</td>
<td>0.034</td>
<td>110.88</td>
<td>3.69</td>
<td>0.033</td>
</tr>
<tr>
<td>End of Life</td>
<td>110.56</td>
<td>5.32</td>
<td>0.048</td>
<td>95.13</td>
<td>2.12</td>
<td>0.022</td>
<td>108.13</td>
<td>3.05</td>
<td>0.028</td>
<td>110.60</td>
<td>2.99</td>
<td>0.027</td>
</tr>
<tr>
<td>Generated energy for lighting</td>
<td></td>
<td></td>
<td></td>
<td>89.32</td>
<td>0.90</td>
<td>0.010</td>
<td>105.79</td>
<td>0.84</td>
<td>0.011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing additional PV panel</td>
<td></td>
<td></td>
<td></td>
<td>89.32</td>
<td>0.90</td>
<td>0.010</td>
<td>105.79</td>
<td>0.84</td>
<td>0.011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overcapacity for one PV panel</td>
<td></td>
<td></td>
<td></td>
<td>77.73</td>
<td>-0.42</td>
<td>-0.005</td>
<td>94.20</td>
<td>-0.15</td>
<td>-0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overcapacity for additional PV panel</td>
<td></td>
<td></td>
<td></td>
<td>63.80</td>
<td>-3.62</td>
<td>-0.057</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 27. Data EVR per step

<table>
<thead>
<tr>
<th></th>
<th>Current Costs</th>
<th>Current Eco-costs</th>
<th>No solar Costs</th>
<th>No solar Eco-costs</th>
<th>One solar panel Costs</th>
<th>One solar panel Eco-costs</th>
<th>Two solar panels Costs</th>
<th>Two solar panels Eco-costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing lighting</td>
<td>14.18</td>
<td>2.76</td>
<td>17.00</td>
<td>0.66</td>
<td>15.00</td>
<td>0.66</td>
<td>15.00</td>
<td>0.66</td>
</tr>
<tr>
<td>Manufacturing first PV panel</td>
<td>18.63</td>
<td>2.76</td>
<td>14.50</td>
<td>0.00</td>
<td>17.00</td>
<td>0.00</td>
<td>19.82</td>
<td>0.88</td>
</tr>
<tr>
<td>Technical and administration management</td>
<td>48.31</td>
<td>0.00</td>
<td>44.07</td>
<td>0.00</td>
<td>37.57</td>
<td>0.00</td>
<td>37.57</td>
<td>0.00</td>
</tr>
<tr>
<td>End of Life</td>
<td>0.06</td>
<td>-0.40</td>
<td>-0.25</td>
<td>-0.38</td>
<td>-0.25</td>
<td>-0.64</td>
<td>-0.28</td>
<td>-0.70</td>
</tr>
<tr>
<td>Generated energy for lighting</td>
<td></td>
<td></td>
<td>-18.82</td>
<td>2.15</td>
<td>-18.82</td>
<td>2.15</td>
<td>-30.40</td>
<td>4.80</td>
</tr>
<tr>
<td>Manufacturing additional PV panel</td>
<td></td>
<td></td>
<td>-11.58</td>
<td>1.32</td>
<td>-11.58</td>
<td>0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overcapacity for one PV panel</td>
<td></td>
<td></td>
<td>-11.58</td>
<td>-1.32</td>
<td>-11.58</td>
<td>-0.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overcapacity for additional PV panel</td>
<td></td>
<td></td>
<td>-30.40</td>
<td>-4.80</td>
<td>-30.40</td>
<td>-4.80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
10. Business case

This business case is written from the perspective of the municipality. Therefore making profit is not the goal; the goal is reducing costs. The municipality has the obligation to provide public street lighting. Indirectly people pay for this service via taxes. The total income from the municipality is divided over different departments based on their yearly expenditure estimation and based on what they have spent the year before. The lighting department then uses this money to provide the city from public street lighting.

10.1. Scenarios

In this business case, three different scenarios will be used, they were discussed before in chapter 9: no solar panel, one solar panel and two solar panels.

The investments and running costs for the new design will be compared with the current situation. Investments, savings, payback period and replacement point will be discussed in this chapter.

