FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

MASTER THESIS

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Evolutionary Algorithms for the Design of Luminaire Optics

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Study programme: Computer Science
Study branch: Artificial Intelligence

Prague 2021

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I would like to thank Mgr. Martin Pilát, Ph.D., supervisor of this thesis, for guidance, time and expertise. In addition to that I would like to thank the team in Sathea Vision company for providing me with all resources necessary for completing this thesis, namely Jan Horák and Ing. Filip Vaněk for inspiration, encouragement and expert advice throughout the course of the work and Ing. Ondřej Gazda, Ing. Marie Ponomarenko and Ing. Zdeněk Kuchař for patience and invaluable support with prototype manufacturing.

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Abstract:

The goal of this thesis was to explore the possibilities of using evolutionary algorithms to design components with specific purpose. We examined the process of designing an optimal shape of reflector from a highly reflective metal sheet. The main goal of this reflector is to evenly distribute light from a light emitting diode.

We created a simplified model of the environment, where our component should be used. Then we used the evolutionary approach to find a suitable reflector shape for an existing device. One selected solution was manufactured and its properties measured. We also used the developed program to search for a design of an optical part for a completely new device proposal.

Both tasks were accompanied by a number of problems that originated in an inaccurate task specification and general disparity between the fields of evolutionary computation and industrial components development. We provided an analysis of issues we encountered and presented solutions that can be applied to other similar tasks.

Keywords: evolutionary algorithms street lighting automated design

Contents

Introduction

Thesis Motivation

The process of designing, prototyping and testing new industrial components is generally very demanding both in terms of time and resources. All steps require highly trained professionals which itself results in high costs. In addition to that specialized software, machinery and quite a lot of material is needed for creating prototypes of components. Finally there is always a great deal of costly testing to be done.

The development of new parts usually requires several cycles resulting in a series of prototypes. It all starts with a demand for a new component with specific purpose. Such order usually comes with a list of requirements both in terms of function and general shape and size of the new component. Designer then creates the first model using computer aided design software. Afterwards, the prototype is manufactured using CNC machines in most cases. Once we have created the part, it can be tested to find out whether it meets given criteria and how suitable it is for a specified task. Now it is time to evaluate not only the outcome but also the whole manufacturing process. Subsequently new rounds of designing, prototyping and testing follow until we have a prototype that satisfies all requirements.

Our idea is to use an evolutionary approach to search for an optimal shape of a given component. We hope that we can eliminate some of the development cycles and thus we can lower the costs and time needed to get from an initial idea to a fully functioning component. Also we would like to exploit the fact that algorithms are not affected by common approaches to solving given tasks like humans are. Therefore we expect that evolutionary search could lead to completely new ideas that haven't yet appeared in a given field. We are curious whether the use of evolutionary algorithms can help to produce quality results while saving resources without adding too much additional work.

Thesis Goals

We aim to use evolutionary algorithms to design a specific component. We will first try to develop a component for an existing device using an evolutionary approach. Our hopes are that the algorithm will quickly find a suitable solution for a given set of requirements. This will eliminate the need for repetitive prototyping, manufacturing and testing. Once we have a suitable candidate, we will manufacture the component, test it and measure its properties.

Another goal is to use the evolutionary approach to search for feasible solutions without limitations by any existing device. We will look for promising variations by specifying only a set of conditions that the outcome should meet without limiting the program by building on currently used solutions.

We will examine the processes of designing, prototyping and testing on a new component for luminaires — reflector from highly reflective metal sheet. The main goal of the reflector is to direct and evenly distribute light rays from light emitting diodes. We will create a program that models the environment and searches for promising solutions. Then we can compare the designing process and results with outcomes from trained professionals.

We are interested in the general overlap of this experiment to other problems and possibly other fields. We intend to discuss possibilities of usage of this or similar approach to a wide variety of tasks concerning designing objects with highly specific purposes.

Thesis Structure

In the first chapter we introduce the reader to the basics of evolutionary algorithms. We start by explaining the main thought behind using an evolutionary approach to problem solving. Then we formalise the idea by explaining the necessary terms and general structure of evolutionary algorithms. We also show examples of the most common genetic operators that are used in this work. To complete the basic structure of the evolution cycle we introduce fitness functions and selection methods that provide data and mechanisms for choosing the next generation. Finally we explain some techniques used for selection with multiple optimization criteria.

The second chapter is devoted to related work review. We start with a brief introduction into the problem of developing components for industrial or scientific use. Then we examine three papers focusing on this topic. The most influential one for us was a paper about automated antenna design that was published by researchers from NASA. We briefly summarize the goal, approach to given task and results for each of the three studies. We intend to point out the merits of each paper as well as discuss their weaknesses. Finally we consider possible contributions regarding our goal.

In the following chapter we introduce the task of designing and manufacturing street lighting. We start with an overview of relevant photometric quantities and other related topics. We follow with a short section on different sources of light. Then we describe a simple model situation for placing street lighting in cities. Afterwards we show the basic structure of the luminaire. Lastly we point out four fundamental requirements for street lamps. Some conditions come from a set of technical standards used in the Czech Republic. Other requirements originate in the effort to produce as much efficient lighting as possible. List of requirements for optimal reflector shape arises from this section.

Fourth chapter is devoted to the search for an optimal shape of the reflector for an existing device. We start with modeling the environment in order to use evolutionary algorithms to look for the best solutions. We explain details of the algorithm we developed with an emphasis on implemented evaluation criteria. Afterwards we introduce properties of the device we are using that are relevant for our work. Finally we describe the use of multi-objective optimization for the search for most promising solutions.

In the fifth chapter we attempt to alter the previous scenario by removing limitations that arise from using an existing device. Instead we explore the search space for completely new designs. Although results from this chapter might not be suitable for manufacturing right away, it can give valued insights into alternatives that have not yet been examined in traditional prototyping procedure. Additionally this unconventional method can lead to a proposal of a completely new device.

In the next chapter we choose amongst the most promising individuals from previous chapters one solution that will be manufactured. We decided to briefly describe observations from this phase also. Although it is not the subject of this thesis, it is important to understand the pitfalls of the whole process, including manufacturing the prototypes. In this part we will also report on testing and measuring properties of the device with manufactured reflectors mounted to it.

In chapter seven we focus on the overlap of our work to related fields. We describe several problems we encountered while applying evolutionary algorithms to a design of an industrial component. We present our solutions and suggest strategies to minimize the amount of similar problems one might experience when attempting to solve a similar task.

