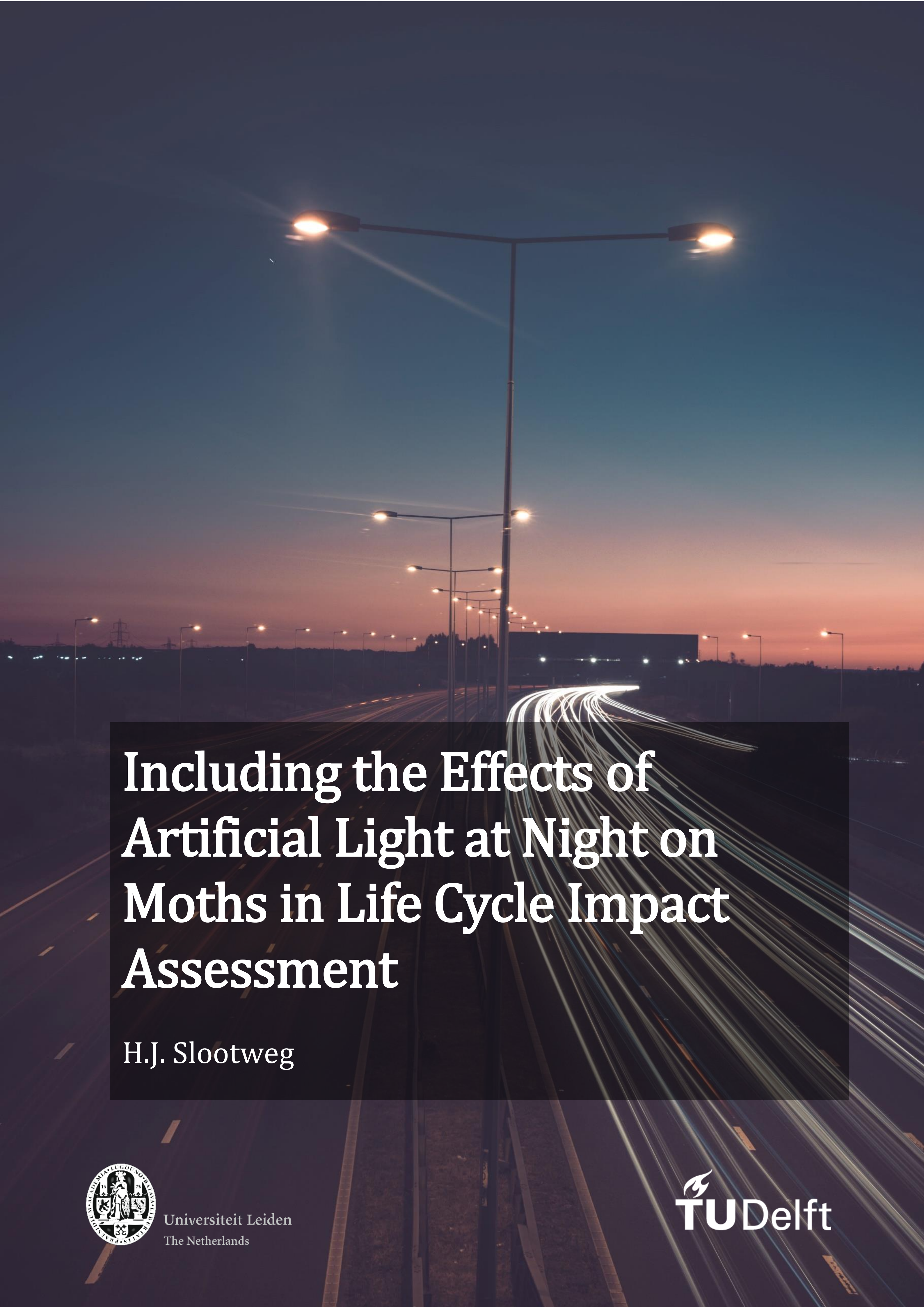

Including the Effects of Artificial Light at Night on Moths in Life Cycle Impact Assessment

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Msc Thesis Industrial Ecology

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These 6 months have been a roller coaster of ups and downs. From the start, this research started very broad by the enormous amount of directions in the field of light pollution and life cycle impact assessment. After consulting a lot of literature, the research started and provided me the knowledge to begin my research. The theoretical background gave me the freedom to gain knowledge to start to build the model and to test the prototype in a given region. Testing the prototype gave me the opportunity to freshen up and develop my skills in the spatial analysis methodology using ArcGIS. Each component of my thesis had its difficulties and challenges, but overall this thesis did go as how I have envisioned it and I am grateful to have been part of the academic research into light pollution and life cycle impact assessment modelling.

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Overall, I am very proud of my accomplishments in this thesis. I have been learning a lot throughout this research. I am pleased to have more insight in this field of research, increased my knowledge even more in spatial analysis and GIS, and eventually learning and practicing more in academic writing.

Content

Abstract

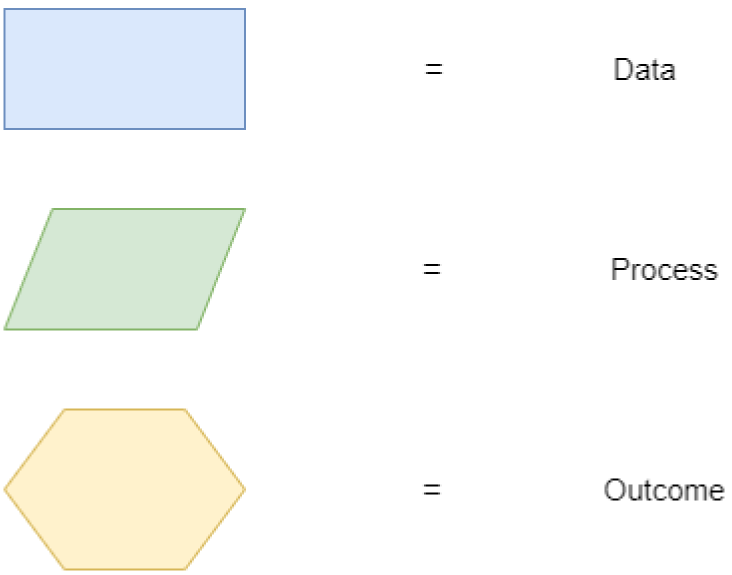
The aim of this research is to implement the effects of artificial light at night on moths in a model that functions as an impact category in the life cycle assessment methodology. The model defines the attraction of moths in a specific region of influence. This attraction might result in multiple direct and indirect effects that could lead to the reduction of moth population, due to an increase in mortality. The region of influence is expressed in square meters and is the area where the intensity of streetlight is higher than the intensity of the background light, which includes the moon- and starlight combined with skyglow of a certain region. The first prototype is tested in two districts of Berlin to demonstrate how the method is used in a region and to show the limitations and the different scenarios per intensity class and mounting height of the streetlight. Practitioners should be able to use this model to implement this in life cycle impact assessment. Weather conditions, moon phase, and skyglow are spatially dependent and should therefore be assessed per region. Including the wavelength of the lamp type of the streetlight and including other objects such as vegetation are seen as limitations in this research and could extent this model by doing further research.

List of Figures

List of Tables

Abbreviations & Symbols

ALAN	=	Artificial Light At Night
HPS	=	High Pressure Sodium
IPCC	=	Intergovernmental Panel on Climate Change
LCA	=	Life Cycle Assessment
LCIA	=	Life Cycle Impact Assessment
LED	=	Light Emitting Diode
MH	=	Metal Halide
SDG	=	Sustainable Development Goals
SSD	=	Species Sensitivity Distribution
UV	=	Ultra Violet



1. Introduction

1.1 Problem Formulation

Life Cycle Assessment (LCA) is used in the academic and business world to assess the whole life cycle of anthropogenic activities and construct an analysis based on the impacts to humans and environment (Guinee, Heijungs 2011). So far, a large body of academic research exists on LCA methods, and companies and consultants apply LCA to asses the impacts of products and services. Each process in a product or service system has products going in and out and raw materials going in and emission going out which are all expressed as a physical entity (Azapagic and Clift 1999). These physical entities are divided into impact categories that would eventually determine the environmental performance of a certain product or service. The goal of LCA is to assess how environmental impactful a product is, compared to other a product performing a similar function in order to support decision-making on the most preferred option.

Examples of traditional environmental stressors is carbon dioxide emitted in the air or phosphorus polluting the water (Acero et al. 2015). These traditional stressor are physical entities that do have a mass (Azapagic and Clift 1999). Since the last decade, researchers consider matter-less stressors, stressors that do not specifically have a defined mass, in the method of Life Cycle Impact Assessment (LCIA) to also account for these extensions in the comparative analysis of products, multiple matter-less stressors, such as land use and noise pollution, are already modelled in LCA or proposed in LCIA (Milà I Canals et al. 2013; Cucurachi 2014). However, other important matter-less stressors may also significantly harm humans and the environment . Yet, they are currently ignored in LCA, since not a lot of research has been carried out in that field of study (Tähkämö 2016). One example is Artificial Light At Night (ALAN). Artificial light is defined as light that is made by humans and used especially during the night. Artificial light is beneficial and necessary for humans, since this provides safety and visibility during dark nights (Haans and de Kort 2012). For example, light is also used in houses, offices and industries for visibility. Thus, artificial lighting is of great significance to contemporary society.

On the other hand, ALAN is damaging the natural environment by distorting the natural daily and seasonal cycle of many organisms and harming entire species, populations and ecosystems (Gaston et al. 2013). A direct effect is that a certain species itself is harmed, but indirectly other species are affected as well since, most species provide a food source or a habitat for others (Macgregor et al. 2015). In particular, moths are being affected by artificial light, since they are the four most species-rich insect species in the world (Merckx and Van Dyck 2019) . Moths are important pollinators and are a big part in the nutrient cycle (Hölker et al. 2010) . Therefore, the loss of species due to the effects of ALAN conflicts more indirect damages to the ecosystem than `just the death of a few moths' (Merckx and Van Dyck 2019).

The vision of this thesis is to have a starting point for the implementation of ALAN into LCIA, which visualises and calculates the attraction of moths by ALAN. It uses an explorative approach to construct a framework that is able to translate the effects of light pollution on a certain species into LCIA and provide a characterisation factor that is used to intensify the emissions modelled in the production system. In order to demonstrate this framework and how ALAN behaves in a specific area, Berlin is used as a case study to see what needs to be assessed in order to fully understand ALAN and its effects in LCIA.

1.2 Relevance

It is of utmost important to include the effects of ALAN in LCIA. For both humans and animal species such as moths. It is showing effects such as the disruption of the natural cycle and even death, if the moths are exposed to ALAN for an extended period of time (Solano Lamphar and Kocifaj 2013). Some evidence that show large exposures to moths is in regions such as the United Kingdom which analyses to see how much effect streetlight has on moths (Macgregor et al. 2017). According to Macgregor et al. (2017) at least half of moths abundance was shown in lit areas and 25% population decrease on the ground compared to the unlit areas. Flight activity is 70% higher in the area of the streetlight. These effects reduce the population of moths and just like they reduce pollination transportation to various of plant species (Hölker et al. 2010). This effect is not only visible in The United Kingdom, but in many parts of the Earth as well. In around 88% of Europe, an increase of 8% of the background night luminosity is seen (Owens and Lewis 2018). According to Owens and Lewis (2018) there is a global increase in brightness of approximately 6% every year. Keeping this trend of increase, the effects on the moths also continue to augment, since more and more moth populations are being affected by the ALAN.

The key issue for ALAN, is that it is particularly important for road transportation, providing visibility and safety throughout the night for amongst others motorized vehicles, cyclists and pedestrians (Haans and de Kort 2012; Pérez-Ocón et al. 2013). Providing safety for transportation helps to sustain the economy by transporting goods and help to improve social sustainability. Yet, light does affect nature negatively as described previously. This is a problem since sustaining safety, streetlight should be kept lit. at the same time artificial light is harmful to species and nature as a whole (Merckx and Van Dyck 2019; Macgregor et al. 2017; van Langevelde et al. 2018). This means that nature needs more natural darkness and lighting but at the same time, stimulating economy and keep safety artificial light is required for safety (Gaston et al. 2013; Haans and de Kort 2012). Therefore, streetlights should be taken into account in LCA and LCIA, to see how far the effects of artificial light on moths reach, from the viewpoint of the transport of a certain product/ service systems. Once the hotspot and amount of effect is known, changes can be made in order to meet both the social and environmental goal requirements. Different policymakers, business people and scientists can combine their knowledge in order to find a solution that balances both goals for humans as well as for the environment.

1.3 Related Work

This research focusses on the area where moths are potentially influenced and likely to be attracted to the artificial light of streetlight in urbanized regions. A lot of research has already been done observing the potential effects of moths and the surroundings. Couple of decades ago, researchers already stated the awareness of an area that potentially attracts moths (Bowden 1982). According to Bowden (1982) This area is determined by the inverse square law and its factors and researched analysed how this contributes to the effect to moths. The research of Bowden (1982) focussed on different lamp types and the radius of influence per lamp type. Also, moonlight and starlight were taken into account. It was concluded that moonlight does influence the radius significantly. Meanwhile, research also obtained results on how moths behave by the intensity of moonlight and at the same time the polarization of moonlight (Yela and Holyoak 1997; Kiss 1979). This shows that the attraction of moths to ALAN is very dependent on the intensity of moonlight and polarization. More recent experimental work supports the conceptual mathematic framework like the work of Bowden (1982). The experiment of Degen et al. (2016) attempted to find the ratio between males and females of multiple moth species. They did not find a significant difference in the attraction to light between males and females, but did specify a radius distance attraction. Other research shows a lower recapture rate at a larger distances from the trap location (Merckx and Slade 2014).

Besides the area of influence, work has been done to analyse the light pollution in cities using satellite imagery and aerial imagery (Cinzano et al. 2001; Falchi et al. 2016; Kuechly et al. 2012). Satellite images were able to capture the artificial light for the entire Earth (Cinzano et al. 2001; Falchi et al. 2016). Aerial imagery is mainly used in smaller areas to capture artificial light in higher resolution. Berlin has been observed by aerial imagery and defines the lit areas as percentage of the total maximum intensity observed by the aerial maps (Kuechly et al. 2012). Another research illustrates a complex model defining the intensity pattern throughout the environment and showing dark and lit locations (Bennie et al. 2014).

The ALAN conference of 2016 started to show awareness of including the mechanics of light from ALAN into LCA (Tähkämö 2016 . It is known that the emissions and maintenance and production of light products are being assessed in LCA. Unfortunately, the direct effects of light on ecosystems, species, and humans are not considered at all. The conference did initiate a raised awareness for the inclusion of the light effects into LCIA. The focus has been more on humans, since the effects on species and ecosystems is still too complex to assess entirely (Tähkämö 2016. Literature research is conducted about evaluating the effects of ALAN on humans. According to Tähkämö (2016) the rhythm circadian disorder, disruption in natural lighting period, could cause cancer, obesity, sleep disorder and other metabolic disorders. The conference did mention that there is currently no approach assessing the effects of ALAN. Yet, impact categories are mentioned and the future plans should be to finalize literature research and state the daily intake to humans from ALAN (Tähkämö 2016). Later on, studies have been done particularly focussing on the effects of ALAN towards rhythm circadian disorder. This research helps to evaluate the impact of light to the end impact on human health. LCA will then assess more than just the energy and material related impacts. Future studies would elaborate more on these effects and eventually implement them in LCIA (Tähkämö et al. 2019). However, it does not include a method that should assess moths as well.

This research supports the body of knowledge by trying to find a methodological approach of assessing the effects of light pollution on moths in LCIA. The research about the inverse square law and the potential area will be used to come up with a method that should be applicable to LCIA and eventually the impact will help assist the LCA. An approach like this would benefit the field of research and take into account, not only the endpoint of human health, but also the endpoint of ecosystem quality. This thesis bases its calculation on relevant technical reports and calculations via software without any field work, in contrast to the field work that underpins more complex yet less widely applicable models.

1.4 Research Questions

To determine the framework of how ALAN is to be assessed within LCIA, the following research question needs to be answered:

"How to translate the characteristics and assessment of the impact of artificial light on nocturnal moths during night time, to life cycle impact assessment?"

The following sub questions are needed to be answered to finally solve a method that functions as a model to implement the effects of light pollution on moths in LCIA.

1. Which life cycle impact assessment framework should be applied to the impact of artificial light on moths?
2. How can artificial light at night be best quantified to capture the effects on ALAN for incorporation in LCIA?

2.1 How should the area of influence be defined?

2.2 How to determine the characterisation factor?

The method of implementing light pollution in LCIA is tested as a prototype on parts of Berlin. It demonstrates the steps and results as they could be presented in the impact assessment part of LCA. How the case study is developed and put into practice is elaborated in the Methods section.