In the current situation the investment costs for lighting one street are almost € 105600. Every year energy costs and technical and administration management costs have to be paid, about € 7750 per year. For 40 years (the lifetime of a lighting system) that is about 311000 euro. In the new scenarios, investments are higher in the second and third scenario and running costs lower. For the first scenario, investments are lower and running costs. However the eco-cost benefit are also quite low in this scenario, as could be seen in chapter 9.

Data is summarized in Table 28 and the results in Graph 16 until Graph 18. The gray lines in Table 28 are costs per street per year, the black lines are total costs in euro per street per 40 years, the gray line, are in euro/street/year.

Two times investments have to be done, at first and after 20 years when the luminaires (and solar panels and inverter) have to be replaced. Both investments are seen in Table 28. Remaining value of the first term is also seen in this table. At the second investment point, the luminaires are fully depreciated however the mounting system is not, the mounting system has a lifetime of 40 years.

<table>
<thead>
<tr>
<th>Data</th>
<th>Current situation [€]</th>
<th>No solar [€]</th>
<th>One solar panel [€]</th>
<th>Two solar panels [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>First investments [€/street]</td>
<td>105600</td>
<td>94000</td>
<td>138000</td>
<td>186000</td>
</tr>
<tr>
<td>Depreciation of investment, first term [€/street/year]</td>
<td>3543</td>
<td>3350</td>
<td>5350</td>
<td>7550</td>
</tr>
<tr>
<td>Running costs, total [€/street]</td>
<td>310827</td>
<td>255532</td>
<td>154268</td>
<td>154268</td>
</tr>
<tr>
<td>Running costs, mean [€/street/year]</td>
<td>7771</td>
<td>6388</td>
<td>3857</td>
<td>3857</td>
</tr>
<tr>
<td>Recycle benefits [€/street]</td>
<td>226</td>
<td>-1005</td>
<td>-1005</td>
<td>-1117</td>
</tr>
<tr>
<td>Recycle benefits [€/street/year]</td>
<td>6</td>
<td>-25</td>
<td>-25</td>
<td>-28</td>
</tr>
<tr>
<td>Investment second term [€/street]</td>
<td>25600</td>
<td>32000</td>
<td>66000</td>
<td>84000</td>
</tr>
<tr>
<td>Rests value first term [€/street]</td>
<td>34750</td>
<td>27000</td>
<td>31000</td>
<td>35000</td>
</tr>
<tr>
<td>Depreciation, second investment + value left [€/street/year]</td>
<td>3018</td>
<td>2950</td>
<td>4850</td>
<td>5950</td>
</tr>
<tr>
<td>TCO total [€/street/40 years]</td>
<td>442253</td>
<td>380527</td>
<td>357263</td>
<td>423151</td>
</tr>
<tr>
<td>TCO mean value [€/street/year]</td>
<td>11056</td>
<td>9513</td>
<td>8932</td>
<td>10579</td>
</tr>
<tr>
<td>Total amount of savings for the municipality [€/40 years]</td>
<td>61726</td>
<td>84990</td>
<td>19102</td>
<td></td>
</tr>
</tbody>
</table>
Scenario one, no solar panels
The first scenario is the scenario without solar panels. The investments are lower and the running costs as well. Therefore payback period of the extra investments is not in the graph.

At the point where the savings potential meets the rest value of the current system (investments minus depreciation) it can be replaced without financial consequences. This is at 12 years in this scenario. Replacing when the current system is older than 12 years will bring financial benefits.

Graph 16. Scenario without solar panel: investments and ownership costs for 40 years, cumulative savings and total savings for 40 years
**Scenario two, one solar panel**

With one solar panel the investments are higher, however energy costs are zero, since the solar panel produces the energy for the lighting. Therefore running costs are reduced a lot and this saves money. After 8.5 years these savings are higher then the extra investments that had to be done.

The total amount of savings in this scenario is 84000 euro. At the point where the current systems value is less then 84000 euro the current system could be replaced without financial consequences. Looking at the line of depreciation of the investments, the new design can be implemented when the current system is only 6 years old. This is true from economical perspective. It depends on what is happening with the current system if this is true from eco-cost perspective as well. Recycling, upcycling or selling the luminaires and poles to an other municipality might be interesting.

*Graph 17. Scenario with one solar panel: investments and ownership costs for 40 years, cumulative savings and total savings for 40 years*
**Scenario three, two solar panels**

Adding an extra solar panel makes the system more expensive, therefore the savings over 40 years are less, still 19000 euro can be saved. This scenario is interesting when taking into account the extra eco-costs benefits that are gained by the extra investment (chapter 9).