In conclusion we summarize achieved goals and present the results. We discuss potential extensions of our work. We propose several paths that could lead to improving our results such as refining our model or modifying fitness functions. We focus on the aspects of manufacturing and practical usage of the component. To conclude the thesis we briefly discuss the importance of the task of automated design.

Chapter 1

Evolutionary Algorithms

Problem solving methods inspired by the process of biological evolution are collectively referred to as evolutionary algorithms (EA). Instead of having one solution and attempting to improve it, evolutionary algorithms work with a group of candidate solutions that are called individuals. Throughout a number of cycles the quality of the population of individuals should be continuously improving due to the use of suitable genetic operators and selection methods. In this chapter we will explain basic terminology and describe the fundamental scheme of EA. Unless stated otherwise the information presented here is based on Michalewicz and Fogel [2013].

According to Mayr [1982] the organisms in nature are continuously evolving to adapt to changes in their habitat. Individuals with traits that help them to survive and prosper in the environment are more likely to produce offspring than less suitable members of the population. Therefore in a course of several generations the average quality of individuals in the population should increase.

In the area of problem solving individuals correspond to solutions of a given problem. The quality of the individual is measured by a fitness function. Initially the solutions are generated randomly and the task is to evolve an individual that will be optimal according to some criterion. The run of a program spans over several cycles, which are called generations. New individuals can be created from the current population by taking parts of two parents and putting them together to form an offspring. This process is called recombination or crossover.

Another way to introduce new traits is to use mutation where small parts of an individual are replaced with randomly generated sections. An important step in each generation is the selection of a new population. The individuals compete, either among themselves or also against their parents, for inclusion in the next iteration. Therefore the search for a problem solution corresponds to the process of natural selection.

1.1 Evolution and Computers

The origins of using evolution inspired algorithms for problem solving can be traced back to the late 1950s. One of the early pioneers was according to Bäck et al. [1997] Richard Friedberg with the publication of two papers which described the use of an evolutionary algorithm for automatic programming. The concept of automatic programming suggests using evolution to develop programs to fulfil specific tasks - in this case to calculate specific input-output function.

While the first attempts for evolutionary computing were mostly theoretical, rather unstructured and scattered over several areas in the mid 1960s the field formed three main research branches: evolutionary programming, genetic algorithms and evolution strategies. Scientific work in the fields continued onwards separately. In early 1990 there was an organized effort to provide a forum for interaction among the various EA research communities. Since then there is more interaction and the three areas are collectively called evolutionary computation.

1.2 Scheme of Evolutionary Algorithm

Figure 1.1 displays the fundamental scheme of evolutionary algorithms. We start by creating an initial population. It consists of individuals suitable for the problem we want to solve. Such individuals vary greatly for different tasks. For some problems it might be enough to work with an array of zeros and ones. For more complex tasks we can use a sequence of integers, decimal numbers or an array representing a permutation. In our case we will design a specific individual with

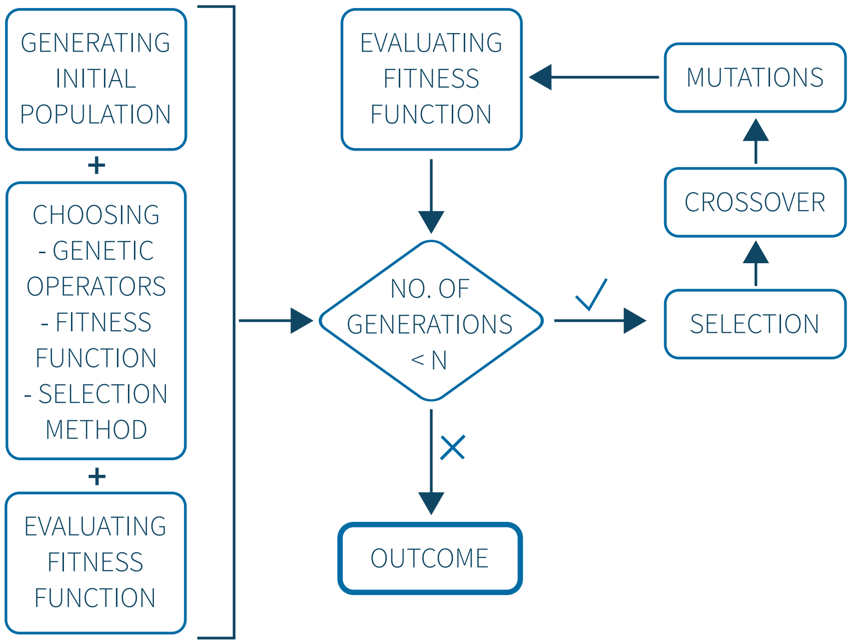

Figure 1.1 Scheme of evolutionary algorithm

properties that can represent qualities of the corresponding solution to our tasks.

The members of the initial population are generated with an element of chance. We want to start with a heterogeneous group of individuals. Some of them might be promising candidates right away while others will lead only to deadends and weak results. One of the strong attributes of evolution comes from genetic operators that are used for combining elements from several individuals into one. Another important aspect is ongoing evaluation of quality of the population which together with available selection methods ensures that we work with a group containing a variety of more or less suitable individuals.

Apart from a suitable type of individual we also need to choose genetic operators, fitness function and selection method in order to produce promising outcomes. We will delve into explaining the purpose and properties of various genetic operators, fitness functions and selection methods later in this chapter.

Before starting the evolution we need to evaluate the initial population. Then we iterate either for a selected number of generations or until some other criterion is met. The stopping criterion can depend for example on the quality of the best individual in the population or it can be conditioned by the difference between individuals from different generations. If two consecutive generations produce very similar outcomes without significant improvement in their quality we might decide to stop the algorithm.

In the evolution algorithm we operate in cycles. We start each iteration by selecting a new generation of individuals. We want to select promising solutions but also we need to preserve diversity in the population. Then we apply genetic operators which modify some of the individuals. Next step is the evaluation of the fitness function for all members of the current population. After that we arrive again at the decision point and based on a stopping condition there we either continue with the selection of the next generation or terminate the evolution and present our results.

1.3 Genetic Operators

The main purpose of genetic operators is to introduce new features or feature combinations into the population. Two most prevalent types of genetic operators are mutation and crossover. We have to carefully pick which operators to use and then we have to implement them properly in order to be usable for our individuals. For each operator we have to state a probability whether it will be used or not.