2. Theoretical Background

This section will elaborate on the core concepts needed for understanding the results of this thesis. The concepts are about LCIA, the effects due to attraction of moths from ALAN, attraction factors on moths, and the area of influence. All these concepts are analysed with the use of academic literature and technical reports.

2.1 Life Cycle (Impact) Assessment

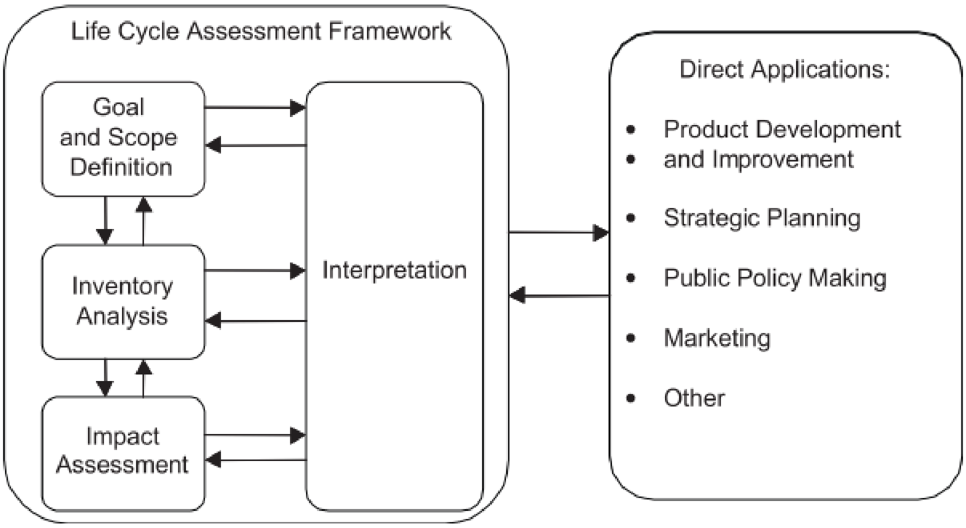


Figure 1 - Life Cycle Assessment Framework (Pennington et al. 2004)

LCA is a method that is used to analyse and assess multiple products and service systems, commonly used in the field of Industrial Ecology. LCA can be used in comparative and absolute modes, but most of the times LCA is used to compare different products with each other and assess each alternative on its ecological performance of its whole life cycle (Guinée et al. 2011). Even though LCA is used quiet common, it still has room for improvement (Koellner et al. 2013). LCA consist of multiple steps before assessing a specific product or service successfully. Figure 1 shows the framework of LCA including the steps required to do an LCA .

The first step of LCA is the 'goal and scope' which motivates why a specific product or system should be compared and analysed. The scope introduces the system boundary, cut off (products which are not considered) and the geographical and technical scope (de Bruijn et al. 2002). According to de Bruijn et al. (2002) the product system consists of processes that include economic flows in and out, such as products. These processes also include the environmental flows in and out, such as raw materials and emissions. All the environmental extensions are in the inventory results section and calculated linearly by its functional unit. These extensions will then be categorized to the impact categories. These impacts can be added manually, or an impact family can be chosen. One of the impact families used in Industrial Ecology department in Leiden is the CML baseline family. This family includes the following impact categories; climate change, acidification, depletion of abiotic resources, ecotoxicity, eutrophication, human toxicity, ozone layer depletion, and photochemical oxidation (Acero et al. 2014).

$$Indicator = \sum_{s} Characterization\ factor(s) * Emission\ Inventory(s) \quad (1)$$

Each impact category consists of multiple indicators assessing the impact, including characterization factors that characterize the extension into a typical impact category (Guinée et al. 2011). Equation 1 shows how an indicator is defined by multiplying the characterization factor with the emission inventory entity. Each characterization factor comes from a mathematical model (Guinée et al. 2011). For example, the impact category of climate change includes multiple extensions with characterization factors that come from the Intergovernmental Panel on Climate Change (IPCC) model (Acero et al. 2014). The impact category results increase linearly with the increase in emissions from the inventory results. The non-generic characterisation factors rely on the following variables (Pennington et al. 2004):

$$Characterization\ Factor_i = \sum_{u} Fate\ Factor_i * Effect\ Factor_i \quad (2)$$

'Fate Factor (FF)' refers to the amount of the change of emission of a certain pollutant substance. 'Effect (EF)' determines the effect of an increased quantity exposed to a given entity in a given time slot of this exposure to the specific entity (Rosenbaum et al. 2007), often characterised by the Species Sensitivity Distribution (SSD). This distribution links the exposure level of a certain toxic substance ('dose') to the effect on a particular species, community or taxonomy. The sensitivity of species can then be described with a certain distribution. SSD is often used in the ecological risk assessment (Posthuma et al. 2001). Equation 2 demonstrates how to calculate a characterization factor for example.

The steps of LCA are all based on mattered physical entities and do not take into account the matter-less stressors besides land use and the proposed noise pollution (Azapagic and Clift 1999; Koellner et al. 2013; Cucurachi 2014) . Land use change is measured by introducing multiple types of land use, such as land use occupation and land use change. These two types have different methods to assess the impact to biodiversity including ecosystem services (Koellner et al. 2013). Within the ReCiPe 2016 family impact assessment, one of the impact midpoint categories is land use (Huijbregts et al. 2017). The meaning of the midpoint category is the land use transformation and occupation, a definition that is non-physical. However, to use this in LCA, a physical entity needs to be related to this non-physical midpoint category. According to Koellner et al. (2013) the unit of land use is therefore defined as m^2 * year annual cropland – equivalent (Koellner et al. 2013). Land use is then accounted as something both physical and measurable, which makes it easier for practitioners of LCA to include this non-physical entity into the LCA model and relate this to the inventory results. For noise impact, Cucurachi (2014) proposed a framework for how sound can be dealt with in the inventory analysis of LCA. Again, this non-matter stressor is also expressed in a mattered entity to make on this matter-less stressor tangible in the life cycle inventory. The proposed unit is therefore expressed in the energy quantity of Joule. This is again measurable for the practitioners to make this implementation feasible in the model.

ALAN is still ignored in this particular method, even though some matter-less stressors are taken into account. ALAN is of utmost importance in the transport sector since vehicles are using the road to go to different destinations. Since LCA is focussed around production systems, transport could be considered a significant part of the production system if a product is transported with trucks. In the ecoinvent database, transport is included and can be used in LCA (Frischknecht et al. 2007). However, it only includes emissions of the vehicle, the building of the road and maintenance. It does not include streetlight, let alone the (negative) impacts to organisms.

2.2 Ecological Effect of ALAN

Light coming from the street is a particularly dominant factor for light pollution (Kuechly et al. 2012) . Still, it benefits humans by enabling visibility in houses, office, industries and on the roads According to Kuechly et al. (2012) streetlight is 31.6% of all the total light observed in Berlin. However, ALAN is not only increasing in urbanized areas (Kuechly et al. 2012). In some protected areas in Europe, Asia, South and Central America, 32-42% have faced an increase in artificial light (Gaston et al. 2015). Moreover, 20% of the total land area of the United States is within 127 meters from a road, which also implies proximity to streetlights (Riitters and Wickham 2003).

Natural light is benefiting nature since the sun is able to give a positive influence to insects for vitality. Sunlight provide a large energy for growth to plants and animals (Gaston et al. 2013). The light from the sun can be used positively as a resource and as an informative entity (Gaston et al. 2013). The energy of sunlight contributes to the photosynthesis of plants, after which it is distributed throughout the whole food web, replenishing a whole ecosystem with energy. Day and night cycles also distinguish the activity cycle of animals and separate species in different time periods. Predators are active in a different time period compared to their prey. This is because of the natural instinct of reducing their competition and risk of being attacked by their predators. Therefore, the day and night cycle separates the predator and prey, automatically reducing the competition for food and also reducing the population of prey (Gaston et al. 2013). Lastly, darkness also facilitates as a recovering process (Gerrish et al. 2009). During night-time, DNA recovers from the over radiation of Ultra Violet (UV) light during the day because of photosynthesis (Cinzano et al. 2001). Furthermore, light also serves as an informational purpose (Gaston et al., 2013). Animals define their perception on different aspects of the environment by following the day and night cycle, seasonal cycle and the lunar cycle. For some animals, light is important for navigation and recognition of certain objects. Not only do species inform themselves visually where to go, they also use light to gain information about temperature, humidity and landscape change, which they can then use predictively. For example, Hatchling turtles use the dark silhouettes of the beach to navigate themselves to the ocean (Longcore & Rich, 2004).

Naturally, sunlight is directly reflected from the moon and defines natural lit and unlit areas. However, artificial light is also lit on top of the natural lit and unlit areas disrupting natural cycles of ecosystems and species (Gaston et al. 2013). 30% – 40% of the insects that are attracted to streetlight die due to predators, dehydration, and exhaustion (Owens and Lewis 2018). For moths it does not matter if their predator bats are around the streetlight, they are still attracted to it (Owens and Lewis 2018). Therefore, using artificial light during night time automatically disturbs and reduces the optimal darkness hours for certain species. This can upset their DNA recovery of UV radiation and their competition for food and predator versus prey division might increase, because the dark night now includes bright artificial light. it is therefore likely to have an increase in food competition and a decrease of the prey population. Moreover, artificial light also disturbs the informative aspect of light (Gaston et al. 2013). Referring to the example of hatchling turtles, artificial light may distort the lunar light and in return, makes it difficult for the young turtles to observe their dark silhouettes (Longcore & Rich, 2004). Hatchling turtles misinterpret the dark silhouettes and cannot find the ocean easily anymore.

A study by Van Geffen et al. (2015) looked into the effects of artificial light on female Mamestra Brassicae Moths (Van Geffen et al. 2015). It turns out that direct contact with artificial light changes their chemical composition, that in return decreases the effect of sex pheromones, reducing the attraction to male moths. According to the research of Van Geffen et al. (2015), 53% of female moths were caught mating in the control environment while an area illuminated with green, white, and red light caught only 13%, 16%, and 28% respectively. This indicates that a reduction of population growth might be possible because of the reduced sex pheromones. Likewise, some species are affected by their visual signals because of ALAN. Some communicate through bioluminescent signals to attract mates (Desouhant et al. 2019). This gets distorted because of the increase of artificial light. Therefore, attraction to artificial light for moths results in a decreasing population (van Langevelde et al. 2011, 2018). The higher the mortality rate, the more population decrease occurs for moths. This would have an effect on other species, since spiders, birds, and bats are highly dependent on moths as a food source. Thus, the reduction of moth population might also reduce the population of other species as well. ALAN could also contribute to a reduction of melatonin in the body and reduce the immune system (Calvo et al. 2013).

ALAN also strongly reduces the fitness and growth of moths. Male moths typically emerged from their pupa within 110 days during nights without any interference from artificial light (Van Geffen et al. 2014). According to Van Geffen et al. (2014) 85% of moths exposed to green light and 83% of moths exposed to white light already emerged from their pupa before 110 days. Although this study turned out to be sex dependent, since this occurred more often in males than in females. It still shows a significant difference between illuminated and non-illuminated areas. Evolving earlier from the pupa indirectly causes a reduction in fitness and therefore reduces mating as well, again stimulating the decrease in population (Van Geffen et al. 2014).

To summarize, the life quality of insects deteriorates as ALAN keeps increasing, due to the increase in traffic and the disruption between darkness and illumination. It has a lot of negative impacts to insects and especially to moths. Insects are attracted to ALAN and therefore face severe problems both directly and indirectly. Attraction to ALAN causes flight-to-light behaviour, which in turn causes exhaustion, resulting into eventual death. Moreover, ALAN also affects sex pheromone reduction resulting a reduction in mating. Other impacts include the reduction of pupa days, growth and fitness.

2.3 ALAN Characteristics

Light can be analysed by looking at the time of the day, the spectral composition of light or the intensity of light, each contributing to the effect of light pollution to nature (Gaston et al. 2013).

2.3.1 Spectral Composition

Throughout the years, streetlight has changed tremendously and effectively attract more insects by introducing the state of the art Light-Emitting Diode (LED) (Wakefield et al. 2018). It first started with the incandescent and mercury vapour street light in the 20th century. Later, the low-pressure sodium (LPS) and high-pressure sodium (HPS) replaced these models. Currently, most streetlights use Metal Hallide (MH) and energy-saving LED. LED emits a broad-spectrum range of wavelengths and most of all, short wavelengths containing UV radiation. The UV radiation attracts a lot of insects (Shimoda and Honda 2013) and therefore, the consequences of installing LEDs is saving energy but at the same time attracting more insects to the lights, which results into a negative biodiversity impact (Wakefield et al. 2018). Figure 2 is showing the different lamp types and their wavelength peak in the radiance spectrum.

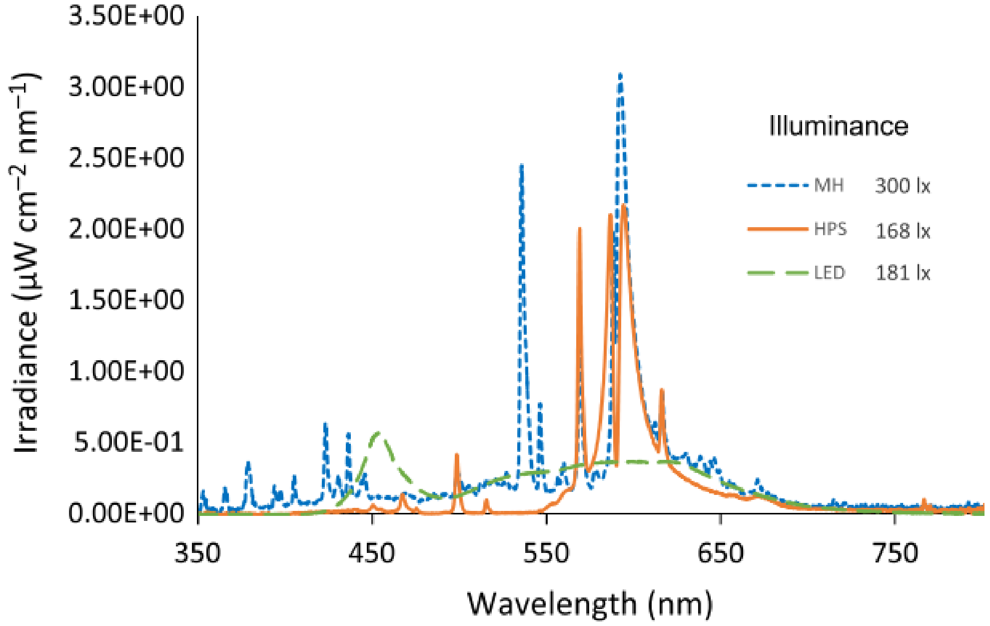


Figure 2 - Spectral composition of MH, HPS, and LED (Wakefield et al. 2018)

Most of the insects are attracted more to broad-spectrum light sources than long-wavelength light sources (Somers-Yeates et al. 2013). Moths in particular are attracted more to shorter wavelengths in the range of UV radiation and blue light in the visible range. The peak wavelengths of attraction for moths is around 400 nm (Longcore et al. 2015). In contrast, houseflies are more attracted in the green and red visibility wavelength region. This concludes that the wavelength of light does contribute to the attraction of an insect to a specific light source. Which wavelength range has the highest attractiveness really depends on the species.

2.3.2 Intensity

The intensity of light is the number of photons that travel to a specific location and the more photons are carried away, the higher the intensity is. The number of photons per square meter is defined as lux and as shown in table 1, sunlight contains the highest intensity. Moths, as well as many other insects, are attracted by the moon for navigational reasons (Gaston et al. 2013). They fly towards the light of the moon and the position of the moon in the sky helps them navigate through the night. Yet, insects are also attracted to artificial light since they confuse this with moonlight (Gaston et al. 2013).

Table 1 shows a clear difference between a full moon and clear starry night, compared to an average street light illuminance. It shows that the streetlight is far more illuminated than a regular full moon night. Space is therefore important to identify the amount of light pollution or the magnitude of effect on a certain species. The effect depends on the species in question. But overall, moths are more strongly attracted to streetlight, because they confuse it with the moon (Gaston et al. 2013). Other species can be also attracted to streetlight or other artificial light sources.

More artificial light is present in urban regions, compared to rural areas. Moreover, it depends on how the urban area is divided. It is possible that more industry is present in one urban area compared to the other.

Table 1 - Lux values for different weather conditions and day and night-time (Gaston et al. 2013).