After 35 years the savings become higher than the extra investments that were done at the start and second investment point. Replacing the current system can be done without financial consequences from 34 years. At this point the current system gets more value and is worth more then the savings of the new design will cause.

---

**Graph 18. Scenario with two solar panels: investments and ownership costs for 40 years, cumulative savings and total savings for 40 years**
10.2. CO\textsubscript{2} emission

For the municipality of Rotterdam, CO\textsubscript{2} emission is important since they have the goal to reduce this emission with 50% by 2025, with 1990 to compare with. In 1990 the emission was 24 Mton CO\textsubscript{2}, from which 85% could be accounted for by industry (Rotterdam Climate Initiative, 2008). In the current situation public street lighting causes an emission of about 1300 kg CO\textsubscript{2} per year per street (one street in this report measures 1.2 km). The savings per scenario can be found in Table 29. To the total amount that should be saved, it is a small contribution, but it does make public street lighting not only CO\textsubscript{2} neutral, the scenarios with solar panels even have a negative CO\textsubscript{2} emission. Therefore they will not only fully compensate their own emission (during the production phase) they can also compensate for other harmful products in the city.

<table>
<thead>
<tr>
<th>Current</th>
<th>No solar panels</th>
<th>One solar panel</th>
<th>Two solar panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg CO\textsubscript{2} equivalent/street/year</td>
<td>1305</td>
<td>642</td>
<td>-250</td>
</tr>
<tr>
<td>Savings kg/street/year</td>
<td>663</td>
<td>1555</td>
<td>2303</td>
</tr>
</tbody>
</table>

Graph 19. CO\textsubscript{2} emissions of public street lighting.
10.3. Market size

An estimation of the market size can be made by looking at several data sources available at the municipality. The first one is a database about installing dates of lighting points (Gemeente Rotterdam, 2013b).

Based on the conclusion in paragraph the scenario with one solar panel is used for estimating the market size. This means everything older then 5 years could be replaced. However this is not very likely to happen because the municipality is low on financial resources at the moment. Therefore everything older then 20 years is taken as a limit, when luminaires should be replaced anyway.

Data is available about all lighting points in the center of Rotterdam (Oude Westen, Cool, Dijkzicht, Nieuwe Werk, CS Kwartier and the Stadsdriehoek). Filters are applied to this database in order to find the amount of lighting points that might be replaceable for the new design. The following points are eliminated

- All lighting points above 12 m, because the design is not suitable for higher heights at this moment.
- All lighting points above 100 W power, because they are mostly used for lighting highways. The new design is suitable for residential areas and not for these situations.
- The Stadsdriehoek and CS Kwartier are eliminated because this is mostly shops, offices and very large buildings, no residential streets
- The Old Rotterdam luminaires, since they have special style characteristics that are preferred in certain areas for a historical look.
- All ‘Schijnwerpers’ because they are used to highlight buildings and art and are not used for public street lighting.
- Lighting points installed after 1995. If this system will be implemented within two years, lighting points from before 1995 are older then 20 years.

What is left is 1100 out of 5800 luminaires, 18%. Not all streets are suitable, because rooftops might face an inefficient angle, buildings might not be suitable for solar panels (monumental buildings, or streets have large gardens. Half of the selected lighting points is assumed to be suitable for replacing them with the new design, this is 9% of the total amount of lighting points or 520 luminaires. For all lighting points in Rotterdam (110 000) this means, almost 10 000 lighting points. With 80 lighting points per street, this is 125 streets.

In the Netherlands 2.6 million street lighting points exist (Bremmers, 2000), since this lighting design is most suitable for urban areas the percentage that is suitable might be a little bit less then the estimated 9%. If 5% is suitable, this would mean a potential market size in the Netherlands of 130 000.

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Figure 108. Selection of buildings less then 12 m high in the Afrikaanderwijk in Rotterdam (Gisweb 2.1, 2013)
10.4. Implementation

The steps the municipality has to take to implement this design are visualized in Figure 111, it can be compared with Figure 110 (hanging street lighting) and Figure 109 (traditional lighting pole). The traditional, lighting pole, has the least steps. However, it does not have the desired outcome for residential streets (obstacle free lighting). The road map for hanging street lighting does have the desired outcome but knows more problems. With the new design developed in this thesis these problems do not occur anymore.