If the probability is too high, we have an ever-changing, varied population and thus we explore quite a lot of possibilities. However, in such settings it is rather challenging to get to a solution of desirable quality since there is a significant chance that all promising candidates will be modified in an undesirable way before achieving the end of the process. If we decide to set the probability of applying a genetic operator too low, we will move slowly in the search space. It will take a vast number of generations before we get to any viable solution. We also risk getting stuck in some local optima without having the chance to explore other regions.

Therefore it is important to run the algorithm with several different settings for the probabilities and their combinations. We can either test a few options and choose the one which led to the best results. Or we can run through a large

Figure 1.2 Individuals before crossover

amount of probabilities while limiting the number of generations in order to find promising settings in a reasonable time frame.

1.3.1 Mutation

Mutation is a type of genetic operator which takes one individual, changes part of it and returns the modified version. One possibility is to make the alteration completely random. In this case we select uniformly randomly from the pool of all possibilities a new value and replace the old one.

Another option is to somehow base the new value on the original one. An example of this method is adding a number randomly generated from Gaussian distribution with mean zero to the initial value.

1.3.2 Crossover

Another genetic operation is called crossover. We take two individuals and combine them in order to generate two new individuals. The most basic type is one-point crossover. We model this operation on two individuals each consisting of a sequence of elements. (figure 1.2) For simplicity we assume that the length of both individuals is the same. We start by randomly choosing a position for the crossover point. Then new individuals are created by taking the beginning part of the sequence up to the boundary point from one individual and adding the end part from the other individual. An illustration of the result is in figure 1.3.

Similarly to one point crossover, we can use two point crossover. Instead of dividing the original individuals into two sections via one point, we use two points to split the individuals into three parts. Afterwards we create new individ-


Figure 1.3 Result after one-point crossover


Figure 1.4 Result from two-point crossover

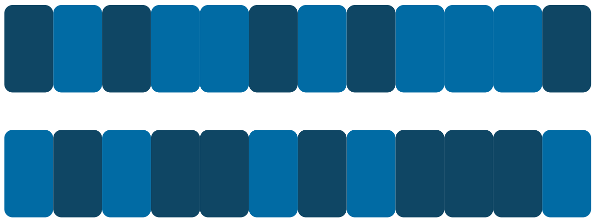
Figure 1.5 Result from uniform crossover

uals by concatenating these sections as displayed in figure 1.4. Another option is to create new individuals by choosing for each position the source individual separately. This method is called uniform crossover. Results after uniform crossover are in figure 1.5.

1.4 Evaluation and Selection

In an evolutionary algorithm we have to be able to evaluate the individual with respect to the objective in a given task. We use a fitness function for that purpose. This function takes one individual and computes a score for it. The output is generally a number which corresponds to the quality of a solution that is represented by the individual. Depending on the problem we either aim to maximize or minimize the fitness function.

While it seems quite natural to want to maximize the fitness function, it might be a little confusing why one would want to minimize it. We illustrate this situation on a well known example. In the traveling salesperson problem we have a set of cities and we know the distances between each pair of cities. The goal is to find a route which goes through each city once, returns to the starting point and is the shortest possible one. We can represent a solution as a permutation of the cities. Then evaluating fitness function would proceed as follows: we add up distances between all consecutive pairs of cities in the permutation not forgetting the distance between the last one and the first one. Therefore the outcome from the fitness function is going to be a number equal to the total distance the salesperson has to travel. For this problem the goal is to minimize the distance, therefore we want to minimize the fitness function. In this task the value of the fitness function is inversely proportional to the quality of the individual.

Once we computed the fitness for each individual in the population, we move to the next step - selecting the next generation. We introduce two common selection methods used in evolutionary algorithms: roulette-wheel selection and tournament selection.

1.4.1 Roulette Wheel Selection

One method for selecting the next generation is based on the idea that each individual is chosen by spinning a roulette wheel once. The wheel has sections with size proportional to relative fitness of all individuals in the last generation. Therefore the better the individual is, the greater is the chance that it will be selected into the next population. One individual can be selected multiple times. Roulette wheel selection method works only for scenarios with non-negative outcomes of fitness function. If we want to maximize the value of fitness, we can use the selection directly. In case our goal is to minimize the fitness function, we can use the inverse value to determine the relative probability that the individual will be selected.

The element of chance in roulette wheel selection ensures that there is variety amongst individuals in the population throughout the run of the evolutionary algorithm. Some solutions are promising from the start while others perform initially slightly worse but eventually can reach more desirable states. Thus there is a smaller chance of getting stuck in some local optima.

1.4.2 Tournament Selection

Another very popular selection method is tournament selection. In its most simple form we work with tuples of individuals. We take two individuals and select the superior one into the next generation. Pairs of individuals are selected randomly from the whole population. This process is repeated until we have a desired number of picked individuals.

We can tweak the settings of tournament selection in many ways. We can use triples instead of tuples or we can decide to choose the best individual with probability less than 1 such as 0.8. These alterations might improve the overall performance of the evolutionary algorithm.

1.5 Multi-objective Optimization

In many real life applications of evolutionary algorithms the individuals need to be optimized according to two or more fitness functions. This is referred to as multi-objective optimization (MOO). The demands are often contradictory. As a result there is no one perfect solution. Instead our goal is to evolve an individual that will achieve some satisfactory results according to all demands or a group of non-dominated solutions that is called the Pareto front.

We say that solution A dominates solution B if A is better than B according to all the criteria we work with. In a set of solutions S we say that solution $X, X \in S$ is non-dominated if there does not exist any $Y, Y \in S \setminus X$ such that Y dominates X. Pareto front contains all non-dominated solutions from a given set.

There are many techniques that can be used as a selection method in multi-objective evolutionary algorithms. In simple tasks one can use a weighted sum of distinct fitness functions for evaluation. For more complex problems there are several methods that work well even with many objectives. We will introduce here the NSGA-II method.

1.5.1 Weighted Sum Method

Very common approach to multi-objective optimization is the weighted sum method according to Marler and Arora [2004]. We have a vector of objective functions $\boldsymbol{F}$ and vector of weight coefficients $\boldsymbol{w}$. The goal is to optimize utility function $\boldsymbol{U}$. Usually we want to search for an individual $\boldsymbol{x}$ that minimizes 1.1 when working with only positive weights.

$$U = \sum_{i=1}^{k} w_i F_i(x) \tag{1.1}$$

Setting weights properly is of a great significance. Especially when one wants to express preferences about particular objectives [Marler and Arora, 2010]. One straightforward approach is to choose weights that correspond to the importance of each objective. However it can be difficult to differentiate between setting weights to indicate the relative importance of an objective and setting weights to compensate for differences in objective-function magnitudes.