Type	Lux
Full Sunlight	103000
Partly Sunny	50000
Cloudy day	1000-10,000
Full moon under clear conditions	0.1-0.3
Quarter moon	0.01 – 0.03
Clear starry night	0.001
Overcast night sky	0.00003 – 0.0001
Operating table	18000
Bright office	400 – 600
Most homes	100 – 300
Main road street lighting (average street level illuminance)	15
Lighted parking lot	10
Residential side street	5
Urban Skyglow	0.15

2.3.3 Time of the Day

The time of day determines the lux value of the streetlight significantly. The evening and morning have a far higher luminosity from the moonlight and sunlight together and reduces the effect of the intensity of artificial light. This is more related to intensity of the time-dependent streetlight. Time includes also adaptive and dimmable lighting. This makes a distinction between continuous and periodically emission of light. The periodically on and off or dimmable intensity of light is not thoroughly researched yet of what the effects might have.

Figure 3 shows the intensity of light from afternoon until midnight. At 15:30 the intensity is at its highest showing 207 lux. During midnight the intensity is reduced tremendously, only relying on moonlight and skyglow from cities. First of all, both dawn and dusk already show some darkness, but not enough to clearly see the full skyglow. Furthermore, during dusk and dawn there might be more skyglow since in the evening and morning more buildings are active and have therefore more luminance compared to the night. However, this would only become interesting when the whole evening, night and morning are fully dark, but this is not the case. Dusk and dawn do have a strong interference during night-time as can be seen in figure 4 by the two graphs of the urban and rural region (Gaston et al. 2013; Kyba et al. 2011).

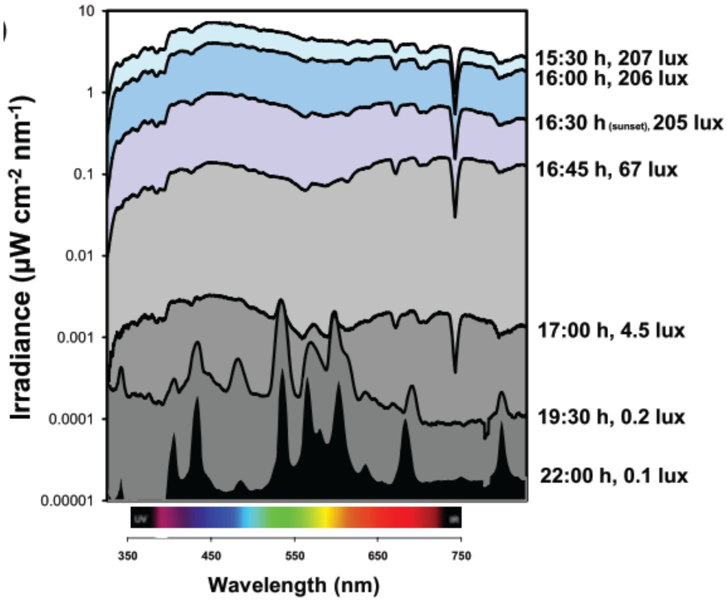


Figure 3 - Visible spectrum of the EM spectrum (Gaston et al. 2013)

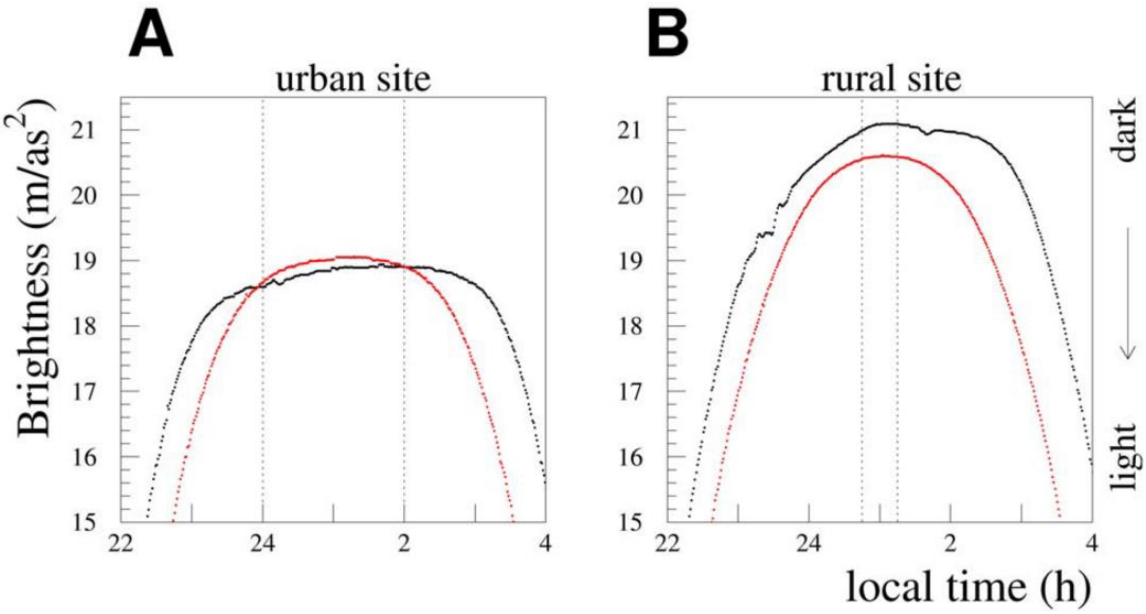


Figure 4 - Luminosity in magnitudes through the night in Berlin in the night of June 16-7 (red) and July 20-21 (black) (Kyba et al. 2011).

In this case, during the evening and the morning, the background light is much higher compared to the night. During dusk and dawn the sunlight of the day does still interfere and therefore shows a higher luminosity. During these hours, the region of influence is much smaller compared to the region of influence during night time. Therefore, if time would be included for the region of influence, not only would background light change, but also the region of influence (Bowden 1982). This would then reduce the area of exposure throughout the night.

2.3 Moth Attraction Factors

There are multiple factors that contribute the attraction of moths and influence their population size. The main factors are moonlight, temperature, weather, vegetation and other artificial light sources. Below are the factors described more in detail in what kind of influence they have towards the population and behaviour of moths.

Moonlight – According to Yela and Holyoak (1997) the number of individual moths caught in a light trap were negatively correlated with the percentage of moon surface being illuminated to the Earth (Yela and Holyoak 1997). The moonlight factor is considered to go into two directions. It is either a factor that describes the general population dynamics of moths, or it competes as an ambient background light to streetlights and therefore attract less moths. Moonlight reflects sunlight back to the Earth and lights up the night. In general, full moon attracts fewer moths (Bowden and Morris 1975) . One may ask: `What causes the reduction in attraction for these moths during full moon?' It has been argued that moonlight competes with the luminosity of streetlight and therefore, the intensity of streetlight decreases (Bowden 1982). The general trend shows that a lower intensity also reduces the attraction of moths. The intensity of the street light becomes smaller, since the background light (reference point) increases (Bowden and Morris 1973). Moonlight depends on the phase of the moon. Each phase has a different value of moonlight being visible on the Earth, since the phase depends on the amount of sunlight being reflected from the moon (Bowden 1982).

Another fact to take into consideration, is that moths navigate using moonlight (Gaston et al. 2013). As previously described, light functions as a navigational tool, where insects use their photoreceptors to navigate through the environment. Yet, not all moonlight helps them to navigate and in essence it is shown that more polarized light attracts more moths. Moths are attracted more to polarized light and therefore attracted more to the first and fourth quarter of the moon cycle were polarization is peaked, compared to the a full moon, when there is no polarization and therefore less attraction of moths (Nowinszky and Puskás 2012).

Other artificial light sources – Streetlight is mostly found next to the street and most of the streets are located in urban regions consisting of other artificial light sources, such as houses, offices, and industry. Streetlight that is close to a very illuminated area causes its own effect to be lower, as the streetlight is relatively less bright in an illuminated environment. The ambient light of the surrounding environment competes with the illumination of the streetlight (Yela and Holyoak 1997). Other artificial light sources might be in different shapes and sizes that moths might not even be attracted to. Yet, artificial light might light up the background ambient, automatically reducing the relative luminosity of the individual streetlight, which in return reduces the effectiveness radius of attracting of moths (Bowden and Morris 1975).

Temperature – Temperature rise correlates positively with the capturing of moths (Williams 1940). According to Williams (1940) the capturing of moths doubled with a rise of 2.8 degrees Celsius. During summer months with higher temperatures, moths develop around three generations whilst during winter their growth stops to conserve their energy (Crozier and Dwyer 2006). Yet, this does not necessarily mean that population continuously keeps rising. The balance is restored since the survival rate during winter is far lower compared to the summer, which indicates that the annual average of population remains the same (Crozier and Dwyer 2006).

Weather - The weather influences whether the ambient light from the moon is transmitted on Earth or whether artificial light is reflected on clouds back to the ground (Yela and Holyoak 1997). It is shown that 1.5-2.3 times more noctuid moths were captured in light traps when the sky was cloudy compared to a clear sky (Yela and Holyoak 1997). A cloudy night would reduce the ambient light and therefore competes less with the artificial light coming from the street. Furthermore, precipitation also determines the attractiveness of moths. Wet seasons attract more moths than dry seasons (Guedes et al. 2000). At the same time, temperature does decrease due to the rainfall, but a combination of a wet and hot season is likely to attract most of these moths. The reason wet seasons does the trick is because of the availability of food resources. At the same time, more food resources also bring more richness of moths. For example, *G. unipennaria* has a more fluctuating relation with rainfall and humidity and less of a particular relation to temperature, because their pupation occurs in the soil (Guedes et al. 2000).

Vegetation – The vegetation surrounding the light pollution also influences the impact on insects. According to (Merckx and Slade 2014) the recapture rate of moths is higher in woodland areas than in open field areas. The method of mark-release and recapture determines the amount of moths being recaptured for multiple different streetlight located in woodland areas and open fields. The results of Merckx and Slade (2014) show that there was a higher recapture rate for woodland than for open field, namely a 7.5% recapture rate for woodland and 1.1% for open field area. Reasoning for this difference is the temperature being 1.3 degrees Celsius lower in open areas, attracting less moths. Skyglow is much more visible and present in the open field, reducing the efficiency of the light-trap.

2.5 Area of Influence

For many decades, light-traps for catching insects are utilised to determine the population and distribution of species in specific locations for research (Plummer et al. 2016; Degen et al. 2016; Wakefield et al. 2018). Light traps are commonly used to assess how many moths are located in a specific area. For example, one research project used light traps to evaluate the population of moths in fragmented forests compared to agricultural habitat (Ricketts et al. 2001).

Previous studies already stated that light behaves according to the inverse square law and therefore makes a good estimation of how light intensity might influence the effect of light towards insects, including moths (Bowden 1982). In order to define the area of influence, distance can be acknowledged by determining when the light from the streetlight equals the background light. In return it can show the performance of light trap, or in this case how big the area of influence is for the insects (Bowden and Morris 1975). According to the article of Bowden and Morris (1975), moonlight does affect the size of how large the radius of the area of influence. Bowden and Morris (1973) state that the catching of moths during full moon is much smaller compared to catchment during New Moon. This makes sense because background light during a New Moon is lower compared to a Full Moon. The radius is automatically larger following the inverse square law.

Equation 3 shows how the inverse square law works. L stands for the luminosity at a given distance. This distance is given as d. so in order to calculate the intensity of luminosity in lux, L_0, the intensity from the point source, divided by the distance squared.

$$L = \frac{L_0}{d^2} \tag{3}$$

3. Methodology

This section describes the methods used for answering the sub questions explained in the introduction chapter. The first question: 'Which life cycle impact assessment framework should be applied to the impact of artificial light of nocturnal moths?' will be explained in chapter 3.1. This chapter covers the reasons why this framework has been chosen and which main components need to be answered for a framework for light pollution. The second sub question 'How can artificial light at night be best quantified to capture the effects to moths for incorporation in LCIA?' is sub divided in 2.1 'How should the area of influence be defined' and 2.2 'How to determine the characterisation factors?'. Sub question 2.1 is answered in chapter 3.2 'Calculation of the Area of Influence'. Sub question 2.2 is answered in the chapter 3.3 'Determine the characterisation factor'. The answer of these two questions will answer the second sub question of how to quantify ALAN in LCIA.

The assessment on streetlight, background light, and roads is applied to Berlin as a case study to demonstrate the prototype of a model for LCIA. Berlin is chosen since it has often been the topic of research concerning light pollution including satellite imagery (Falchi et al. 2016) and aerial survey of light pollution (Kuechly et al. 2012). Additionally, Germany includes a well-developed weighting system to classify roads into required intensity per streetlight pole (Stockmar 2018).

After assessing all the roads in Berlin using the method of 3.2.2, two districts are chosen to clarify how ALAN behaves with the different streetlight heights and intensity classes. The level of 'districts' is chosen, since the analysis of the area of influence is very computationally intensive and this research only develops the first approach to a model and not a full analysis on the whole city of Berlin. Kreuzberg is chosen since this district is close to the centre of Berlin and has the skyglow value determined earlier. Tiergarten is next to Kreuzberg and is chosen because it contains a park and includes the M6 class, which Kreuzberg is missing.

3.1 Framework Assessment

The LCIA framework for light pollution is taken from the methodology of LC-impact.eu. Its aim is to provide a global and general LCIA method in three categories; human health, ecosystem quality, and resources (LC-Impact 2019) . This framework is used to substitute the light pollution concepts in the different parts of this framework to provide a general overview of what needs to be included in LCIA. It is chosen since this provide a fully operational structure for LCIA models including spatial models as well (LC-Impact 2019).

The main components of LC-impact is; cause-effect pathway, modelling approach, value choices, spatial variability, characterisation factors.. Chapter 3.2 describes the methods and steps used to identify the area of influence and 3.3 presents the calculations needed to specify the translation from final result to a characterisation factor (LC-Impact 2019).

3.2 Area of Influence

To measure the attraction of moths to streetlight, the area of influence is going to be defined in this research. The area of influence is defined by the area around the streetlight where the intensity of the streetlight is higher than the background light. to define this area, background light, intensity of streetlight, and the steps for calculating the area must be defined.

3.2.1 Background Light Assessment

There are many external factors that determine the attraction of moths, but the essential factors for the area of influence are moonlight, starlight and skyglow. Other factors that contribute to the attraction and increase of moth population will be neglected from this research. These are amongst others; precipitation, temperature, and vegetation. These factors contribute to the population distribution of moths in a specific area. Moths in urban regions have a fairly homogeneous distribution and therefore the factors that change distribution are neglected in this research (Degen et al. 2016; Merckx and Dyck 2019). The moonlight phases, including phase-dependent luminosity, are taken from (Kiss 1979). The moonlight cloud coverage transmission is taken from the article of (Bowden 1982) and the cloud amplification originates from (Kyba et al. 2011). The starlight is taken from (Gaston et al. 2013). These values are multiplied by the cloud formation transmission factor, visible in the table below. The lux value for the moonlight during clear sky is 0.25 lux, for starlight the clear sky value is 0.001 lux and skyglow has a lux value of 0.00374 lux.

Table 2 - Different weather categories and their transmission factors for moonlight and starlight(Bowden 1982).

category	transmission factor
1	1
2	0.8
3	0.75
4	0.7
5	0.6
6	0.47
7	0.35
8	0.21
9	0.17
10	0.1

Table 2 shows 10 categories evaluating different cloud formations and the percentage of lux being transmitted. According to these categories, a clear sky has a transmission factor of one, meaning that all moonlight is transmitted to the Earth's surface. Cloud formation within category 10 means that the sky consists of heavy thunderclouds. Then, the actual intensity of moonlight and starlight is 10% of the value during clear sky. The following equation calculates the amount of moonlight and starlight reaching Earth. Equation 4 describes the relation of moonlight and starlight with the transmission factor and what eventually the total luminosity of the sky is.

$$L_{sky} = (Moon_{clearsky} + Star_{clearsky}) * f_{trans} \quad (4)$$

Table 3 - Okta's and its definition (Kyba et al. 2011).