A lighting pole has the least steps and knows

Road map

A new project is initiated by the municipality (1). An Urban Plan is designed by the landscape architect (2) who consults the light architect for the Lighting Plan (3). When they have a concept the executing department of the municipality will inspect the outdoor environment to check whether the plan is feasible (4). If not, changes will be made (5). When the plan is approved the executing of the plan can start. From here on for different kinds of lighting (lighting pole, hanging lighting, rooftop mounting) the steps are different.

The problem with Stedin does not occur in the new road map, it is also easier to convince building owners to cooperate.

The resident is informed with a letter. It will contain explanation about the project and information about their house (14). In the letter a phone number and email address of a contact person at the municipality is given. The resident

Figure 109. Project roadmap for a lighting pole, an expensive process which does not always give the desired results (obstacle free lighting is the preferred result in residential streets)
The diagram illustrates the project roadmap for obstacle-free lighting, which includes the following steps:

1. Municipality needs to redesign a street or the lighting system is depreciated.
2. The landscape architect designs an Urban Plan (UP).
3. The light architect designs a Lighting Plan (LP).
4. Outdoor inspection by the executor lighting.
5. Change UP and IP.
6. When UP is approved.
8. Contractor installs products above ground.
9. Contractor maintains products above ground.
10. Contact Stedin to ask for grid connection.
11. Contractor installs products underground.
14. Sending letter to residents/building owners with project info.
15. Wait for response.
16. External company does calculations.
17. Change lease/purchase agreement.
18. Information what to order.
19. Resident agrees.
20. Resident does not agree.
21. Calling resident to explain and convince.
22. Resident agrees.

Figure 110. Project roadmap for obstacle-free lighting, this results in more problems, compared to a lighting pole.
is informed about the benefits the system will bring for them (discount on energy bill). And it is explained what they can do to ease the installation process (make an appointment for rooftop calculation, installation and decide whether extra panels will be bought).

When all residents are informed about the plan (they are not allowed to refuse (Gemeente Rotterdam, 2012a) but installation is easier when they cooperate) the next step is to calculate if their rooftop is strong enough for the system.

When the inspection and calculations have a positive outcome the lighting system can be ordered. The municipality of Rotterdam is doing procurement themselves. They will buy the needed parts from several suppliers. The parts will be delivered to a contractor together with a plan describing for each address, which parts need to be installed and which luminaire lay-out is needed. The contractor then installs all parts.

Ownership
The municipality does not want to be responsible for high voltage (above 48 V) inside houses. Two options exist for handling this problem; first is designing a low voltage DC system and a second option is to set up a contract with the involved housing cooperation.

The low voltage DC system (which needs a battery) is discussed in paragraph 8.3, an expensive system since it needs four large PV panels and an expensive battery. Therefore the second option is more feasible.

The municipality will outsource the responsibility for (the maintenance of) the public street lighting to the housing cooperation. They will receiving a fee from the municipality to cover the involved costs. This would mean that the housing cooperation is owner of the entire system. A clear solution since they are owner of the houses as well.

When no housing cooperation is involved, but individuals are owners, it is more difficult. When a homeowner association exists this association can become responsible. When the individuals in a street are not part of a homeowner association individuals should be owner, this is difficult and expensive to manage, therefore this design is not likely to be implemented in those cases. When the residents would really prefer this lighting and ask directly for it, they should set up an association for this.
1. Municipality needs to redesign a street or the lighting system is depreciated

2. The landscape architect designs an Urban Plan (UP).

3. The light architect designs a Lighting Plan (LP).

4. Outdoor inspection by the executor lighting

5. Change UP and IP

6. When UP is approved

7. Municipality orders products

8. Contractor installs products

9. Contractor maintains products

10. Shift responsibility to housing cooperation or homeowner cooperation.

11. Suppliers

12. Information what to order

13. Addresses and information of involved buildings

14. Sending letter to residents/building owners with explanation of benefits and project info:
   - Building height
   - Street width
   - Rooftop angle (0 to 60)
   - Rooftop orientation
   - Energy company
   - kW/h meter type
   - Residents makes appointment for rooftop calculation
   - Residents can see project roadmap
   - Resident can call/email municipality with questions
   - Resident can decide weather to buy extra solar panels

16. External company does calculations

17. Change lease/purchase agreement
   - Resident makes an appointment for connecting the system inside their house
   - Resident registers at www.energieleveren.nl
   - Resident downloads monitoring app

18. Project roadmap for the new design, more steps than a lighting pole, less problems.
11. Prototyping

The goal of building this prototype is proving the concept and communication the idea.