For fitness functions with different orders of magnitude another option is weighted product method formulated in 1.2. Weight $\boldsymbol{w}_i$ indicates relative significance of objective i.

$$U = \prod_{i=1}^{k} [F_i(x)]^{w_i} \tag{1.2}$$

When working with weighted sum, weighted product or other similar methods there are two possible approaches. We can either use a single set of weights to get one solution or run the algorithm with several different weight vectors and get a set of promising solutions.

1.5.2 NSGA-II

In Non-dominated sorting genetic algorithm II (NSGA II), [Deb et al., 2000], the authors work with the concept of Pareto front to choose the next generation. First the populations of parents and offspring are combined and non-dominated individuals are identified and moved to the next generation. In the next step we take the remaining candidates and again pick only the non-dominated ones and add them to the new generation. We continue until we reach the desired population size.

If the last selected set of solutions does not fit into the next generation, we take only some individuals in order given by crowding distance. This measure is defined as an average distance between two nearest neighbors on either side of the solution in its non-dominated front for each fitness function. The goal is to keep the population diverse throughout the evolution so we prefer solutions that are far from other individuals in the search space.

Chapter 2

Related Work Review

The problem of designing a specific component that fulfills several requirements appears in a great variety of fields. The traditional procedure is to employ engineers with domain specific knowledge to propose the design of the component that meets all required criteria. Additionally they may be tasked to try to optimize the component according to one or more measures. However when there are too many constraints to work with and qualities to optimise, this approach might not be sufficient. At this point some type of computer aided automation needs to be introduced into the process.

There have been several attempts to use evolutionary computation to look for suitable candidates in the space of all possible solutions. We introduce here three papers that are focused on optimal design of various components using evolutionary approach. The most influential from our point of view is a paper about automated antenna design therefore we will examine it here the most. Other research that will be mentioned in this chapter is also closely related to our area of interest and brings valuable insights both from a theoretical and practical perspective.

2.1 Automated Antenna Design

In Automated Antenna Design with Evolutionary Algorithms [Hornby et al., 2006] the authors described several projects that utilized evolution to search for optimal design of antennas for NASA's Space Technology 5 mission. Their motivation was very similar to ours. Idea of using EA developed because designing antennas by hand is time and labour intensive and requires a significant amount of domain knowledge. Part of the search for an optimal solution can be automated using EA, thus the human involvement can be reduced. Additionally evolutionary algorithms can produce novel and innovative solutions that are more effective than results of more traditional methods. We will not delve into technical details and requirements for evolved antennas. Instead we will look into the process of automated design and we will briefly summarize the results.

In the first attempt researchers worked with open ended generative representation. This means that the antenna had a tree-like structure consisting of wire segments. They decided to evolve a single arm of a four-arm antenna. When candidate solutions were evaluated, four identical copies of one arm were placed together, each rotated 90° from its neighbors. We will use a similar strategy in our work - instead of combining multiple variants, we will develop only one and then use several copies to evaluate the candidate in a more realistic scenario.

After developing an antenna with four identical arms, the research team got new mission requirements that lead to changes in the antenna shape. Now the prototype consisted of only one arm. Also unlike in the previous scenario, in this case the antenna should be non-branching since fabricating prototypes with multiple branches with required precision appeared to be rather difficult. The aspect of manufacturing evolved components should be always kept in mind when forming the criteria that the solution should meet. In our work we intend to evolve components that will be manufactured and therefore we will try to anticipate possible problems and set program parameters accordingly.

The results presented in the paper on Automated antenna design are very promising. The evolved solution was manufactured and thoroughly tested. It met all of the mission requirements and was launched into space. This antenna is the first computer-evolved hardware in space. The designing process and the performance of the final product were compared with outcomes of a team of engineers that used traditional techniques for the same task. The evolved antenna had a number of advantages. It had much better efficiency and also it had fewer parts which resulted in greater reliability. It took approximately three personmonths to evolve and fabricate the prototype whereas the conventional antenna required about five months. The comparison with the traditional approach is of great importance since it shows that evolved components can achieve much better results and also it can take less time to develop them.

2.2 Design of Welded Steel Plate Girder

Another paper on a similar topic is Optimum design of welded steel girders using genetic algorithms [Agarwal et al., 2013]. The main goal of this research is to find a shape of steel girder that will have desired physical properties such as flexural and shear strength and at the same time the weight of the structure will be minimized. Reducing overall weight reduces the amount of used material and therefore it reduces the overall construction cost.

Plate girders are constructed from steel plates that form an I-section. The plates can be tailor-made which offers a great variety of possibilities. Also there are many options for the thickness of the plates. Designing steel girders consists of choosing dimensions for the plates so that the resulting girder meets all criteria while the overall weight is minimized. This task is demanding for humans since there is a vast amount of feasible solutions and it is rather tricky to find the most optimal one.

Authors introduce the task of designing steel girders and present the structure of the algorithm they used to look for the optimal ones. They also explain the fitness function that is used and the technical criteria that the solution must meet. Unfortunately they do not give details about the encoding of individuals and genetic operations.

The conclusion includes a valuable section devoted to comparison of results of conventional design with evolutionary approach. It shows that evolving solutions leads to a minimum of 8.5% and maximum of 10.5% reduction in weight of the girder. The comparison is made on a variety of situations with different demands on length and loading of the girder. It shows that a well designed fitness function, operators and overall algorithm structure can be used in many versatile cases. In our work we will definitely aim to develop a program that can be used to design components for various scenarios according to parameter setting.

2.3 Aerodynamic Shape Design

In paper on Aerodynamic shape design using evolutionary algorithms and new gradient-based metamodels [Giannakoglou et al., 2006] authors used evolutionary algorithms and other search techniques to find a number of 2D and 3D shapes. The problems included both single- and multi-objective optimization tasks for airfoils or turbomachinery blades design. The computations for these types of problems are very demanding since it includes numerical solutions of flow equations. Evolutionary algorithms have many indisputable advantages however they require a great amount of evaluations to reach global optima.

To reduce the amount of necessary computations the authors decided to use approximate evaluation models (metamodels) as surrogates to the exact analysis tools. They described several strategies that can be divided into two basic classes - online and offline metamodels. When using offline metamodels their training is carried out separately from the optimization loop. Online trained metamodels are used inside of each evolution cycle. The goal in both cases is to limit the total number of costly computations while achieving satisfying results.

In our work we used approximate evaluation to search for most suitable settings of the program for evolutionary design. More sophisticated approximate evaluation strategies and possibly metamodels might be used in the future for more demanding computations.