Okta	Category
0	Fine clouds/ clear sky
1	Fine clouds
2	Fine clouds
3	Partly Cloudy
4	Partly Cloudy
5	Partly Cloudy
6	Cloudy
7	Cloudy
8	Overcast
(9)	Overcast + more

The research of (Kyba et al. 2011) measures the amplification of clouds in accordance with the Okta categorization (amount of clouds coverage in the sky) and the distinction between rural and urban areas in Berlin. The following table shows the cloud amplification in Berlin during the night:

Table 4 - Amplification of cloud cover in Berlin (Kyba et al. 2011)

Oktas	0	1	2	3	4	5	6	7	8
Rural (mag/arcsec^2)	21.0	20.8	20.7	20.9	/	20.5	20.4	20.1	19.9
Urban(mag/arcsec^2)	19.0	18.9	18.7	18.7	/	18.3	17.8	17.0	16.5
Rural amplification	1	1.2	1.3	1.1	/	1.5	1.7	2.3	2.8
Urban amplification	1	1.1	1.3	1.3	/	2.0	3.1	6.1	10.1

In order to determine the final lux value over Berlin, the clear sky skyglow lux value must be multiplied with the urban amplification factor shown in Table 4 according to the right Okta category in Table 3. A clear sky means that there is no amplification of the skyglow because the amplification factor is 1 and therefore the skyglow value remains the same. If the sky would be overcast, then the amplification for urban would be 10.1, meaning that it amplifies with the skyglow value from a clear sky by 10.1. The total skyglow including the urban, rural and weather factor is given in equation 5.

$$L_{Skyglow} = L_{skyglowclear} * f_{amp} \quad (5)$$

The total background light is the combination of moonlight and skyglow together is presented in equation 6.

$$L_{Background} = L_{Skyglow} + L_{sky} \quad (6)$$

3.2.2 Streetlight Source Assessment

Besides the background light, an assessment for streetlight needs to be done to define the intensity from the streetlight itself. The European Union of Region Development has set some standard rules applied to Central Europe for guidance of the intensity of streetlight per road type (European Committee for Standardization 2020). A set of standard rules and specifications are set for how public light should perform in order to maintain the safety of vehicles and pedestrians, provide energy efficiency and take into account the environment (Stockmar 2018). This guideline for determining which street light intensity to use is chosen because this method and approach will be eventually tested in Berlin and it is therefore necessary to use standard rules and parameters that are applicable in Berlin as well. Public lighting needs to fulfil different variables to determine where and how much light is needed. The main variables are traffic speed, traffic composition and variety, traffic volume, separation of directional lanes, parked vehicles, road guidance and ambient lighting (Stockmar 2018). Furthermore, public lighting also depends on the weather. A distinction is sometimes made between dry roads and wet roads. There are different classes that describe situations when specific classes of light should be used.

Numerous parameters are needed to calibrate the amount of luminosity needed for a particular situation on the ground. The illuminance on the ground depends on the mounting height of the streetlight and the type of road the streetlight is installed on. The streetlight on roads designed for motorized vehicles or a mixture of traffic including motorized vehicles is classified as 6 M categories, each one determining the lux value on the ground (Stockmar 2018). See table 5 for the different M classes together with the road surface luminosity requirement. Table 6 consists of these parameters that will determine which M class the streetlight needs to have. In order to do so, first the road needs to be classified in a particular M class. Focussing on the transportation sector in LCIA, streetlight is the most important light pollution source and therefore makes the M class highly important to analyse. Streets in Berlin have the largest area and impact from light pollution compared to other factors such as industrial or public service locations (Kuechly et al. 2012). Hence, this research focusses mainly on the M class, since it covers all the roads used for transporting goods such as trucks. Other classes are neglected in this research.

Table 5 - Lighting class M (Stockmar 2018)

Lighting class	Road surface luminance in lux
M1	2.00
M2	1.50
M3	1.00
M4	0.75
M5	0.50
M6	0.30

Table 6 - Parameter weighting road type Berlin (Stockmar 2018)

Parameter	Options	Weighting (W)
Speed	>50 km/h	1
	=< 50 km/h	0
Separation of the directional lanes	No	1
	Yes	0
amount of traffic	Normal	0
	Low	-1
Mode of transport composition	mixed, high, not motorized	2
	Mixed	1
	Only motorized vehicles	0
Luminance of the environment	high	1
	Middle	0
	Low	-1
Parked vehicles	allowed	1
	Not allowed	0
Increased requirements	Available	1
	Not available	0
		Sum of W
		Lighting class M = 6 - W

The road type set by The European Committee of Standardization is used to distinguish the roads in the 6 M classes, in order to identify which intensity of the streetlight should be implemented to which roads and location. Both the parameter weighting by the European Committee of Standardization itself and the proposed scheme of Germany is used in this research. The proposed version of Germany is used to identify the M classes, see table 6, while the one from the European Committee itself is used to clarify the parameters with some explanation (Appendix B). The M classes for all the roads in Berlin have been adjusted to the data from the table provided by the European committee of Standardization and the open source wiki data. Traffic speed data originates from the Berlin open data source. The other parameters besides traffic speed such as separation of lanes, amount of traffic, mode of transport composition, luminance of the environment, parked vehicles, and increased requirements are taken from several literature sources.

A distinction in the dataset is made in the form of motorways, primary, secondary and tertiary roads. This road selection is done by python (Spyder 3.3.6) and this script is used in 'selecting of attributes' in ArcGIS. Motorways are considered to be large roads that have separation of directional lanes, mostly with low luminance since there is no large ambient light source from city centres. Only motorized vehicles are present on the road and no parked cars are allowed (Openstreet map Wiki 2020a). Primary roads are important large roads designed for only motorized vehicles (Openstreet map Wiki 2020b). Primary roads are usually not separated. The other parameters besides traffic speed and separation of lanes are practically the same as the motorway, only the luminosity differs, since it connects larger towns, the luminosity is assumed to be medium illuminated (Openstreet map Wiki 2020b). Secondary roads are connecting national roads and are a just under the primary roads. These roads do often have a separation in directional lanes. Also, since secondary roads are often passing through cities and towns, these roads frequently deal with crossing pedestrians and bikes next to the roads and traffic lights, so therefore this road type has a mixed composition of traffic (Openstreet map Wiki 2020c). Tertiary roads are small local roads connecting local parts of towns and cities or centres and shops (Openstreet map Wiki 2020d). The traffic is mostly low on this road type. No lane separation is assumed here, just like mixed vehicles, low traffic, high luminance and parked cars on the side of the street (Openstreet map Wiki 2020d). See appendix B, table B.2 for evaluating the check list of parameters. Track roads are mostly unpaved roads connecting agricultural areas. Therefore, a mixture of traffic is allowed, including parked vehicles (Openstreet map Wiki 2020e). Even though there are no specific parking spaces designed next to these roads, still it is possible and allowed. Furthermore, the ambient light is low and there are no roads signs available.

Besides these main roads there are multiple other roads that link the main roads. These linking roads are called 'secondary_link', 'motorway_link', 'primary_link', and 'tertiary_link'. Since these linking roads are not very long, the assumption is made that they do not deviate from the main secondary road. Roads such as bridle path, pedestrian, footpath, service and bicycle paths are not included since the focus is on the M classes, which only consider roads that are either only motorized vehicles or a mixture that includes motorized vehicles.

Lastly, the mounting height needs to be determined in order to clarify how much lux the streetlight contains. The mounting height is from the technical report of premium light pro, funded by the European Union (Premium Light Pro 2017). The mounting height differs a lot per different road type or utilisation. Normally footpaths and bicycle paths require a mounting height between 4.5 – 6 meters, whereas 8-10 meters is required in residential and commercial areas and 10 – 12 meters is used in wider streets of commercial and industrial areas (Global Designing Cities Initiative). Since the information on mounting height is not specifically given in the datasets used, multiple mounting heights are used to test the difference, namely 4, 6, 8 and 10 meters.

3.2.3 Area of Influence Radius

The assessment of the characteristics of artificial light and the background light influencing the streetlights light is done in R studio 1.1.456. Spatial analysis is done with ArcGIS 10.7.1.

The distance of influence is the radius of the region of influence by using the inverse square law principle together with the lux value of the M class and background light. This analysis is based on the area of influence considering a circle of the horizontal plane of each streetlight (top view). To calculate the radius, the background light is determined by summing the moonlight, starlight and skyglow value. Equation 7 shows the inverse square law principle together with the background light and light from the streetlight.

$$d = \sqrt{\frac{L_0}{L_{background}}} + 1 \qquad (7)$$

L_0 is the lux value from 1 meter distance of the streetlight. this depends on the mounting height and the ground lux requirement coming from the M class. To calculate back to the 1 meter distance of the streetlight is again using the inverse square law. Equation 8 demonstrates how to calculate.

$$L_0 = L_{ground} * d^2_{mountingheight} \quad (8)$$

After the radius is determined, the total area of influence per streetlight is determined as the area of a circle, shown in equation 9.

$$A = \pi * d^2 \quad (9)$$

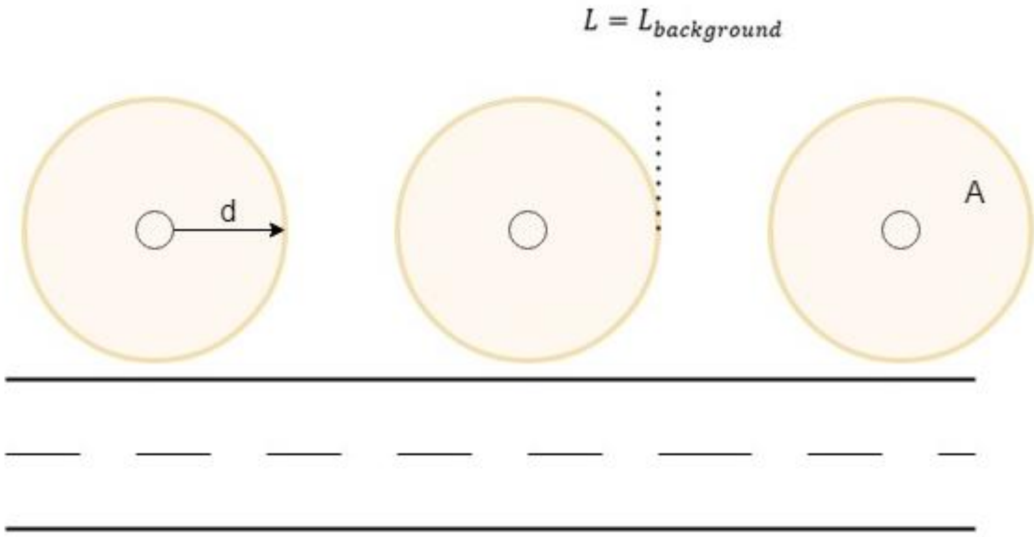


Figure 5 - Overview of calculating the area of influence

Figure 5 shows a small overview of what is eventually meant by the area of influence. This image is a top view of a road with three streetlights. The streetlights are indicated as the three small circles. The area of influence is shown as the larger circle surrounding the small circle. The streetlight on the left demonstrates what is meant by the distance. 'd' is defined as the radius of the large circle. The middle circle shows why 'd' stops as a certain point. This point is when the luminosity of the streetlight equals the background light. and lastly, the circle at the right described the area of influence shown as 'A'.

The classification of streetlight luminosity together with the background light should be enough to determine the total area of influence per streetlight. In appendix D the R code is shown where these parameters are combined into equations that give the radius of influence for a specific background light value and streetlight lux value.

3.2.4 Final Calculation of Area of Influence

Once the radius is determined the area is established by using the tool 'buffer' in ArcMap. For each streetlight point on the map, a buffer analysis can be used to determine the area of influence of each streetlight. Therefore, equation 9 is done by the buffer tool. The buffer tool is used for each streetlight alongside the road that a truck drives through for the transportation of products. The 'select by location' tool makes a selection of the streetlights alongside the selected road, within a distance of 10 meters. The same tool is applied for buildings, set within a distance of 50 meters from the road.

Furthermore, the height of the buildings is calculated by assuming an average floor height of 2.5 meters (BRIS bouwbesluit 2003). The dataset of the buildings in Berlin does contain the number of upper floors per building. Using this dataset, the following equation is applied to the height to the buildings:

$$Height = 2.5 + (2.5 * \ upperfloors) \qquad (10)$$

The analysis in ArcGIS is used to determine the constraints that occur during the calculation of the region of influence such as the interferences of streetlight with each other and objects such as buildings. The interference of streetlight is not taken into account in the final results, but a first order approach is shown in the result section. The buildings surrounding the region of influence constrain the area and therefore also need to be taken into account. First, Viewshed is used to check the visibility. The visibility in this case is defined as how far the light from the horizontal plane illuminates the air. The assumption is made that no light penetrates through houses and the reflection of light from buildings is ignored. The region of influence is defined as buffers around each streetlight. The radius of this buffer is determined by the distance the light needs to travel before it equals the background light.

In this research, all the roads of Berlin are categorized in the 6 M class categories by 'selecting features' and defining each street with parameters to assess the kind of streetlight intensity it actually needs. Some roads require more luminosity than presented in the M classes because of conflict areas such as cross overs with pedestrians and cyclists. However, the luminosity of the streetlight is sufficiently generalized for the purpose of this study. The roads and streetlights are selected by location of the chosen district. The districts that are chosen are Kreuzberg and Tiergarten. Both roads and streetlight intersecting with the polygon of the district are selected. The raster data of the height of the buildings is clipped according to the polygon of the selected district.

Again, the selection of streetlight that falls within 10 meters from the road class is used to attribute six different streetlight types for each class. Each streetlight point has a buffer around it, which is adjusted to the lux value and the mounting height of the streetlight. If there are multiple different classes in one district, the buffers are first 'merged' and then 'dissolved' to create one larger polygon.

Subsequently, a new field is added to the buffer, named 'value' with the number 100. This polygon is transformed into raster with the same cell size as from the viewshed raster. The viewshed is subdivided between not visible (1) and visible (2). Using the tool 'raster calculator', the two rasters are summed. This gives a distinction between the values 101 and 102. 102 is the summation of the value 100 from the buffer raster and 2 of the visible part from the viewshed raster. In the statistics, the count is the number of cells that intersect with each other. These cells are multiplied by the area of one single cell to determine the area in square meters. The count of 102 cells is the total area that influences the moths, since this is the intersection between the visible part and the buffer part.

3.3 Characterisation Factors Determination

The final step in the framework of LC-impact is the characterisation factor. It is needed to cover the impact from a specific product chain or service chain This research focusses on transport and streetlight and therefore the final result is linked to the transport section of a product- or service system. The characterisation factor connects the inventory table results with the final impact assessment results. Equation 11 presents the relation between these two parts.

$$IndicatorResult_{cat} = \sum_{subs} CharFact_{cat,subs} * InventoryResult_{subs} \tag{11}$$

The indicator in the impact assessment is defined by multiplying a characterisation factor with the amount of substance in the inventory results. The indicator is then a quantifiable representation of the impact category (de Bruijn et al. 2002). This equation is essential to determine light pollution in LCA. It determines the light pollution effect to moths using the transportation values in the inventory results, multiplied by the given characterisation factor. Figure 6 presents an overview of the methodology described in this chapter. The blue boxes give the data needed to get the results. The green boxes are the processes and calculations needed to eventually provide the results given in the yellow boxes.

3.4 Case Study Data

To test the method developed in the previous section, the districts Kreuzberg and Tiergarten from the city of Berlin are used as a case study. In order to test this prototype, some data is needed in order to perform the analysis. The data that is essential in this research is streetlight location, buildings, roads, and districts. Table 7 summarizes all the datasets needed for the case study in order to assess light pollution in LCIA.

The table below shows the datasets used for this case study including a description and source. The OpenStreetMap of roads of Brandenburg is updated daily. It is essential to know that this dataset is obtained on the 30th of April 2020. Results might deviate when downloading the data on a different date, since the dataset is updated regularly.

All these datasets are used to calculate the radius of influence following the methodological steps of 3.2. 'Ortsteile' is used to locate the districts and determine their total area. Subsequently, the area per M class can be calculated and compared with the total area of the district. This result can be expressed in percentages. A more detailed flow chart of all the steps that have been taken in ArcGIS 10 for the region of Berlin and the districts Kreuzberg and Tiergarten can be found in Appendix A.