Several companies were consulted to help realizing this concept. The solar panels are provided by Solsolutions. For the duration of this project, these panels could be used. The luminaire is provided by Schréder, they helped choosing the right one and donated a sample. The frame that was designed during the design phase was built by students from the Albeda college.

The luminaire is a catalogue model from Schréder, the Piano Mini with a 24 LED array which needs 28 Watt. The solar panels are 195 Wp monocrystalline panels from the brand Risen. These are not the panels as proposed in the design section, but for purpose of the prototype the aesthetics are more important, they have a black anodized frame which fits the Rotterdamse Stijl.

The luminaire is switched with an external light sensor. Prototyping a circuit for using the solar panel as light sensor was not within the scope and time boundaries of this project. Using an external light sensor, connected to an Arduino microcontroller, which steers a relay was. Dimming according to height is also included with a potentiometer (Figure 112).
Figure 114. Prototype for flat rooftop

Figure 115. The luminaire with ribs to increase stiffness and heat sink surface

Figure 116. View from residential perspective

Figure 117. Size of the solar panels and luminaire can be estimated with this image
12. Testing

The light output of this luminaire will be evaluated and experiments will be done to determine improvements. The research question is:
- Is the light shining into houses? The prediction is that this will happen with the current lenses. With calculations done in Dialux it was found out that an angle of 25 degrees would give the preferred light output. This test will confirm or reject this hypothesis.

In the test the angle and distance from facade will be varied, in order to find their influence.

The test is set up in a dark room (baseline measurement of 0.01 lux), the luminaire is connected to a table which has a cardboard ‘wall’ attached to it with a window cut out. Behind this window it can be measured what the light intensity in the house would be.

![Figure 118. Setting the angle](image1)

![Figure 119. Test set up](image2)
12.1. Results

The illuminance of the lighting inside the house is seen in Table 30.

To get an idea of what these numbers mean, Table 3 can be checked for reference, for example a living room is lit with about 50 lux. This means that still quite a lot of light is shining into the house. However a curtain will block a part of the light, now the measuring is done without any curtains.

Unfortunately the angle of 25 degrees could not be tested since the range of used ball joint only allowed 20 degrees. However with Graph 20 it can be predicted what would happen.

In Figure 120 and Figure 121 the light pattern on the wall can be seen. A problem occurs, when the luminaire is placed under angular the light is shining more towards the sky. This will cause light pollution and that is not desired.

Solutions for this problem and the desire to reduce the light shining into the house even more will be explored by adding several shields to the luminaire (pictures of the test can be found in appendix 9). Sheets on the front of the luminaire increase the light shining into the house since the light is reflected towards the facade. The sheet on the back of the of the luminaire decreases the light inside the house, with about 10 lux.

<table>
<thead>
<tr>
<th>Distance</th>
<th>25 cm</th>
<th>50 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle [degrees]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>190 lux</td>
<td>126 lux</td>
</tr>
<tr>
<td>5</td>
<td>128 lux</td>
<td>83 lux</td>
</tr>
<tr>
<td>10</td>
<td>95 lux</td>
<td>61 lux</td>
</tr>
<tr>
<td>15</td>
<td>60 lux</td>
<td>45 lux</td>
</tr>
<tr>
<td>20</td>
<td>47 lux</td>
<td>27 lux</td>
</tr>
</tbody>
</table>

Graph 20. Illuminance inside the house

Figure 120. Zero degrees

Figure 121. Increased angle, light shining towards the sky causes undesired light pollution
12.2. Conclusion

The optics of this luminaire are not fulfilling the requirements of not shining into the house and no light pollution. The luminaire cannot be placed under a large angle because the light would exceed the 180 degrees limit. Therefore a smaller light beam is advised.

Two directions exist for making this possible. Adding sheets and placing the light more to the inside of the luminaire. Another options is designing different lenses. The last option is most efficient in terms of light output and material use.