Chapter 3

Street Lighting

The main purpose of this chapter is to offer a brief introduction into fields related to the goal of this thesis. We will start with a review of some areas of physics which include photometry or ray reflection. Then we proceed to present several different light sources that are being used nowadays with emphasis on light emitting diodes. Next section is devoted to the topic of street lighting. It offers a short summary of the history which is followed by an explanation of necessary terminology. Then we delve into the structure of the luminaire itself. This enables us to specify what is exactly our task. Last section looks at requirements and technical standards for modern, safe and efficient street lighting. These demands determine the criteria for design of an optimal optical component.

3.1 Light and Optics

Unless stated otherwise all the information presented in this section are based on textbook Physics of Light and Optics by Peatross and Ware [2011]. Visible light is a type of electromagnetic radiation. It corresponds to electromagnetic waves with wavelengths in the range from 390 nm to 790 nm. Rather than operating with light in terms of waves, we will work with the thought of rays pointing along the direction of wave propagation. Using ray representation is sufficient for our level of detail when dealing with street lighting.

Luminous flux / Luminous power (of a source):
Visible light energy emitted per time from a source.
Units: $lumens(lm)$
Luminous Solid-Angle Intensity (of a source):
Luminous power per steradian emitted from a point-like source.
Units: $candelas(cd)$
Luminance (of a source):
Luminous solid-angle intensity per projected area of an extended source.
Units: cd/m^2
Luminous Emittance or Exitance (from a source):
Luminous Power emitted per unit surface area of an extended source.
Units: lm/m^2
Illuminance (to a receiver):
Incident luminous power delivered per area to a receiver.
Units: $lux; lm/m^2 = lux$

Figure 3.1 Overview of photometric units

3.1.1 Photometric Quantities and Units

In this thesis we will work with several photometric quantities therefore we decided to include an overview of their definitions and units as well as explanations of relations in between in figure 3.1.

Most relevant for us are luminance and illuminance. However we decided to include more fundamental photometric quantities to offer better understanding of the meaning of luminance and illuminance.

3.1.2 Ray Reflection

We aim to design a component that will direct light rays from luminaire in a suitable way to ensure proper illumination of the street. This component will be manufactured from highly reflective silver coated aluminium sheet.

When light falls on a surface, part of it is reflected, part is transmitted through and the rest is absorbed by the material. Proportions between these three parts depend on the material and can vary greatly. In our case we will work with metal sheets with reflectance that is close to 1.

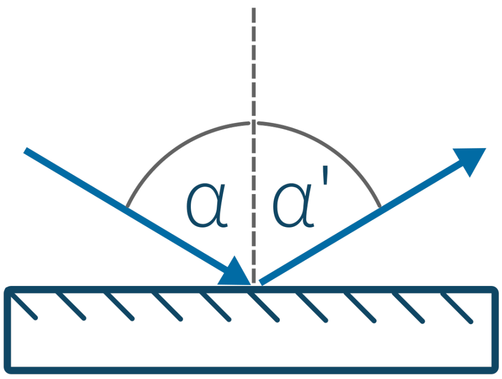

Figure 3.2 Ray reflection

When talking about ray reflections one of the key terms is the angle of incidence. It is the angle between a ray incident of a surface and a line perpendicular to the surface at the point of incidence. In figure 3.2 there is the angle of incidence marked by a letter α. The other angle, marked by a letter α', is called an angle of reflectance. According to the law of reflection, $\alpha = \alpha'$.

3.2 Sources of Light

Earlier sources of light such as incandescent light bulbs used thin metal wires, which emitted light when heated up by an electrical current passing through. This method was very inefficient since a great part of the current was transformed into heat instead of light.

3.2.1 Light Emitting Diodes

The foundation of light emitting diodes (LEDs) is based on semiconductors. Light emitting diode is a component that emits light when current flows through it. Electrons and holes recombine in semiconductors and photons are emitted as a result. This method is much more efficient than incandescent light sources. The amount of light that is emitted varies for different directions. The intensity of light from LEDs usually corresponds to Lambertian distribution (figure 3.3).

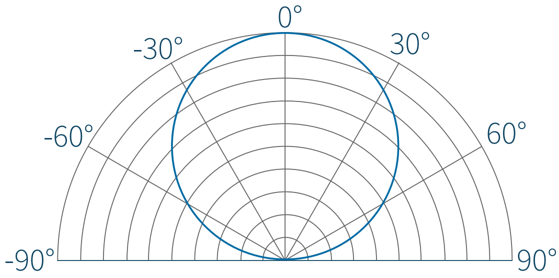

Figure 3.3 Lambertian distribution

We will be using LEDs manufactured by Samsung, more precisely the LH351B type, in our experiments. This type is suitable for indoor, outdoor and industrial applications since it offers a CRI (color rendering index) of 80. Color rendering index measures the ability of a light source to display colors compared to the ideal natural light. The properties in terms of light distribution can be approximated with aforementioned Lambertian distribution. Images of the LED are in figure 3.4.

Figure 3.4 LED - type LH351B, Source: Data Sheet LH351B, Samsung

3.3 Street Lighting

The field of street lighting does not receive much attention even though street lamps are ubiquitous and towns and cities spend significant parts of their annual budgets on maintenance and construction of street lamps and related infrastructure. There is on average one street lamp per seven residents in cities and towns in the Czech Republic, [Tesař, 2010].

The presence of street lighting improves safety in towns and cities. According to Chalfin et al. [2021] the investments into street lighting in new public housing areas in New York City returned after approximately six years thanks to reduced criminality and related costs in the examined area. Similar studies were carried out in Britain according to Painter and Farrington [1999]. In addition to reducing crime rate the safety of citizens is increased in other means. Well lit pavements and roads prevent unnecessary accidents in urban areas. Therefore street lighting has become an integral part of all modern municipalities.

History of street lighting goes back to the middle ages when torches were used to illuminate the streets. Since then improved, safer and more efficient methods were developed. In the nineteenth century gas lighting was introduced in European cities and to this day several major cities have kept gas lamps as a part of their historical centers, [Schulte-Römer, 2014].

Another step was the introduction of electrical street lighting towards the end of the nineteenth century in central Europe and in a few decades later in the United States, [Holden, 1992]. Electrical street lighting remained to this day and the main focus throughout the last century was on improving the efficiency. One of rather widespread types nowadays are high pressure sodium-vapour lamps, which can be easily recognized by their yellow to orange light color. Their drawbacks include poor color rendering. Also in some configurations they achieve low efficiency.