Table 7 - Dataset and source of case study Berlin

Dataset	Data Features	Source
Openstreetmap: roads (Brandenburg)	Speed limit, direction of lanes, and the type of road (motorized or not, highway, primary, secondary, and tertiary) in Brandenburg and Berlin.	(Geofabrik downloads 2020)
Strassenbeleuchtung Berlin	Location and the reference number of streetlights.	(ESRI - Deutschland 2019a)
'Gebäude Berlin'	Type of building, number of upper and basement floors, and the area per building in square meters of all buildings in Berlin	(ESRI - Deutschland 2019b)
'Ortsteile Berlin'	Berlin district borders, name and area.	(ESRI - Deutschland 2018)

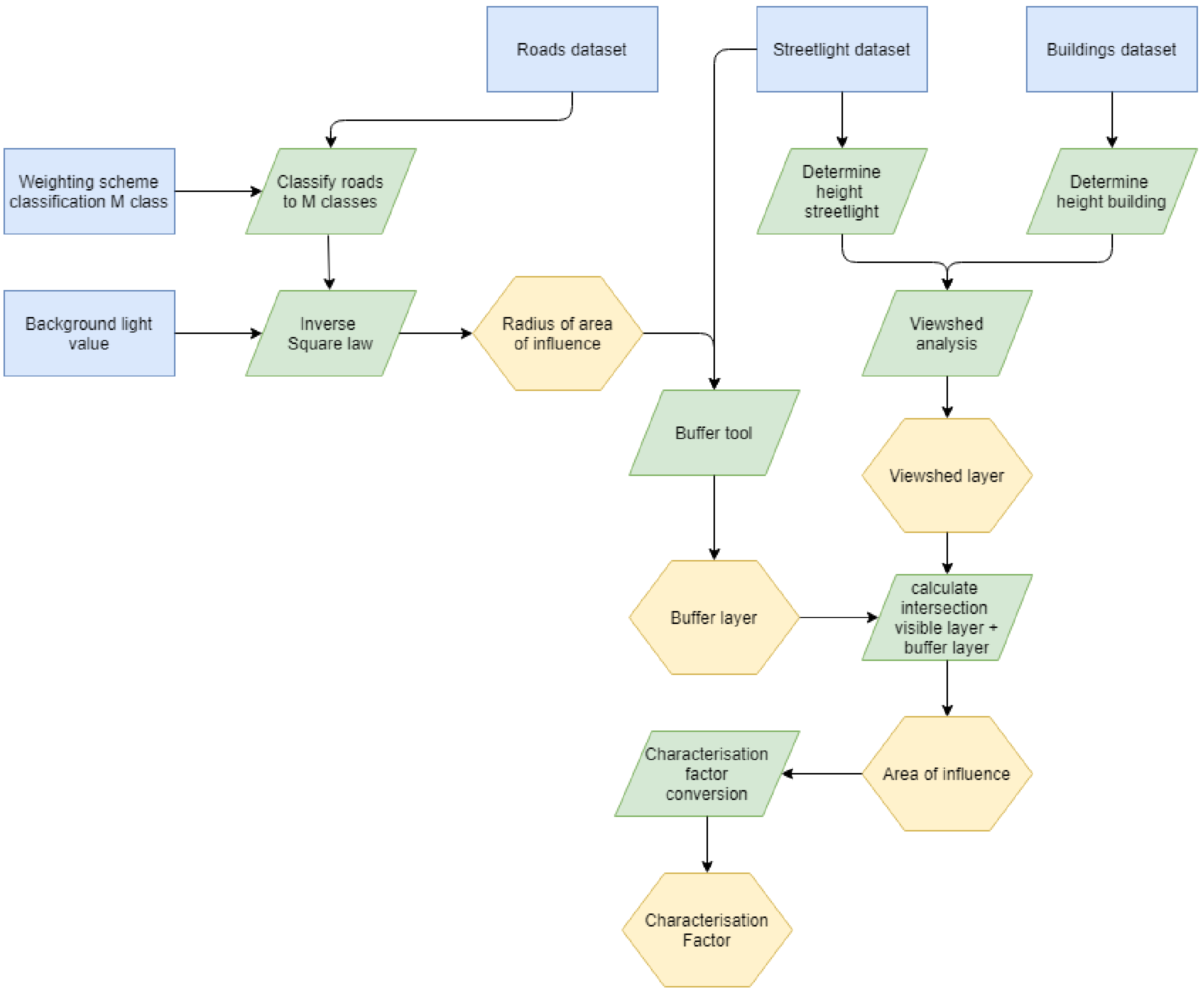


Figure 6 - Flow diagram of spatial analysis in ArcGIS

4. Results

The results consist of two parts. The first part explains the framework of including artificial light in LCIA. The proposed option of calculating the area of influence is then used in the second part by using the prototype in a case study. This case study then explains what needs to be done before the area of influence can be calculated and analyzed.

4.1 Framework for including Artificial Light Impact in LCIA

In order to assess the effect of artificial street light on moths in the production chain, light pollution needs to be implemented in the life cycle impact assessment model.

Cause and effect pathway

Both Humans and Ecosystems are affected by light by disorder the biological cycle in the body. This research takes the effect pathway that is for how the impacts are beneficial to humans and damaging to ecosystems. Figure 7 shows the cause and effect pathway. This diagram shows only the positive note for light to humans and the negative impact to ecosystems, but this is what is happening at the moment. Light is considered to be fundamental to humans, but influencing the moths negatively.

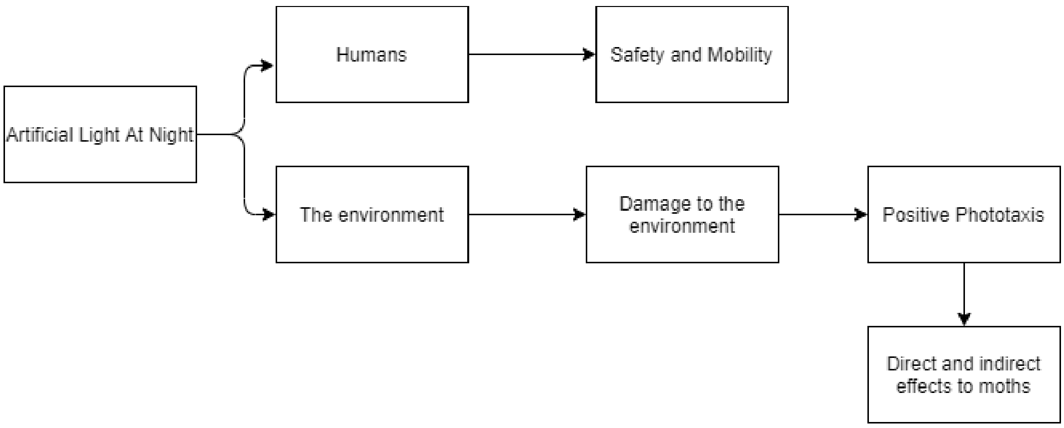


Figure 7 - Cause and effect pathway of ALAN

Modeling approach

The characterisation factors follow a model that takes into account to the transport sector and the distance travelled per motorized vehicle. Eventually, the result will specify how a specific area is affected by light pollution in square meters, when a motorized vehicle travels through that particular area.

Value choices

A number of choices and assumptions are made in order to define the characterisation factors. Each choice and assumption can be used differently and give different scenarios with different results. However, the method will remain the same. The following choice categories are:

- The type of weather and cloud formation in the sky.
- Choice of species; moths. Some other species might not be influenced by streetlight, since they do not navigate themselves by point source for example.
- Width and classificiation of roads. Some parameters for streetlight categorization per road is assumed and the width is gerenalized.

Spatial Variability

Light pollution at night is a global phenomenon. However, in order to asses light pollution in LCIA, adjustments in the type of streetlight, buildings, and backgroundlight are required. Therefore, this approach needs spatial information, since weather, buildings and streetlight types are regionally dependent.

Characterisation factors

The results of the impact on moths have to be defined as characterization factors (CFs) that in return would reflect the intensification of the inventory results to an impact category. These CFs are spatially dependent.

$$buffer_i = \pi * \left(\sqrt{\frac{L_{lamp_i} * H_m^2}{((Moon_L + Star_L) * f_t) + (Skyglow_L * f_{amp})}} + 1 \right)^2 \qquad (12)$$

$$CF_i = \frac{\left(\sum_{i=1}^{pole_{total}} buffer_i \right) \cap Viewshed_{visible}}{Distance_{total}} \qquad (13)$$

The equations 12 and 13 are a general overview of what needs to be included before stating the CF. First, the buffer is calculated in equation 12 by calculating the lux value from a distance of one meter from the streetlight pole. The inverse square law is used to determine the radius and then the area is calculated. This buffer is determined by the H_m , the mounting height of the streetlight in meters, and the L_{lamp} , which is the required lux value on the ground. $Moon_L$ is the moonlight in lux on a specific phase and $Star_L$ the lux value for clear starry sky with f_t the transmission factor through the clouds. $Skyglow_L$ is the skyglow value in lux for a clear sky and f_{amp} is the factor that accounts for the amplifying from clouds.

Equation 13 represents the determination of the CF. Each buffer is summed up. Since the overlap is not accounted for in this research, it should be subtracted from the total. As this depends on numerous parameters, it is best to calculate it using ArcGIS to dissolve all the buffers into one polygon. This summation continues until all the streetlights, including their buffer where motorized vehicles, are summed. The visibility part of the viewshed, which gives the intersection between these two, is then included. Subsequently, the total area, defined as CF multiplied by the total distance, is divided by the total distance travelled by the truck. In fact, this equation does not actually need a division of $Distance_{total}$, but, to make the relation between CF and inventory clear, this division is used.

Eventually the characterization factor is expressed as $\frac{meter^2}{meter}$ in order to determine the entire area that potentially influences moths it should be multiplied by the amount of distance travelled a motorized vehicle that would transport the goods that is analysed in LCA. Therefore it is proposed here that the inventory result should be expressed in the meters travelled by the transportation. Including a process such as transportation requires distance as the environmental stressor in order to translate this into the total impact of light pollution on moths in LCA.

4.2 Testing the Prototype: Case Study Berlin

The background light is set to be the sum of skyglow and moonlight luminosity. Both weather categories are set to be in the middle (Okta 5 and cloud transmission 5). Summing up the two luminosity sources and multiplying with the transmission factor and amplification factor the background light, gives a total of 0.062984 lux. The ground requirement lux from the M class is used to determine the lux value of 1 meter in front of the streetlight.

Firstly, Berlin is divided into the 6 classes of category M. A selection is made where roads are visible just for motorized vehicles or a mixture of motorized and other traffic. Bridle path, bicycle lanes, and pedestrian roads are omitted. The table of parameter weighting of the M class from Germany is used to determine the weighting value which in return determines the M class. Assumptions for separation of lanes, parked vehicles, requirements on the road and luminosity are motivated from the open source wiki data of open source roads. Figure 8 demonstrates all the roads in Berlin that includes motorized vehicles. These roads are all classified in different M classes according to the weighting parameters described previously.

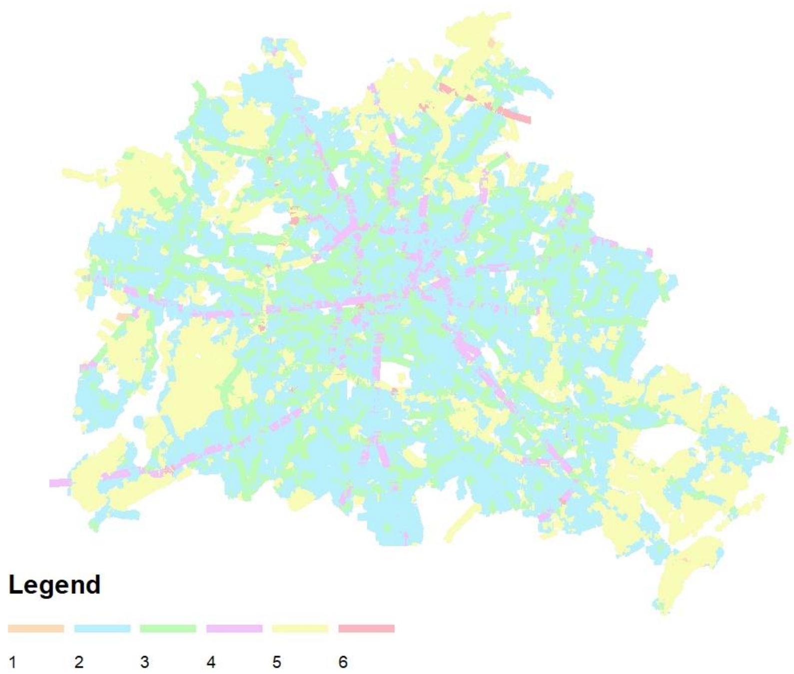


Figure 8 - M classification of selected roads in Berlin

Table 8 shows the percentage of the length of total road length that is within a specific class:

Table 8 - Percentage of total M class roads in Berlin.

Class	Length (m)	Percentage
M1	6532.23	<1 %
M2	4384329.95	58 %
M3	1187740.34	16 %
M4	312126.03	4 %
M5	1669821.36	22 %
M6	40938.77	<1 %
TOTAL	7601488.67	100 %

Class M2 dominates, following M5 class. Both M1 and M2 are the least appearance in Berlin. This is shown in table 8. Table 9 establishes the radius of the area of influence per M class and per mounting height. These results do show that M1 class overall has the higher radius compared to the other M classes. Te higher the mounting height, the larger the radius will become.

Table 9 – Radius in meters for buffer of different M class and mounting height.

Mounting Height	M1	M2	M3	M4	M5	M6
4	24	21	17	15	12	10
6	35	30	25	22	18	14
8	46	40	33	29	24	19
10	57	50	41	36	29	23

Two districts are chosen for zooming in and show the results on local level. The two districts that are chosen are Kreuzberg and Tiergarten. See figure 9 for the location of the two districts. Appendix E has all the viewshed maps for every mounting height for each of the districts.

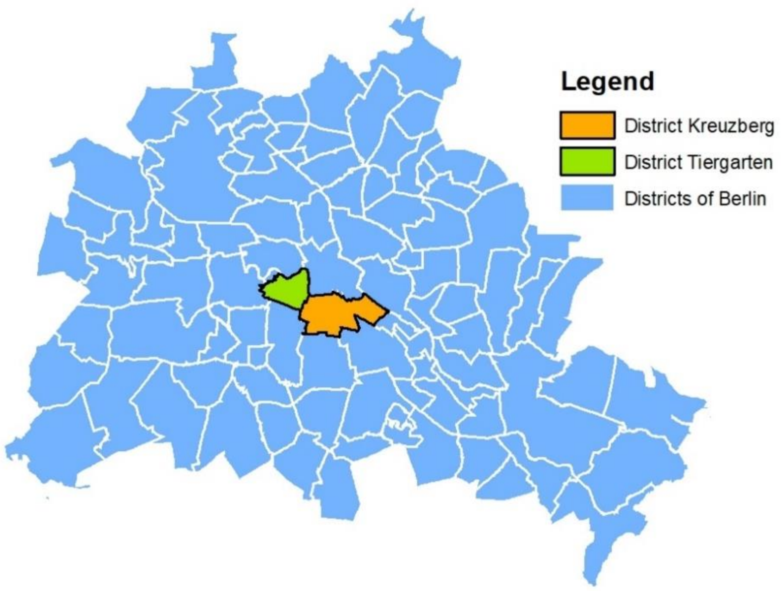


Figure 9 - Location of district Tiergarten and Kreuzberg

4.2.1 Results of District Kreuzberg

To give an example of the following procedure, a representative district is chosen to make the procedure tangible and computationally approachable. The Kreuzberg district of Berlin was chosen. Kreuzberg is near the center of Berlin, with a total area of 10.4 km^2 and a total population of 153,887 habitants. The district is known for its richness of art and artists. The district attracts a lot of students and artists and consists of a great diversity of different etnities (Downey 2007). Figure 10 shows all the motorized vehicles of Kreuzberg classified in the M categories.

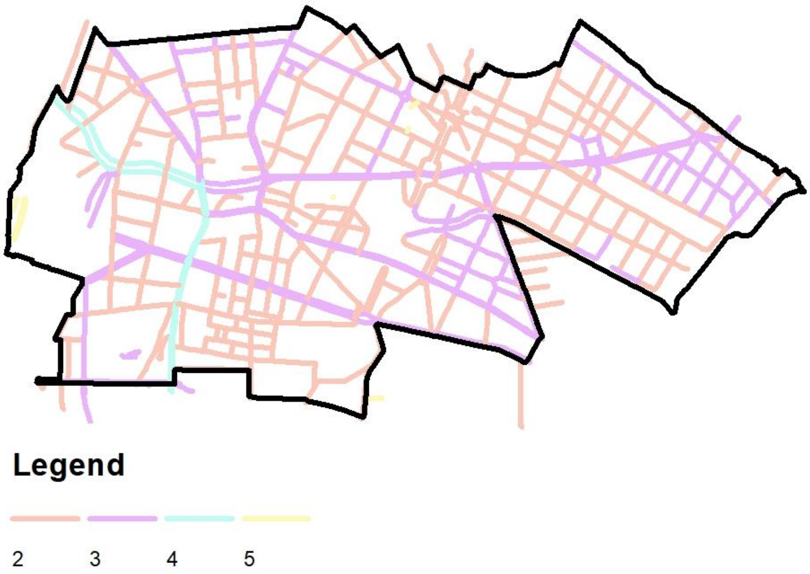


Figure 10 - M class road type of all the roads in Kreuzberg

Overall, Kreuzberg does not contain M1 nor the M6 class, see table 10. The important M class in this district is M2 class dominating over the other M classes. The results are shown in table 11 defining the amount of area influencing moths over the total area of the district. The largest area comes from the mounting height 10, having a total of 66% of the area potentially impacting the moths. Furthermore, M2 class is the highest amongst other classes.