With these test as inspiration a new lens design can be made. In order to do this, first the standard state of the luminaire should be decided, this will be done according to the Rotterdamse Stijl, this means a small angle of 5 degrees and a distance of 0.75 m from the facade.

The light output towards the side may not exceed the 180 degrees limit, as could be seen in Figure 29, smaller angle is better. The angle from the tested lens is about 160 degrees, this will be okay for the new lens as well. The light output towards the back and front should be asymmetric, to the back the angle should be as small as possible, towards the front the angle should be 60 degrees.

Figure 122. Specifications of the new lens design, in 2D side and front view. with the data a optics designer need
CONCLUSIONS
13. Evaluation

In this chapter the final design is evaluated by checking if it meets the predetermined requirements. The requirements will be repeated and per group of requirement it will be explained if they were met. The final design was also evaluated together with the stakeholders and resident who participated in the research. Their feedback is discussed in the second paragraph.

13.1. Requirements

Costs
1. The design should reduce energy consumption costs

This requirement is met, energy consumption is reduced from 36 to 28 Watt and the power needed is produced by the design itself, energy costs for the municipality will therefore be.

2. The design should reduce technical management costs

3. The design should reduce administration management costs

The mentioned costs are reduced by using LED technology, which has a longer lifetime and therefore need less replacement. Also, LED is more reliable compared to PL lighting.

4. The design should ease the installation process

The design is connected to the grid of the resident and this negates the need for involving the grid manager. That eases the installation process. Involving the resident is predicted not to be a problem, because they benefit from the installation on their rooftop.

Environment
5. The amount space for urban nature should be increased

The design does not use space on floor level nor need extra space underground. Also, the design is suitable for combining with trees in the street, because the high lighting point can create a nice shadow pattern

6. The eco-costs of energy consumption should be reduced

7. The eco-costs of the manufacturing phase should be reduced

Eco-costs in all steps of the life cycle are reduced. The main reasons: elimination of the pole which saves enough material for allowing solar panels to be installed without the rise of the eco-costs in the production phase.

8. Tree roots may not be damaged during installation of the system

Digging is not necessary anymore. Therefore tree roots will not be damaged during the installation process.

9. Air or water should be filtered

10. Materials should be as less harming to the environment as possible

11. Used materials should be recyclable

Aluminum is the largest part of the material use, a mix of recycled and new aluminum is used. The aluminum parts can be easily disassembled and recycled. Because of the energy production of the solar panels the eco-costs are negative at the end of life of the system. The design fully compensates its own eco-costs and can even compensate for other harmful products in the city, because of the negative eco-costs. The total CO₂ emission of the city will be reduced, if it is this cleans the air as well can not be proven yet, more research is needed for this.

Aesthetics
12. The design should be integrated in the environment

13. The design should fit the Rotterdamse Stijl

14. The design should not consume space at floor level (obstacle free)

When large trees are located in the street the luminaires will not be visible from many positions in the street. Without large trees the luminaire will be seen, if it feels integrated in the environment is difficult to judge from a rendering. The Rotterdamse Stijl was partly applied, because the mounting situation is completely different from the description in the Rotterdamse Stijl vision. Criteria 12 and 13 are difficult to be judged at the moment. With a pilot this could be researched further. Criteria 14 is met by mounting the luminaire to the rooftop.
13.2. Stakeholders

Many internal and external stakeholders were contacted and gave input during the development of the concept. This chapter will discuss their reactions on the final design, but first an overview is given of the most important stakeholder benefits:

**Municipality**
- No energy costs anymore
- Less maintenance and administration costs
- Reduction of CO₂ emission
- No digging, no extra grid connection
- Grid manager is not involved
- Obstacle free lighting
- Easy to convince building owners

**Resident**
- Discount on energy bill
- Possibility to buy extra solar panels
- Safe feeling because of high uniformity rate
- Less light pollution inside the house

**Energy company**
- Local production of energy
- Increase of building value (Nu Zakelijk, 2013)
- Lower classification of building energy label

**Housing cooperation**
- Sustainable housing
- Decrease of building energy label
Landscape architect

“De vormgeving van het armatuur zelf heeft een zekere stroomlijn nodig om het aan te laten sluiten bij armaturen die we verder in de stad willen toepassen. Ook voor de uithouder hebben we binnen Rdam ons eigen ontwerp. Daar wijkt die van jouw van af maar zou daar wel op geënt kunnen worden. Pas dan en met voldoende toepassingsmogelijkheden zou je kunnen overwegen dit armatuur toe te passen.”