3.3.1 Simplified Street Lighting Model

In order to describe our goal regarding using the evolutionary approach to develop a component for street lamps, we have to explain some terminology first. In figure 3.5 there is a basic scheme of a street lamp. Letter A represents a pole, which is usually a part of the necessary infrastructure for each lamp. In some special cases, we can mount a street light directly onto a building. However such installations are quite rare and rather impractical, so we will not discuss them

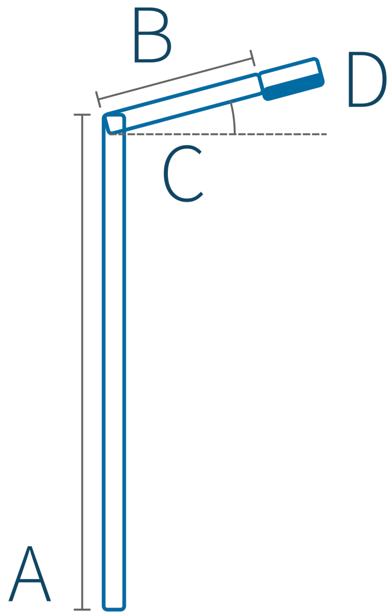

Figure 3.5 Scheme of a street lamp

here. The most significant property of street light poles is their height.

Next component of the majority of street lamp installations is the bracket arm (letter B). It is usually a metal rod connected on one end to the pole and on the other end to the lighting fixture. Most important properties are its length and tilt angle (letter C). Together with the height of the pole these characteristics determine the final height of the light fixture and its tilt angle. The light fixture is marked by letter D.

The pole is usually placed next to a road and the arm bracket is perpendicular to the road. There is a great variety of different scenarios. Generally the luminaire should illuminate the road below and ahead the fixture. In some cases we want to direct part of the light also behind the fixture or even behind the pole. The reason for that is usually a pavement for pedestrians that is placed behind the lighting pole.

In most cases several street lamps are placed along one or both sides of the road. The spacing of individual lamps is another key parameter that influences the quality of the lighting system as a whole greatly.

3.3.2 Luminaire Structure

There exist many variants of the overall structure and individual components for luminaire for street lighting. Each single device contains distinct parts that fulfill specific functions from power supply to water resistance. We will be interested mostly in light emitting diodes and accompanying optical components. In this section we will introduce some basics that are fundamental for understanding the following segments.

Figure 3.6 Luminaires with LEDs

In figure 3.6 we show two fundamental types of luminaires with light emitting diodes. On the left there is a device with only one LED that is rather large. The other image displays a device with an array of tens of smaller LEDs.

Next component, the optical part of the device, is the focus of our research. The main purpose of the luminaire optics is to reflect light rays outwards from the fixture and direct them towards the road below. It is usually manufactured

Figure 3.7 Optical part - reflectors

Figure 3.8 Luminaire Satheon L

from some type of highly reflective aluminium sheet. Previously only one vast aluminium reflector was used with sodium-vapour or mercury-vapour lamps. Its main purpose is to reflect rays that would otherwise end up in vain in the device itself. Another possible approach is designing a small reflector for each single diode that is in the light fixture. This strategy can enable directing light rays more precisely. Example is shown in figure 3.7.

In our experiments we will work with a type of luminaire called Satheon L (figure 3.8), which has 32 diodes. We will aim to develop a universal shape for a small reflector that can be placed around each diode. The goals for this reflector and its properties arise from technical standards and modern efficiency demands.

3.4 Requirements and Technical Standards

There are four main requirements for lighting systems today: uniformity, glare reduction, efficiency and elimination of obtrusive light. It is recommended to attempt to optimize the optical part of the luminaire for all of the requirements at the same time since sometimes these goals can result in conflicting demands. If we were to optimize the device according to one parameter at a time the result might not be suitable at all. In the rest of this chapter we explain all the individual requirements for street lights together with corresponding technical norms and other related technical, environmental and safety concerns.

3.4.1 Longitudinal Uniformity

First requirement deals with uniformity of light coming from the luminaire and the lighting system as a whole. Light emitted from street light should fall on the ground as uniformly as possible. The main goal is to avoid scenarios where some areas are illuminated a lot while other areas are in darkness. Such situations are dangerous for pedestrians, cyclists and drivers.

The amount of light and its distribution should be appropriate for a given street class. In the Czech Republic we have three main types of streets: P (area dominated by pedestrians), M (area dominated by motorized vehicles) and C (conflict area) as stated in technical norm ČSN EN 13 201, [ČSN 13201]. There are several classes for each type of the street such as M1, P1, C1, M2, P2, C2 and so on.

Classification to a particular class is determined according to a number of different conditions. Relevant information include number of cars, pedestrians and cyclists that are using the road, the width of the street, number of traffic lanes, whether there are parked cars on the street and few other similar parameters.

There are precise requirements for quality of street lighting specified by the standard ČSN EN 13 201 for each class. They include average road luminance, minimal and average illuminance, longitudinal uniformity, average uniformity, threshold increment and few others. The exact values are given for each type and class. Quiet streets in residential areas with minimal traffic have different safety needs than large roads with multiple lanes or situations where cars, pedestrians and cyclists have to coexist together.

In our thesis we will not aim to develop models achieving some specific values for luminance or illuminance since these values depend on power consumption and efficiency of a given device. Instead we will focus on longitudinal uniformity of road surface luminance which is defined as the ratio of the lowest to the highest value over all sections of the road. We will work with two thresholds for the uniformity criterion. If the outcome achieves a value of at least 0.4 it will be considered as satisfactory. In case it surpasses 0.7 it is assessed as excellent.

3.4.2 Glare Reduction

Another aspect that is definitely worth taking into account is glare produced by the luminaire and its elimination. This problem arises from the fact that LEDs are very small and at the same time they produce a lot of light. Glare causes discomfort or reduction in the ability to see objects and details, [Kasahara et al., 2006]. One approach to limiting glare effect from street lights is using more LEDs that are less powerful instead of using only few powerful ones in the luminaire. Another possibility is enlarging the area that directs the light from the luminaire.

In our simulations we will choose one of two possible scenarios. We will either use a device with many small LEDs that are spread out over a large surface or we will use only a few more powerful LEDs and use reflective segments to expand the area which directs the rays towards road users.

3.4.3 Efficiency

Third important goal for modern street lighting is its overall efficiency. Our goal is to develop optics that will direct light from LEDs only onto the road and adjacent infrastructure. If light rays are emitted or reflected into the luminaire itself it is clearly not an efficient device.