Table 10 - Percentage M class roads in Kreuzberg

M1	M2	M3	M4	M5	M6
-	55.8%	38.5%	4.8%	0.8%	-

Table 11 – Percentage of area of influence per M class in Kreuzberg

Mounting Height	M1	M2	M3	M4	M5	M6	TOTAL
4	-	21%	11%	1%	<1%	-	33%
6	-	28%	15%	2%	<1%	-	45%
8	-	35%	18%	2%	<1%	-	55%
10	-	42%	21%	3%	<1%	-	66%

4.2.2 Results of District Tiergarten

The district Tiergarten is next to Kreuzberg and therefore also an example of a district near the city centre. This district contains a large nature park called 'Grosser Tiergarten' including the well-known statue 'Siegessäule' (van der Wall 2011). This district includes more M classes. Kreuzberg only contained M2, M3, M4 and M5. Tiergarten includes M6 as well. Figure 11 shows all the motorized roads classified into the different M classes for Tiergarten.

Figure 11 - M classes of the roads in Tiergarten

Table 12 includes the total roads per M class expressed in percentages. The dominating class is again the M2 class almost considering the half of all the roads. M1 class is not considered in this district. Table 13 gives the results of the amount of area potentially impacting the moths.

Table 12 - Percentage M classes in Tiergarten

M1	M2	M3	M4	M5	M6
-	42.5%	23%	24.9%	0.1%	9.5%

Table 13 – percentage of area of influence per M class in Tiergarten

Mounting Height	M1	M2	M3	M4	M5	M6	TOTAL
4	-	13%	5%	4%	<1%	<1%	22%
6	-	17%	8%	6%	<1%	1%	32%
8	-	21%	10%	7%	<1%	1%	39%
10	-	26%	12%	9%	<1%	1%	48%

In this research, the model is tested on two districts in Berlin to show what kind of results will be shown by the model and how the M classes and mounting height are influencing the results. The trend shows an increase in distance from M6 to M1 and also shows an increase in distance when the mounting height increases as well. It is true that from M6 to M1 an increase in distance is shown since the lux value of

M6 is only 0.3 lux on the ground while M1 needs 2 lux on the ground. Next to the M class difference, the mounting height also shows a significant difference in distance. For example, the M2 class in Kreuzberg has a significant change. If the mounting height would be 4 meters high, the radius is 24 meters, while height of 10 meters shows a radius of 58 meters, an increase of 42%. This is also clear for the percentage of moths being affected. Mounting height 4 has an effect on 21% of the moths in Kreuzberg, whilst a mounting height of 10 meters shows an effect on 42% of the moths, twice as much as the effect from 4 meters high. This is because the requirement of visibility of the M2 road type should be the same since visibility is defined on the luminosity on the ground. The visibility of M2 class should be 1.5 lux on the ground. According to the inverse square law; for mounting height 4, the lux value from 1 meter distance of the streetlight is 24 lux. For mounting height 10, the lux value from 1 meter distance of the streetlight is 150 lux, an increase of more than 5 times the value of the streetlight with a mounting height of 4 meters.

4.3 Approach to include Interference Streetlight

In this section a first approach is made in order to see if there is a significant difference in the radius of the buffers when the interferences of streetlight with each other is accounted for. The M2 class is taken as an example with multiple distances between streetlights. One streetlight interferes with the streetlight on its right, on its left and opposite of itself. All the three distances are the same. Figure 12 shows the situation. The green circle is the area of influence, but it gets interfered by the left, right and opposite area of influence.

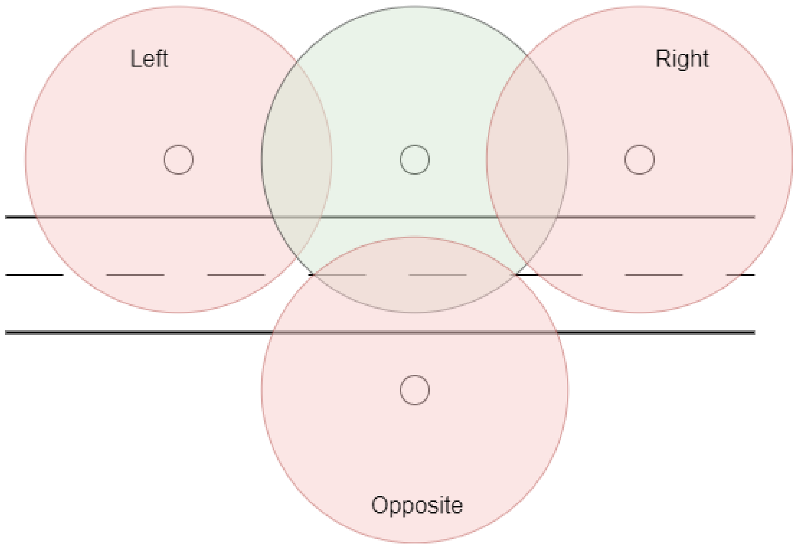


Figure 12 - Top view of streetlight interference situation

The calculation is based on the inverse square law. From each streetlight, the inverse square law is used to calculate the lux when one streetlight reaches the other streetlight. These values are then added and again the inverse square law is calculated what the new buffer radius is and what the significant change is. Table 14 shows a comparison of multiple distances with M2 class streetlight with mounting height of 6 meters. Distance without interference is just one streetlight and the distance with interference is the radius when three other streetlights would interfere by the distance given in the first column.

Table 14 - radius of area of influence from interference streetlight

Distance streetlight (m)	Radius without interference (m)	Radius with interference (m)	Percentage increase
30	26.00	26.04	0.002%
25	26.00	26.06	0.002%
20	26.00	26.09	0.004%
15	26.00	26.17	0.007%
10	26.00	26.38	0.015%
5	26.00	27.51	0.058%

For all the scenarios of a mounting height of 6 meters, there is no large difference, since all the changes are under the 0.1%. Besides, governments and municipalities will never put streetlight that close that it would significantly interfere, because that would not be economically beneficial. Municipalities and other governing entities would put streetlights at a distance where the lights overlap minimally with each other, while still properly illuminating the road. Some countries do consider a distance between streetlight between 35 – 80 meters if the streetlights are at both sides of the roads. At one side this is around 30 meters (Degen et al. 2016). Normally, the streetlight should have a distance equal to 2.5- 3 times the height of the streetlight (Global Designing Cities Initiative). This would mean that in this particular example, the distance between the street poles should be between 13 – 18 meters. Therefore, taking 15 meters for example, the increase in radius will be 0.007%. This means that the phenomenon of interference of streetlight would not be significant and if it would, the change would be very small and would not notably change the area of influence results.

To conclude, this is the first order approach to define the interference of streetlight. For now, it seems that accounting for interference would not change the key results significantly. This means that the interference can be neglected directly from the research since each buffer, area of influence, would not increase significantly. Because rounding the value of radius will remain the same if the distance between streetlight is between 15 – 30 meters.

5. Discussion

This research represents a first steps towards making streetlight tangible and including it in LCIA. The effect of light pollution to moths is diverse and it is not easy to assess this phenomenon in the product system assessment of LCA. This first approach has enabled the identification of light pollution as an effectiveness area where moths are potentially attracted to the point source. The attraction does follow up on the several severe impacts that cause disruption or even death to moths. Extensive exposure results in reduction of sex pheromones, reduction in growth and fitness, and visibility for predators (Gaston et al. 2013).

This model is of utmost importance, since streetlight is considered the largest light polluter of other light emitting objects. Especially in Berlin the light coming from the street is 31 % compared to a total light emission of all the lighting objects in the city (Kuechly et al. 2012). Besides Berlin, 32-42% of proportions of protected areas have also faced an increase in artificial light (Gaston et al. 2015). 30 to 40% of the insects being attracted to the streetlight also die because of exhaustion, dehydration of predators catching these insects (Owens and Lewis 2018). These disruptions to insects and especially moths will disrupt there temporal and spatial recognition and will likely cause a reduction in reproduction because of the reduced sex pheromones, reduced fitness and growth which reduces automatically the life span of moths as well. Collision with cars might occur since moths and other insects do not have accurate navigation, because there photoreceptors are disrupted and not fully functioning (Owens and Lewis 2018).

It is of great importance that light pollution impact is taken into account in environmental assessment. When this remains to be ignored, insect population will decrease and will eventually result in extinction. Transportation is an important mode in the product system, since many processes are very dispersed around the globe. Not all transport is by road, but still many trucks are driving daily to their destination all around the globe. If streetlight is to be 30 meters apart from each other (Degen et al. 2016) , around 34 streetlights are present per kilometre. This can even be doubled if streetlight is on both sides of the road. Considering the effects per streetlight, the effect per kilometre is enormous. This should remind us that transportation is not only causing effects by its emission of gas and petrol. It also shows effect on the non-physical side of emissions. Sound and land use are contributing as emission in the transportation sector, but especially light is showing its impact towards moths.

5.1 Time-dependency of Weather

LCA practitioners should be aware that the weather and moon phase conditions are important to know beforehand in order to get the radius of the area of the influence. This model made sure that the phase of the moon and weather can be adjusted and used in the model. The prototype in Germany just took one moment in the weather conditions and moon phase to demonstrate one situation, but once practitioners want to assess another situation, weather and moon phase should be analysed thoroughly, since they can significantly change the outcome of the model.

Moonlight and other background sources determine the distance before the lux of the streetlight equals the background light (Bowden 1982). A rough estimation of skyglow and starlight is taken for Berlin and full moon average is taken for the total luminosity of moonlight. Weather also matters since the thickness and the amount of clouds determine the transmission of moonlight and starlight and the amplification factor for skyglow. This research took the middle category of the amount of clouds for each background source. However, cloud thickness does make a difference. For mounting height 4, M2 class gives a radius of 24 meters. This is from the original background adjustments of this research. If we would adjust the parameters of clouds into clear sky, the radius will change. Keeping the moonlight and skyglow value and changing the clouds into clear sky, the radius of effectiveness will be 17 meters, while normally the radius would be 24 meters. Table 16 elaborates more on these moon phases including the first quarter and last quarter of the moon. This does make sense, since the clear sky would increase the moonlight on the ground, which in return reduces the distance for when the streetlight luminosity would equal the background light. Keeping the skyglow the same value, the following table shows the different radius for different scenarios of cloud thickness and moon phase.

Table 16 - Adjusting cloud thickness for sensitivity analysis

Moon phase	Clear sky	Maximum cloud thickness
Full Moon	17	24
First Quarter	56	26
Last Quarter	51	26
New Moon	57	26

Given the results from this table 16, weather does present a significant difference in radius and therefore a difference in area of effectiveness. Not only moonlight phase makes a difference in the radius, also skyglow presents a change depending on the amount and location of clouds. Besides background light, weather also plays a role in the attraction and the population of moths in a specific area. According to (Williams 1940) the catching of moths doubled with 2.8 degrees Celsius temperature rise. Also, in the study of (Guedes et al. 2000), it has been found that the species richness and abundance of the moths was the highest during the wet seasons. This means that other weather aspects do influence the population of moths in a specific area. However, this research focussed on constant distribution which ignored these aspects as these aspects changes the total distribution per area. Both background light and weather impact significantly change the population of moths and the area of attraction of moths. This concludes that the results are location- and time dependent. If these results are to be used in the LCIA, weather and moon phases should be included, as well as the skyglow from a particular region.

These results reflect on the results of previous studies. The literature explains that with the inverse square law the mercury vapour ultraviolet, mercury vapour (with tungsten filament, ultraviolet) and Tungsten filament incandescent lamps' radius of influence for full moon has a lower radius compared to the new moon (Bowden and Morris 1975). This means that for more intense background light, the radius is smaller compared to a less intense background light, which is also explained in the method of this research. This shows a similar finding, since background light also is one of the parameters that determine the radius of effectiveness (Bowden 1982). Trap potential is measured using the inverse square law to determine the radius of trap potential. According to (Bowden and Morris 1975) the trap potential between new moon and full moon has a ratio of 10:1 or 15:1. This means that moonlight does have an effect on the radius of effectiveness and again shows proof that the inverse square law should be used to determine the effect.

Even though this research still has its limitations and the model still needs to be adjusted, it is a breakthrough in the LCIA network for making the first approach of light pollution into LCIA. This method is computationally intensive, since software needs time to distinguish visible and non-visible cells for each streetlight luminosity penetrating through the urban area. Therefore, this research used cell size 5x5 and was able to determine the viewshed layer for district level within reasonable time. This research focusses on looking into a method that enables this translation, as doing a very compute-intensive analysis on Berlin was not needed. The viewshed computation time for Kreuzberg took approximately

50 minutes. Trying to make the data more precise by reducing cell size to 3x3 took 8 hours and still did not reach one percent of completion. The precise calculations do require a very long run time before being completed. This is also true for doing this analysis for a whole city or even an entire country. Viewshed tool might be a good tool for just a particular route since this does not require too many buildings and other objects to be identified.

Practitioners should be able to calculate the total area by dividing roads in the different classes and by observing which roads are used for transportation, in order to use the right buffer for the right road. As described earlier, the reason why light pollution has not been used in LCIA, is because light pollution is a non-physical entity and it is complex to discuss the effects to the entire biodiversity of an area. It is difficult to determine the light pollution for the entire biodiversity, because of the large diversity of species. However, light pollution can be transformed into a physical entity and makes it easier to relate this to multiple species. This research is able to translate light pollution into square meters. Since the distribution is fairly homogeneous in urban regions (Degen et al. 2016; Merckx and Dyck 2019), the area that is affected is also the area that attract a number of moths. Once moths are attracted, other effects do occur as well.

5.2 Area of influence vs Remote Sensing

Analysis of light pollution in particular areas are mostly done by remote sensing. Satellite imagery is available on most of the places on Earth. Remote sensing techniques have been used in many researches. DMSP is one of those satellites that is often used to detect light pollution in urbanized areas (Cinzano et al. 2001). This satellite is mostly working in cloud free situations such as researching light pollution in China (Han et al. 2014). The DMSP resolution is at its best around 1 km. Pixels from the DMSP are presented in digital number between 0 and 63, with zero being relative darkness and 63 the brightest value. Even though satellite imagery is able to detect luminous areas, it is different compared to the research presented here.

First of all, the resolution of the remote sensing techniques of satellite imagery is not the most optimal to work with for the level of this research. Research does prove that moths in particular are attracted to light source such as streetlight since they compare this with the natural moonlight when it is brighter (Gaston et al. 2013). Resolution of 1 by 1 kilometre makes it hard to individually detect luminosity of streetlight compared to other artificial light sources and makes is harder to prove whether the whole area attract moths. The most accurate resolution that is publicly available is the imagery taken by the international space station and has a resolution of 45 meters (Kuechly et al. 2012). This still is too large to detect any individual light objects.

Secondly, satellite imagery needs clear skies to detect light pollution at its most optimum. As described in the theory, clouds transmit moonlight and amplify skyglow (Kyba et al. 2011; Bowden 1982). Satellite imagery would record mainly the reflection of the moon during cloudy sky instead observing the light pollution coming from urbanized areas. This concludes to the fact that satellite imagery is not the most optimal using it while cloud formation in the sky happens. Although satellite imagery is good for broader areas, it is still not as detailed as defining just by using the requirement rules for streetlight placement.

However, aerial imagery is more detailed than satellite imagery and even more detailed than the research done here. The resolution aerial survey imagery has taken throughout berlin is 1 by 1 meter (Kuechly et al. 2012). Even though the resolution is higher compared to other methods, the method for aerial imagery is the same for the method that is applied to this research. Eventually, a unit needs to be defined that is measurable and usable to multiply with the inventory results. Ultimately the results of the aerial map are given in the unit 'brightness factor' (Kuechly et al. 2012) . To measure the number of moths attracted to the streetlight, the area needs to be assessed to see whether the brightness factor is higher or equal to the background light, also transformed in brightness factor. This equals the method taken by this research.

Aerial survey is very detailed and is able to determine the area of influence as well. This remote sensing technique would include all the obstacles in one map, also including vegetation and blocking of buildings etc. However, it is quite expensive and time consuming to fly over the area you want to calculate. The requirement table for determining M class is applicable already to the entire country of Germany. Multiple other countries in Central Europe also developed their own requirements table to account for the intensity needed on the ground per streetlight. The other component needed is the background light and this can be taken from the literature of moonlight and satellite images. The issue is then that cloudiness sky is needed, but the resolution does not particularly have to be very high since skyglow is taken a bigger area than just one single streetlight pole.

5.3 Limitations

The road is assessed by including the speed limit, directional lanes separation, amount of traffic, mixture of traffic, ambient light, parked vehicles and requirements on the ground. Some assessment is assessed according to the literature provided for the open street data sources. Speed limit is in the dataset itself and directional lane separation, parked vehicles, and mixture of traffic are taken from this literature. Besides these, the other assessment of the road, such as amount of traffic, ambient light, mixture of traffic and requirement on the ground is assumed to the fact where these roads are located. Amount of traffic is in most cases assumed to be normal or low, depending on the usage of the road type (see Appendix B). However, some locations and some roads might have high traffic amount. This also depends of the time. This research focussed on night, not including dusk and dawn. If the time is more towards the evening or morning, the traffic might change because of rush hours. Again, rush hour is very spatially dependent.