Executive manager lighting

“Ziet er leuk uit en goed bedacht. Mijn persoonlijke mening zegt dat deze oplossing zou kunnen werken. Geen Stedin meer nodig en geen ingravingen meer. Wel is het zo dat de burger moet mee werken. Dat kan zeker in nieuwbouw wijken waargemaakt worden door afspraken te maken vooraf bij verkoop aan bewoner of organisatie.”

The executing department of the municipality is happy with the fact that Stedin is not involved anymore. Cooperating with resident is still seen as an obstacle, they would rather apply this design in new building projects. For convincing them that it could also be applied to the current situation a pilot project should be done.

Urban nature expert

“Grootste voordeel lijkt me dat je geen bekabeling meer nodig hebt en dat er geen extra objecten (palen) in de straat staan.”

The urban expert likes the fact that no extra cables are needed and that more space for urban nature is created. He would prefer to combine this design with large trees which give some nice shadows on the street.

Light architect

“Dit zouden we wel kunnen toepassen.”

The light architect can see the implementation of this design happening. It is a more work for him, because building height is an extra parameter in the design but it could bring better result and he thinks it is an interesting solutions for some situations.

Resident

“Ik zou deze zonnepanelen wel op mijn dak willen hebben, maar het is niet mijn eigen huis. Voordeel is dat er geen kabels in de grond nodig zijn en in geval van een storing ook de grond niet open hoeft. Geen palen meer in de straat. Voor mij als fietser wel een nadeel hahaha want dan zijn er minder gelegenheden om er je fiets met een ketting aan vast te zetten.”

This resident is positive about the design since the street tiles does not have to be removed for digging. Extra bike stands would be nice because the pole can not be used as bike stand anymore.

Resident

“Ziet er goed uit zeg! Ik zou zelf wel voor zijn, ik vind wel de zonnecellen vrij groot, dus ik zou wel willen weten hoeveel nodig is voor de verlichting en hoeveel ik dan zelf als bewoner nog aan zonnecellen zou kunnen plaatsen. Ook het feit dat er bij ons veel garages zijn en dus weinig ruimte voor masten, is een voordeel van jouw ontwerp. Of ik het zou willen, is ook wel een beetje afhankelijk van het licht zelf, als het eruit komt te zien als een bouwlamp dan zou ik passen.”

The solar panels are too present in the design according to this resident. However she is interested in more panels if it will bring benefits. Next to this she points out that the light should
be warm en not looking like a stadium or construction work light.

**Resident**

“Dat ziet er slim uit. Ik zou zeker geen problemen hebben met zulke verlichting op mijn dak.”

He is enthusiastic about the design. The main reason is that it will bring financial benefits.

**Resident**

“Wow! Dat is mijn eerste reactie! De lichtuitstraling op straat is heel erg plezierig. De verlichting creëert ruimte en openheid, zonder overdadig te zijn is mijn beleving als ik naar het beeld kijk. Voor bewoners blijft het natuurlijk wel belangrijk dat ze geen ‘bak licht’ in hun slaapkamer hebben de hele nacht - ik kan niet beoordelen hoe dat is. Het armatuur, gekoppeld aan een zonnepaneel, vind ik heel elegant.”

She is enthusiastic about the spaciousness the light creates. She is doubtful about the light not shining into houses. The included solar panels are completing the design according to her.
14. Recommendations

Some subjects have to be researched and developed further, starting with the electronics. Other subjects can be researched and developed on the longer run, they are meant to expand the functionalities of the design.

First, with a new student project, the development of the electronics needed for this concept can be continued. The assignments for this projects will be shortly described in this chapter. Second, developments for the close and far future will be described. The final recommendation is to start a pilot project, the chapters ends with why a pilot is needed and what can be learned from this.

A new student project
Public street lighting should go on when the light level of the environment is below a certain value (value differs per city). Preferably all lighting points should go on at the same time. Using a light sensor to do this is a simple and cheap solution.