When a light ray is reflected from a surface it loses part of the intensity. Although the silver coated aluminium metal sheets that are being used nowadays in luminaire optics are highly reflective, the reflectance is still not perfect. When developing a new optical part one must count the number of ray reflections and calculate the loss of intensity to assess the overall efficiency of the device. For the fixture to be usable in practice it has to achieve efficiency of at least 80%.

3.4.4 Obtrusive Light Elimination

Light rays that are directed outwards but fall outside of assigned areas are also wasteful. Moreover the light that goes outside of the designated area can disrupt the surroundings. This is a problem in rural areas, where redundant lighting can unnecessarily affect the environment. In urban areas poorly directed light can bother the residents during night time. This is usually referred to as the problem of obtrusive light.

Closely related is the issue of light pollution. Artificial light and its significant extent affect not only astronomical observations and related fields but there are growing concerns about its impact on human health and ecological processes according to Bennie et al. [2014]. Therefore it has been recognized as a significant global environmental issue.

Street lighting is one the most common contributors to light pollution. Other causes include billboards with LED lighting, advertising panels or illuminated industrial areas. When designing a luminaire prototype one should definitely avoid directing any part of the light rays upwards or in fact anywhere but the designated segment of the road below the lamp. This can be problematic in situations which involve illuminating historical sites or other monuments since they are usually illuminated from floodlights that are placed on the ground and the light is directed upwards. In our case we focus on street lights only so the situation is easier. Still the elimination of light pollution is an important factor to consider when designing a street light.

When selecting promising individuals we want to eliminate upwards directed rays completely. The amount of obtrusive light should be minimized. However the transition from illuminated road to its surroundings must be gradual. Otherwise the situation could be dangerous for drivers. The scene would not appear three-dimensional which causes errors in judgement for velocity and distance of oncoming vehicles. We will attempt to reduce the amount of obtrusive light and then when selecting individuals for further work we will also take related problems into consideration.

Chapter 4

Improving Existing Device

Our first goal is to design an optical part for luminaire that is used in street lighting. In this chapter we focus on evolving optics for an existing device — luminaire Satheon L. First, we introduce the street lighting model we designed and an algorithm we developed to search for potential solutions for our problem. We also describe all genetic operators we designed. To wrap up the section on the street lighting model we briefly touch on the aspect of visualization of evolved solutions. Then we proceed to explain several criteria for optimization. We follow with an introduction of the device Satheon L and its properties that are most relevant for our work. We conclude this chapter with a section on multi-objective optimization where we present our evolved solutions.

4.1 Street Lighting Model

Instead of working with a three-dimensional model directly we decided to use two perpendicular two-dimensional cuts. One of them depicts the cross section of the road directly below the luminaire. The other one illustrates the longitudinal section of the street which intersects the luminaire. We designed a street lighting model that can be used to evolve and visualize solutions for both two-dimensional sections. The final component is created by running the algorithm with two different parameter settings and combining the results.

In our model, we started with a luminaire that is in a given height over a road

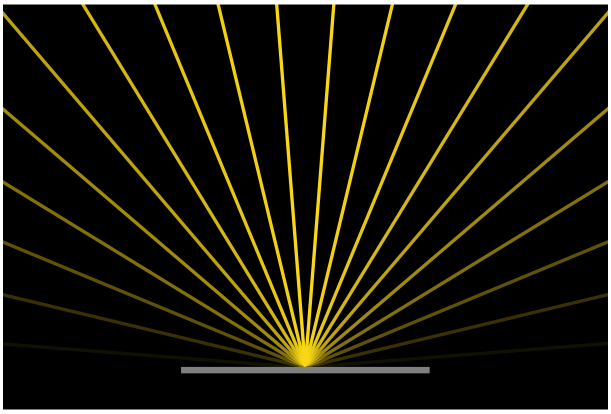

Figure 4.1 Ray distribution

segment of a given length. The luminaire for now consists of only one LED with Lambertian distribution of light intensity. The light emitting diode is placed on a base that forms a given angle with a horizontal line. Luminaire height, road length, base angle and many other parameters can be set as required.

One very important parameter for the model and the subsequent evolution run is the number of rays that should be used. We decided to model the Lambertian distribution as follows - we send the same amount of rays in all directions in the half-plane however the ray intensity varies and is determined by the angle that the ray forms with a line perpendicular to the base. In figure 4.1 there is an illustration of a LED with 20 rays where the intensity of each ray is represented by the color opacity.

The strategy for designing optics for devices with light emitting diodes we used is placing several reflective segments next to each diode. When ray intersects the segment, it is reflected according to the law of reflection. The reflectance of the surface of the material for reflective segments can be set as a parameter of the program as well. We worked with silver coated aluminium sheets with reflectance of 98%. Therefore when a ray R with intensity I is reflected, the intensity of reflected ray R' is $I' = I \times 0.98$. Figure 4.2 displays a diode with 20 rays and two reflective segments. While some rays leave the device directly, other rays can be reflected once or even multiple times as can be seen in the highlighted ray in the figure.

In figure 4.3 there is a visualization of a model where we have one LED placed

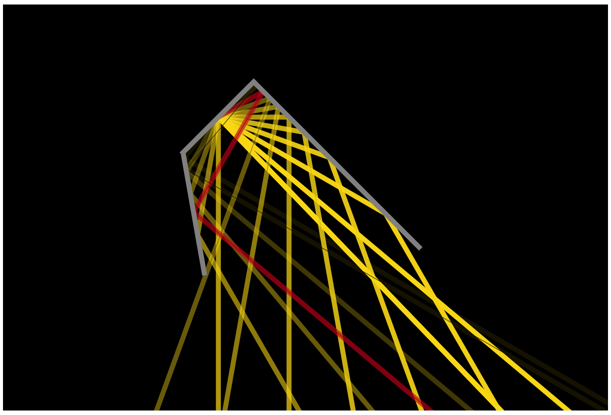

Figure 4.2 Reflecting Rays

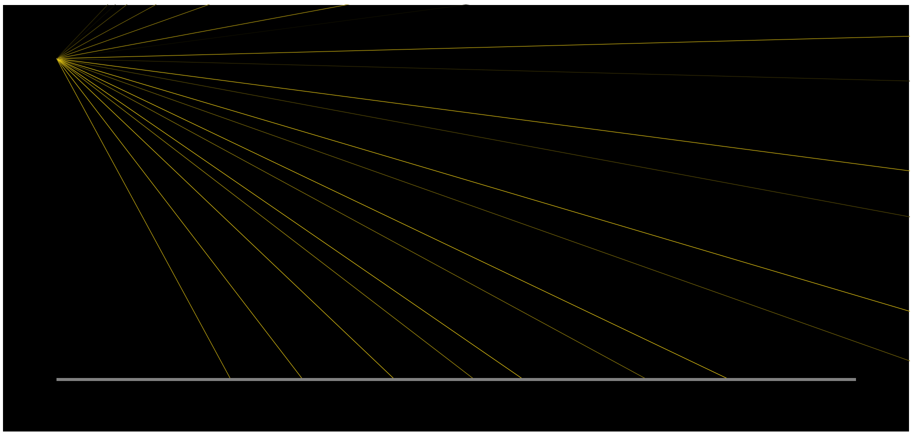

Figure 4.3 Two dimensional model

6 meters above the road attached to a base that forms an angle of $60°$ with horizontal line. The road starts right under the luminaire and stretches 15 metres to one side. There are two reflective segments connected to the base.