Both districts show the same trend of the attraction of moths towards specific streetlight intensities. The theoretical background section of this research explained that the higher the intensity, the longer it takes before the lux equals the surrounding ambient light. The inverse square law is the proof of showing the distance of effectiveness for the attraction of moths. The higher the mounting height, the higher the intensity for the streetlight, since the ground requirement should stay equal for each mounting height. The discussion arises about which mounting height should be used. The M classes, where the distance is based on, do not include the mounting of the streetlight nor the width of the road. The European Committee of standardization (Global Designing Cities Initiative) mentions how high the streetlight should be determining the width of the road. However, the typical width per type of road is not explicitly stated and therefore it is not possible to make a selection since each road, no matter which M class, can have multiple widths and therefore multiple mounting heights. This research thus focussed on multiple mounting heights to include several scenarios and analyse what happens when mounting height increases.

It is true however that the further away the moth is from the streetlight, the smaller the chance will be that they are attracted to the light since the intensity is getting lower and whilst they are normally attracted to the moon since the influence from the moon's luminosity is relatively stronger (Van Grunsven et al. 2014). Yet, the area of effectiveness demonstrate that those moths are affected because of higher intensity compared to the moon, which they are normally attracted to. If the distribution is not considered to be constant, the population and distribution of moths would be much higher, closer to the streetlight compared to being further away (Van Grunsven et al. 2014).

Therefore, besides the area of effectiveness, the higher the intensity, the more distribution around the streetlight and the higher the area of effectiveness will be. This research only focussed on one specific class while neglecting the other classes. Streetlight in conflict areas, areas that have a higher risk in collisions, does have a higher intensity compared to the M class. Using fieldwork to assess potential conflict areas might change the results. Although this class has a much higher lux value compared to the M class, it still is very complex and time consuming to implement them in the model. Class for conflict areas could be considered for each intersection, but since the luminosity is much higher it is meant for complex situations as well. In order to set these classes as well in the model, each situation should be assessed individually before stating which intersection or other complex situation needs which class. It does also depend what route the motorized vehicle is taking before evaluating if other classes besides the M class is needed. If the amount of intersections of complex areas is at its minimum compared to the distance of the road travelled, then the results would not be significantly different, since more streetlights are assessed by the M class than the C class.

This research mainly focussed on the intensity of light and how the intensity of streetlight relates to the area of influence. However, intensity is not the only cause of light pollution to moths. Wavelength and time both play a significant role in light pollution.

Overall, moths are attracted more towards shorter wavelengths than to broader wavelengths (van Geffen et al. 2015). At the same time, moths with bigger eyes and wings are more abundant around streetlight that contains short wavelength (van Langevelde et al. 2011). Moths are attracted to more white lights such as Metal Hallide lamps (MH) (Wakefield et al. 2018). The area of influence determines the area where moths are potentially influenced by light. However, some light attracts moths more compared to other light sources. Especially if looking at the spectral composition of the streetlight. Overall, Light Emitting Diode (LED) and MH attract more moths considering white and short wavelengths. More and more cities and countries are installing LEDs, resulting in more streetlight with short wavelengths. This would mean that more abundancy of moths will develop around streetlight compared to other light such as HPS light. Including the weighting of the spectral composition might divide the area of influence into different attraction areas by combining the intensity together with the spectral composition.

Another component that might influence the distribution is the time of the day. The results are based on one specific value of the background light. Yet, this does change throughout the night, since dawn and dusk have a higher intensity value for the background since the background light is a mixture of moonlight and direct sunlight. These results are based on moonlight and skyglow only. If these results are measured around the evening or morning, the area of influence will be much smaller since the background light would almost overrule the intensity of streetlight itself. Time can be included if the time a specific truck is driving through these roads is known. Also important to take into account, is that a streetlight is not always turned on. Lastly, this research focussed on the literature on the impact to moths. There are many other insects and animals that are influenced to artificial light as well

Even though this research shows its limitations, this models is still highly functional and applicable for the LCIA framework and assessment.

6 Conclusion

This research looked at the first approach of implementing the impact of light pollution from streetlight into LCIA. This first approach encompasses the development of a method, calculating the so called area of influence. The area of influence is determined by the distance for when the luminosity of the streetlight equals the background light following the inverse square law. The background light is defined to be the summation of moonlight, starlight, and skyglow. The intersection between buildings and the area where luminosity of the streetlight is higher than the background light is considered to be the area of influence where moths are potentially attracted to.

The moths show a positive phototaxis in this area which results in direct and indirect impacts. Moths show dehydration, exhaustion and predator visibility which might result in death. Besides these direct effects, the effects of ALAN also reduce the sex pheromones that reduces the reproduction of moths. The growth and fitness of moths are also reduced as well resulting in a reduction in population and at the same time a higher mortality rate in the moths. This model is able to identify how much the area of influence is per transportation situation of a given production system. The model has its limitations by not including wavelength and time of light, and more accurate data for road and streetlight. However, this should not reduce the importance of this model in the LCIA work field. This model is the first approach and therefore the beginning of a fully developed model that would include the impact of light pollution in LCIA.

LCA practitioners should use this model to compare the transportation of products and determine how much area has effect to moths. This could help to map the amount of pollution the manufacturing or the use of a certain product brings. These findings can then be taken into account and reduced by using the right measures. Overall, this research made a jump start into the implementation of light pollution in LCIA. It cannot be stressed enough how important including light pollution is in LCIA knowing that ALAN is very harmful to nature and it should be assessed whenever a product or service system would have a nocturnal transport mode in its system. Hopefully the addition of light pollution impacts to LCIA would increase a more sustainable life endurance for moths and other insects as well.

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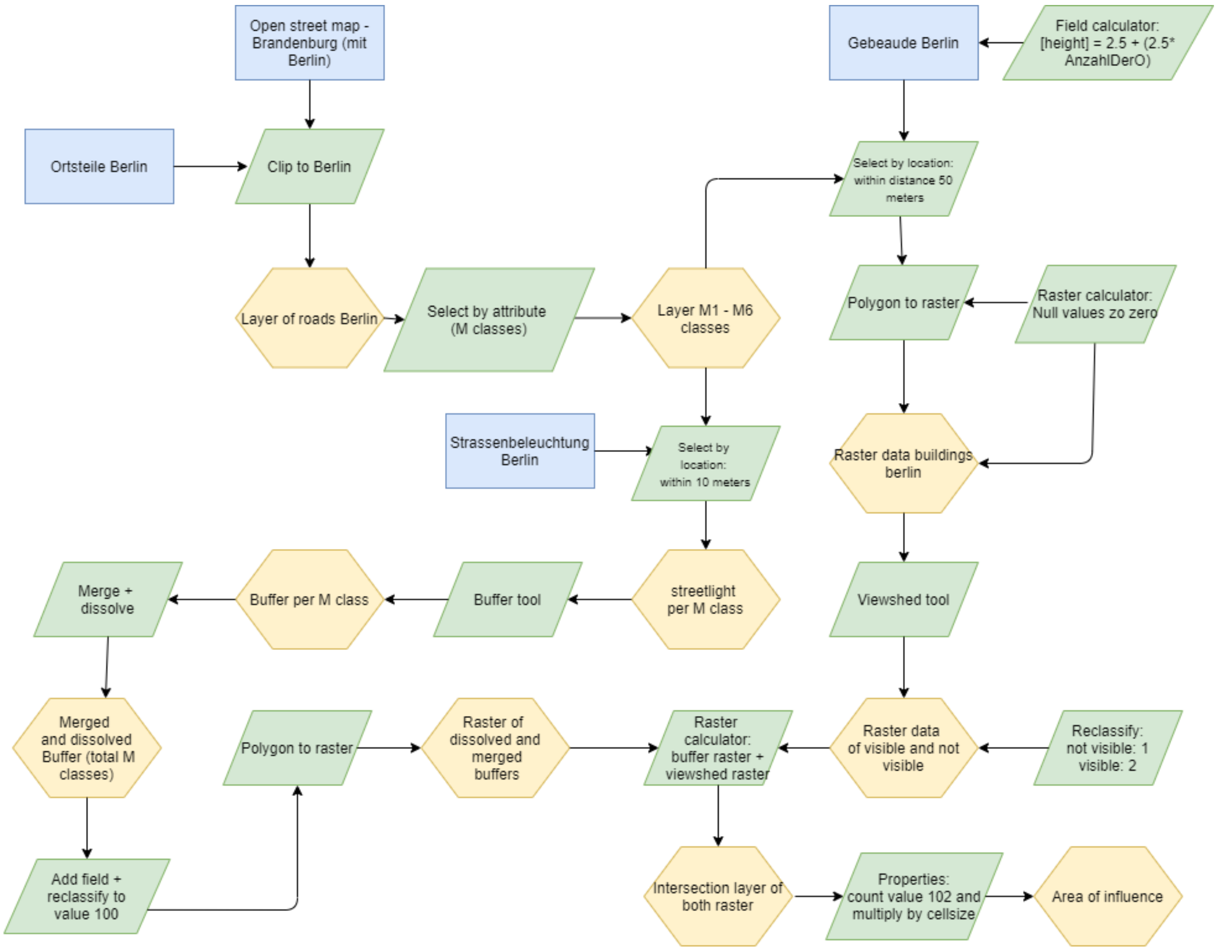
Appendix A: Detailed flowchart ArcGIS case study



Appendix B: M class selection and classification

Table B.1 (Stockmar 2018)

Parameter	Options	Description		Weighting value
Speed limit	Very high	v >= 100 km/h		2
	High	70 < v < 100 km/h		1
	Moderate	40 < v < 70 km/h		-1
	Low	V =< 40 km/h		-2
Traffic Volume		Motorways, multilane routes	Two lane routes	
	High	>65% of maximum capacity	>45% of maximum capacity	1
	Moderate	35% - 65% of maximum capacity	15%-45% of maximum capacity	0
	Low	<35% of maximum capacity	<15% of maximum capacity	-1
Traffic composition	Mixed with high percentage of non-motorized			2
	Mixed			1
	Motorized only			0
Separation of directional lanes	No			1
	Yes			0
Junction Density		Intersection/km	Interchanges, distance between bridges, km	
	High	>3	<3	1
	Moderate	=<3	>= 3	0
Parked vehicles	Present			1
	Not Present			0
Ambient Luminosity	High	Shopping windows, advertisements expressions, sport fields, station areas, storage areas		1
	Moderate	Normal situation		0
	Low			-1
Navigational task	Very Difficult			2
	Difficult			1
	Easy			0

Table B.2

Type road	Seperation of lanes		Amount of traffic		Mode of transport		Luminance of environment		Parked vehicles		Increased demands		TOTAL
Motorway	yes	0	Normal	0	only motorized	0	Low	-1	Not allowed	0	Available	1	0
Primary	No	1	Normal	0	only motorized	0	Middle	0	Not allowed	0	Available	1	2
Trunk	Yes	0	Normal	0	only motorized	0	Low	-1	Not allowed	0	Available	1	0
Cycleway													0
Footway													0
Living_street	No	1	Low	-1	mixed	1	Middle	0	Allowed	1	Available	1	3
Motorway_link	Yes	0	Normal	0	only motorized	0	Low	-1	Not allowed	0	Available	1	0
Path													0
Pedestrian													0
Primary_link	No	1	Normal	0	only motorized	0	Middle	0	Not allowed	0	Available	1	2
Residential	No	1	Low	-1	mixed	1	High	1	Allowed	1	Available	1	4
Secondary	Yes	0	Normal	0	mixed	1	Middle	0	Allowed	1	Available	1	3
Secondary_link	Yes	0	Normal	0	mixed	1	Middle	0	Allowed	1	Available	1	3
Service													0
Steps													0
Tertiary	No	1	Low	-1	mixed	1	High	1	Allowed	1	Available	1	4
Tertiary_link	No	1	Low	-1	mixed	1	High	1	Allowed	1	Available	1	4
Track	No	1	Low	-1	mixed	1	Low	-1	Allowed	1	Not available	0	1
Track_grade1	No	1	Low	-1	mixed	1	Low	-1	Allowed	1	Not available	0	1
Track_grade2	No	1	Low	-1	mixed	1	Low	-1	Allowed	1	Not available	0	1
Track+grade3	No	1	Low	-1	mixed	1	Low	-1	Allowed	1	Not available	0	1
Track_grade4	No	1	Low	-1	mixed	1	Low	-1	Allowed	1	Not available	0	1
Track+grade5	No	1	Low	-1	mixed	1	Low	-1	Allowed	1	Not available	0	1
Trunk_link	Yes	0	Normal	0	only motorized	0	Low	-1	Not allowed	0	Available	1	0
Unclassified													

B.3 - Python code for classification of roads per category

```
def lux_class(speed, typeroad):
    weight = 0
    if speed > 50:
        weight = 1
    if speed <= 50:
        weight = 0
    if typeroad == 'motorway':
        weight = weight + 0
    if typeroad == 'primary':
        weight = weight + 2
    if typeroad == 'trunk':
        weight = weight +   0
    if typeroad == 'living_street':
        weight = weight  + 3
    if typeroad == 'motorway_link':
        weight = weight  + 0
    if typeroad == 'primary_link':
        weight = weight  + 2
    if typeroad == 'residential':
        weight = weight  + 4
    if typeroad == 'secondary':
        weight = weight  + 3
    if typeroad == 'secondary_link':
        weight = weight  + 3

    if typeroad == 'tertiary':
        weight = weight  + 4
    if typeroad == 'tertiary_link':
        weight = weight  + 4
```

```
    if typeroad == 'track':
        weight = weight  + 1
    if typeroad == 'track_grade1':
        weight = weight  + 1
    if typeroad == 'track_grade2':
        weight = weight  + 1
    if typeroad == 'track_grade3':
        weight = weight  + 1
    if typeroad == 'track_grade4':
        weight = weight  + 1
    if typeroad == 'track_grade5':
        weight = weight  + 1
    if typeroad == 'trunk_link':
        weight = weight  + 0
weight2 = 6 - weight
    if typeroad == 'cycleway':
        weight2 = 'other'
    if typeroad == 'footway':
        weight2 = 'other'
    if typeroad == 'unclassified':
        weight2 = 'other'
    if typeroad == 'service':
        weight2 = 'other'
    if typeroad == 'steps':
        weight2 = 'other'
    if typeroad == 'path':
        weight2 = 'other'
    if typeroad == 'pedestrian':
        weight2 = 'other'


    return weight2
```

Appendix C: Lunar cycle with lux value

Table B.1: the brightness of the moon per phase angle and together with relative polarization (Kiss 1979)

Approx. Lunar days	phase angle	relative brightness (lux)	relative polarization	brightness (lux)	Note
0	0	1	0	0,25	Full Moon
1	12	0,724	-0,0111	0,181	
1,9	23,5		0	0	
2	24	0,533	0,0015	0,13325	
3	36	0,391	0,0191	0,09775	
4	48	0,288	0,0418	0,072	
5	60	0,211	0,0541	0,05275	
6	72	0,147	0,0708	0,03675	
7	84	0,1	0,0812	0,025	
7,9	90	0,078	0,0878	0,0195	Last Quarter
8	96	0,066	0,0859	0,0165	
9	108	0,044	0,0875	0,011	
10	120	0,026	0,0721	0,0065	
11	132	0,014	0,0585	0,0035	
12	144	0,006	0,0436	0,0015	
12,2	146,5		0,04	0	
12,5	150	0,005		0,00125	
13	156	0,002	0,024	0,0005	
14	168	0,001	0,009	0,00025	
15	180	0	0	0	New Moon
16	192	0,001	0,012	0,00025	
17	204	0,003	0,027	0,00075	
17,5	210		0,0356	0	
18	216	0,007	0,0408	0,00175	
19	228	0,009	0,0518	0,00225	
20	240	0,025	0,06	0,00625	
21	252	0,041	0,0637	0,01025	
22	264	0,067	0,0654	0,01675	
22,5	270	0,082	0,0649	0,0205	First Quarter
23	276	0,105	0,0637	0,02625	
24	288	0,155	0,0589	0,03875	
25	300	0,211	0,0495	0,05275	
26	312	0,292	0,0343	0,073	
27	324	0,395	0,0184	0,09875	
28	336	0,535	0,0008	0,13375	
28,1	336,5		0	0	
29	348	0,74	0,01	0,185	
30	360	1	0	0,25	Full Moon