Problem
A light sensor has a small measuring area and when it gets dirty accuracy is decreased. Increasing the measuring surface decreases this problem. This can be done by using the Photo-voltaic panels as light sensor. However, an electronic circuit for this does not exist yet.

Assignment

*Develop a switching circuit that uses a PV panel as light sensor.*

The goal of this assignment is to design and prototype this circuit and use this prototype in a pilot project. The complete power system should be researched in order to integrate his circuit in the power system.

Research the characteristics of a PV panel, what is the current and voltage output based on several light intensities? And which one could be used best as input of the sensor?

How is the on/off threshold set? Every city needs an other threshold (e.g. in Rotterdam it is 40 lux in Amsterdam 11 lux).

What would be the implication of: integrating the switching circuit with the inverter, integrating it with the LED driver or designing a stand alone device?

Analysis the failure risk of the system, what is the chance of failure of the parts and what it the effect of those failures? How can the risk of failure be reduced? Important is, is that the light works during the night.

Approach

The approach suggested for this follow up project includes research, experiments, simulation and prototyping.

The research will be on the subject of PV panels, what types exist and do they have different voltage and current output characteristics? Also inverter types and components sold be researched. Next to this doing interviews with experts is suggested. Interesting companies to contact are, Eternalsun (specialized in measuring of PV panels), Twilight (designing luminaire controlling soft- and hardware) for information about LED driver software and hardware. Other student projects could be used as input too.

If data about the light intensity and voltage or current output cannot be found during the research, data should be gathered with an experiment.

When these two stages of the project are passed, enough data is gathered for starting the design process. Computer simulations of electronic circuits can be done and the circuit should be prototyped and integrated in the system.

With this prototype the design can be tested and evaluated.

Further developments

Research and write an advise on juridical procedures.

For the close future, the juridical implications of this design should be researched. An advise should be given on two subjects: ownership and responsibilities.

- Who will be the owner of the several components (municipality, housing cooperation, energy company, resident or other parties)?
- Who will be responsible for the installation, maintenance and failures?
Include dimming and a motion sensor in the design. For the far future extending of functionalities can be researched: reducing the energy consumption. This is beneficial for the resident (more overcapacity) or for the municipality (smaller and cheaper solar panels). Because of both reason energy reduction is interesting, therefore dimming should be researched further. When dimming is included, motion detection is also necessary in residential streets. The location of the motion sensor, the way luminaires turn on and off and communicate with each other and amount of dimming should be researched.

Include projections in the design that create a cozy atmosphere in the street and that accentuates the characteristics of the street. A second proposal for further research is about atmosphere lighting. In the concept phase, lighting the facade with light lines was included. This turned out to be unrealistic to develop within the time span of this thesis. It could be developed after this project. Questions would be:

- What to project (light lines or other forms, shapes and colors)?
- How to project this?
- Test the influence on atmosphere perception of the projection.

Pilot
The final advise for the municipality is to execute a pilot project. In the evaluation session it was suggested many times, for testing if several requirements are met. The showcase of the ICOR program offers an opportunity for this. The housing cooperation, Woonbron, already agreed to cooperate. During the pilot other parties need to be contacted for cooperation as well:
- Greenchoice could be asked to sponsor solar panels
- Schréder can help with their expertise on LED lenses, they could be asked to develop a new lens
- Because Rotterdam prefers to cooperate with local companies and schools, the Albeda college, could make the aluminum frames needed for the luminaire connection.
- The student project could be carried out by the Hogeschool of Rotterdam.
- CityTec has expertise on installation of lighting points, design and testing of public street lighting. The are an interesting party to contact and ask for cooperation with their expertise and for doing the installation work.

For a pilot project the frame and luminaire connection have to be redesigned. Because the ball-joint luminaire connection turn out not to be strong enough and will suffer from vibrations. Designing a new lens as proposed after the test would be advised as well, in that case the research of the light design is more relevant. The main question in this research is:

The pilot project has several goals:
- Test the electronic circuit: How accurate is the on/off switching system and what is the time range the luminaires switch on and off?
- Research the light design: How much of the light is shining through windows? How do people experience the atmosphere in the street?

With the pilot the concept can be proved and the municipality can add a unique and sustainable, innovative lighting solutions to their project portfolio.

“This design offers a sustainable solution to the municipality: an innovative public street lighting product service system from which all involved stakeholders will benefit.”
15. References


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