Appendix D: R code for Radius calculation

```
# variables
#lum_lamp    -->  indicate the amount of lumens of the lamp
#moon_phase  -->  choose; 'full moon', 'first quarter', 'last quarter', or 'new moon'
#weather     -->  category from 1 to 10. 1 being clear sky and 10 heavy cloud storms.
#land_type   -->  choose between 'field' and 'woodland'
#okta        -->  type of cloudiness. 0 is clear sky and 8 is fully cloudy
#type_city   --> choose between rural or urban area
#skyglow_clear --> what the value of skyglow is without clouds


lux_lamp = 1.5
weather = 5
moon_phase = 'full moon'
okta = 4
type_city = 'urban'
skyglow_clear = 0.00374
mounting_height = 4
starlight = 0.001


# FILTER THE BACKGROUND LIGHT FACTORS TO DETERMINE THE OVERALL BACKGROUND AMBIENT
LIGHT

if (moon_phase == 'full moon'){

 moonlight = 0.094}

if (moon_phase == 'last quarter'){

  moonlight = 0.00605}

if (moon_phase == 'first quarter'){

  moonlight == 0.0699}

if (moon_phase == 'new moon'){

  moonlight = 0.00425}


if (weather ==1){

  transfac = 1

  }

if (weather == 2){

  transfac = 0.8

  }
```

```
if (weather == 3){
  transfac = 0.75
  }
if (weather == 4){
  transfac = 0.7
  }
if (weather == 5){
  transfac = 0.6
  }
if (weather == 6){
  transfac = 0.47
  }
if (weather == 7){
  transfac = 0.35
  }
if (weather == 8){
  transfac = 0.21
  }
if (weather == 9){
  transfac = 0.17
  }
if (weather == 10){
  transfac = 0.1
  }

# determining the reflection coefficient of cloud cover to artificial skyglow

if (okta == 0) {
  if (type_city == 'urban'){
    amp_fac = 1
  }
```

```
  if (type_city == 'rural'){
    amp_fac = 1
  }
}

if (okta == 1) {
  if (type_city == 'urban'){
    amp_fac = 1.1
  }
  if (type_city == 'rural'){
    amp_fac = 1.2
  }
}

if (okta == 2) {
  if (type_city == 'urban'){
    amp_fac = 1.3
  }
  if (type_city == 'rural'){
    amp_fac = 1.3
  }
}

if (okta == 3) {
  if (type_city == 'urban'){
    amp_fac = 1.3
  }
  if (type_city == 'rural'){
    amp_fac = 1.1
  }
}
```

```
if (okta == 4) {
  if (type_city == 'urban'){
    amp_fac = 1.6
  }
  if (type_city == 'rural'){
    amp_fac = 1.3
  }
}

if (okta == 5) {
  if (type_city == 'urban'){
    amp_fac = 2.0
  }
  if (type_city == 'rural'){
    amp_fac = 1.5
  }
}

if (okta == 6) {
  if (type_city == 'urban'){
    amp_fac = 3.1
  }
  if (type_city == 'rural'){
    amp_fac = 1.7
  }
}

if (okta == 7) {
  if (type_city == 'urban'){
    amp_fac = 6.1
```

```
  }
  if (type_city == 'rural'){
    amp_fac = 2.3
  }
}

if (okta == 8) {
  if (type_city == 'urban'){
    amp_fac = 10.1
  }
  if (type_city == 'rural'){
    amp_fac = 2.8
  }
}



background_sky = (moonlight + starlight) * transfac
skyglow = skyglow_clear * amp_fac
background_light = skyglow + background_sky
lux_lamp2= lux_lamp*(mounting_height^2)
lux_lamp3 = lux_lamp2 + background_light
radius = (((lux_lamp3)/background_light)**0.5) + 1
print(radius)
```

Appendix E: Viewshed maps

Figure E.1 – Viewshed map of Kreuzberg with mounting height of 4 meters.

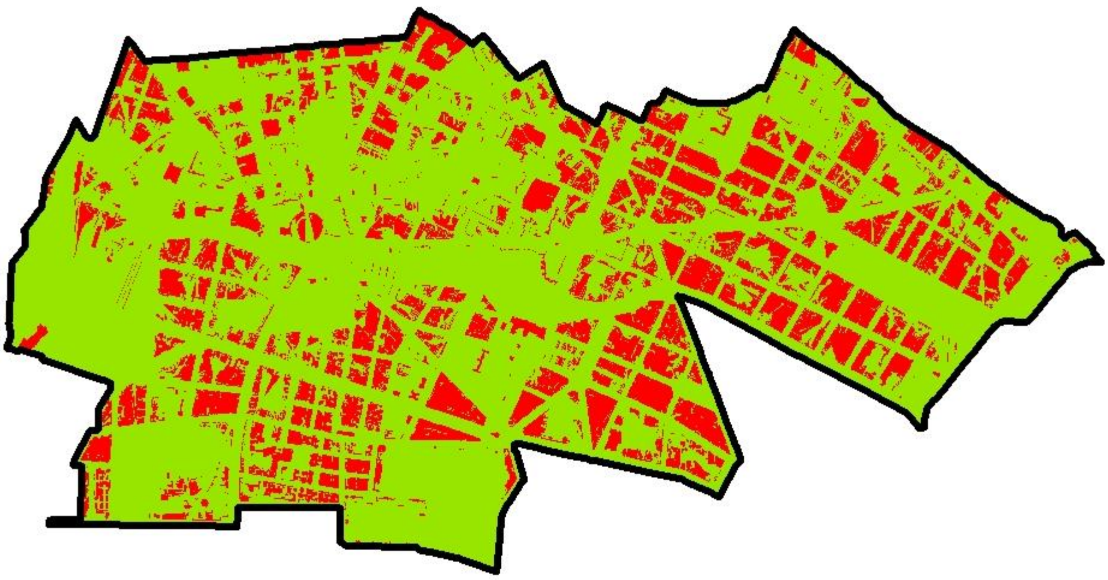


Figure E.2 – Viewshed map of Kreuzberg with mounting height 6

Figure E.3 – Viewshed map of Kreuzberg with mounting height of 8 meters.

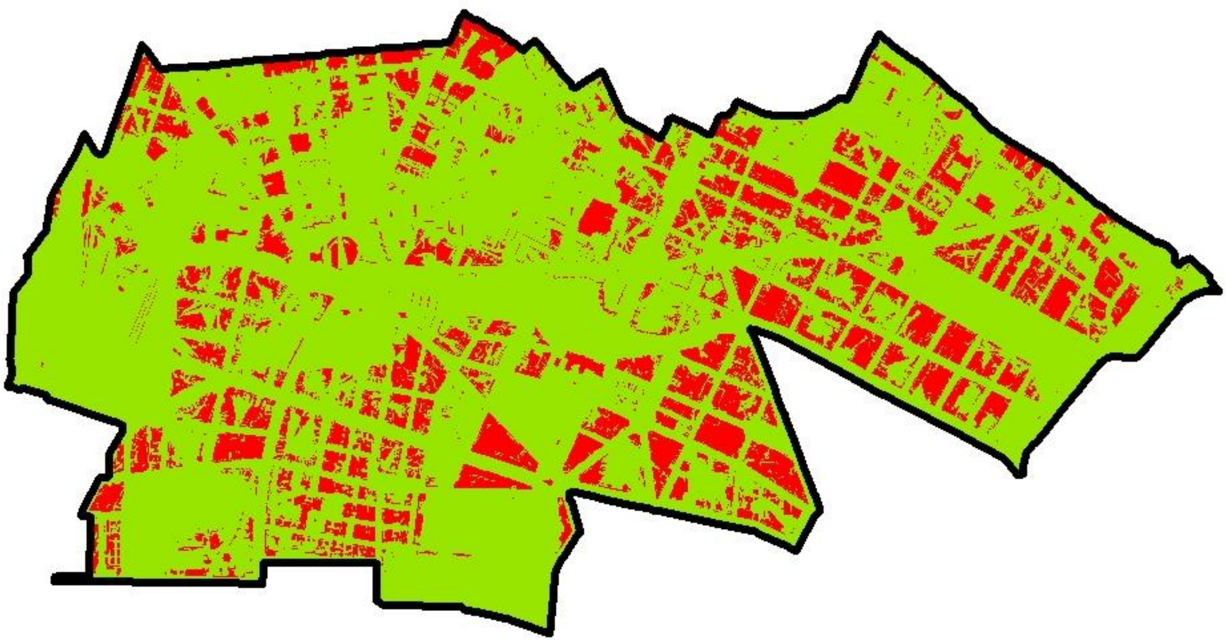


Figure E.4 – Viewshed map of Kreuzberg with mounting height of 10 meters.

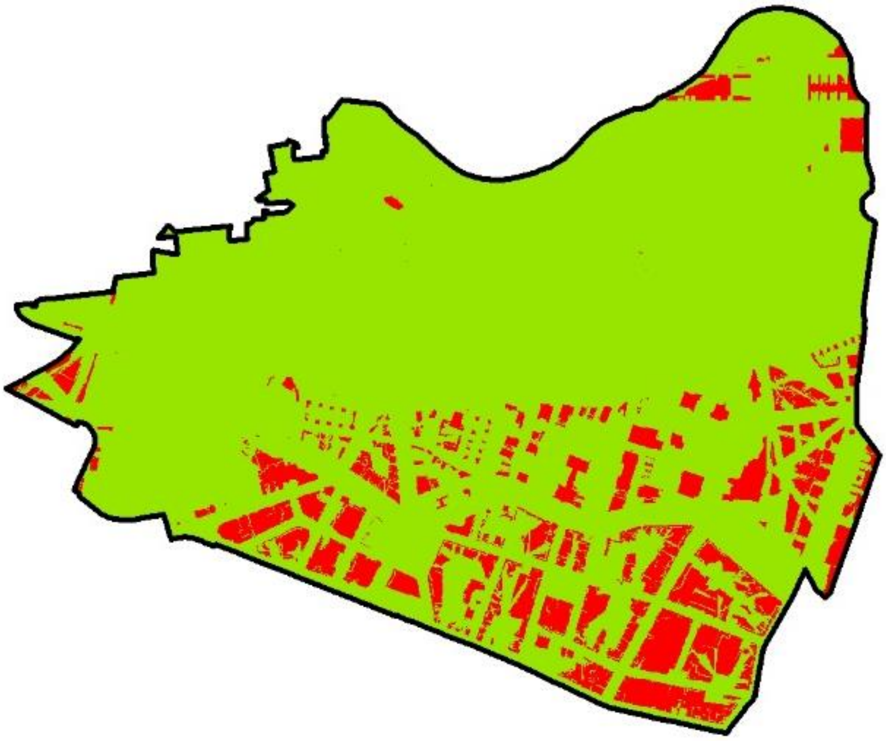


Figure E.5 – Viewshed map of Tiergarten with mounting height of 4 meters

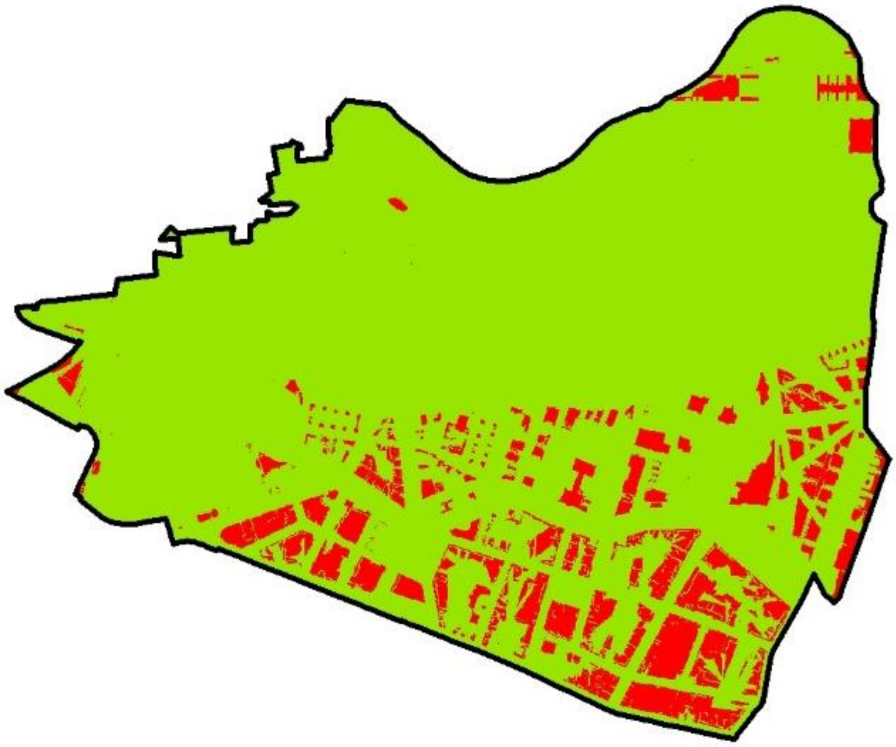


Figure E.6 – Viewshed map of Tiergarten with mounting height of 6 meters.

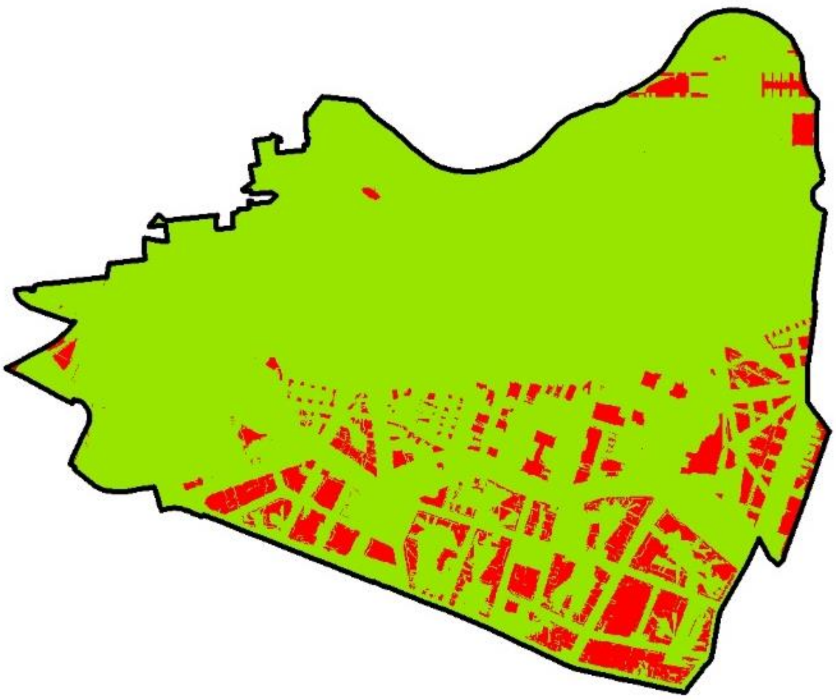


Figure E.7 – Viewshed map of Tiergarten with mounting height of 8 meters.

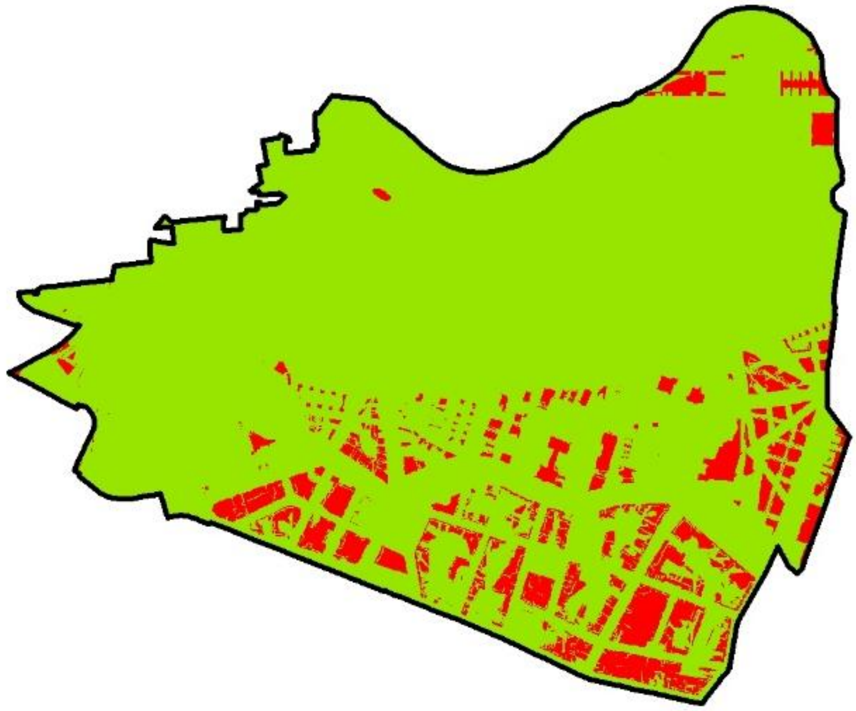


Figure E.8 – Viewshed map of Tiergarten with mounting height of 10 meters.