4.1.1 Algorithm

When searching for optimal configuration of reflective segments we started with a population of randomly generated individuals and then used suitable genetic operators and tournament selection to evolve a solution according to specified fitness function. In the most restricted configuration, the base angle is fixed together with luminaire height, road start and road length.

Individual (Component) — *configuration with two reflective segments connected to the base*

Base (2D segment): calculated from base angle and length, midpoint is at point (0, 0)

Right angle (int): the size of angle formed by base and right segment

Left angle (int): the size of angle formed by base and left segment

Right length coefficient (float): determines the length of right segment

Left length coefficient (float): determines the length of left segment

Right segment(2D segment): calculated from base coordinates, right angle and right length coefficient

Left segment(2D segment): calculated from base coordinates, left angle and left length coefficient

---

Figure 4.4 Structure of an individual - existing device

In figure 4.4 we describe the structure of one individual. The angle size and length coefficient for each reflective segment is generated randomly from a specified range during initialization. We limited the angles to be from $90°$ to $180°$. This should ensure that no light rays are reflected back into the device and thus the optics is efficient. We set the lower bound for coefficients to 1 and upper bound to 3. The total length of a segment is equal to the base length multiplied by corresponding length coefficient.

During the run of the evolution several different mutations can be applied. The angle the segment forms with a base can be modified as well as the length of the segment. During angle mutation a number generated from range (-10, 10) is added to the original value. In the length mutation operator we generate a random number from range (-0.1, 0.1) and add it to the length coefficient. If the angle or the length of the segment was to surpass specified upper or lower bound for the quantity, it is replaced by the limit value. Another genetic operator that was used is crossover. This operator takes two individuals and swaps one of the two segments.

The probability for each genetic operator can be set in parameters of the

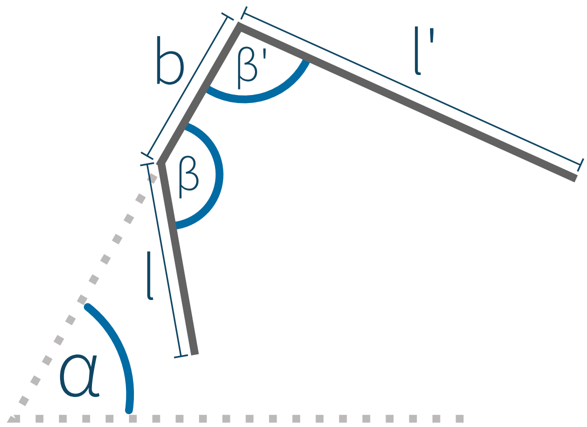

Figure 4.5 Reflective segments parameters

program. Also all dimensions, angles and limitations can be set. We worked with millimeters for lengths and degrees for angles. The length of reflective segments depends on the length of the base.

In example 4.5 the base angle is denoted by α, base length is marked by the letter b. Upper bound for the size of angles β and β' is $180°$ while lower bound is $90°$. The length of reflective segments l and l' can range from b to $b \times 3$ unless specified otherwise.

Over the course of the run of the program we employ elitism. It means we keep one best solution throughout all generations. If an individual with better fitness is evolved it replaces our elite individual in so-called hall of fame. This ensures that we do not lose the best solution due to mutation or crossover. For each generation we log fitness of best individuals as well as average fitness in population. We also keep length and angle records for the top solution in each generation. This enables us to see the progress in the evolution and also it provides data necessary for creating a prototype of the component. Best individual in each generation is also visualized.

4.1.2 Visualization

Visualization is done through generating images in SVG (Scalable Vector Graphics) format. The dimensions of the generated image depend on the position of the luminaire and coordinates of road start and road end. Each ray is depicted as a set of lines that trace all of its reflections. We selected the color for rays to be light yellow to contrast with black background. The color opacity of each ray corresponds to the original intensity once it is emitted from the LED. If we work with multiple LEDs all of them are visualized in the image together with their base and reflective segments.

The SVG format has many advantages. It can be modified either in any text editor or in a vector graphics editor. Therefore we can easily examine the details as well as overall results for individual solutions. Visualizations were essential both for development of the program and for assessment of results from a practical point of view.

4.2 Evaluation Criteria

We decided to work with three different criteria for automated evaluation of the quality of individuals: longitudinal uniformity, obtrusive light reduction and overall efficiency of the device. In this section we present examples of individuals that are most suitable and least suitable according to these three criteria separately. We also discuss properties of these examples as well as relations between different quantities. Experimenting with this simplified scenario offers valuable insights for our work in more complicated settings.

$$efficiency = \frac{\sum_{ray \in rays-after-all-reflections} intensity(ray)}{\sum_{ray \in rays-emitted-from-LED} intensity(ray)} \tag{4.1}$$

In efficiency calculations we take the sum of intensities of rays that are coming from the device and divide it by the total intensity of all rays that are emitted from the LED (4.1). The losses in ray intensity are caused by reflections in the device and depend on the reflectance of used materials. For some luminaires the inefficiency is also due to overall flawed design which can lead to directing significant part of the rays back into the device itself. In our case we work with a specific luminaire design where together with suitable parameter settings we should be able to avoid this problem completely.

In figure 4.6 we display prototypes with high efficiency on the left and low efficiency on the right. Although we use highly reflective silver coated metal sheets with a reflectance of 98%, if there are too many ray reflections in the device, some part of the intensity is lost. While most suitable candidates have an efficiency of almost 100%, displayed poor solution has efficiency of only about 95%. Still this is very good since acceptable prototypes have to have an efficiency of at least 80%. However if the parameters of the program were different, the efficiency could be lower and thus we should always check the 80% threshold when selecting a viable candidate for further work.

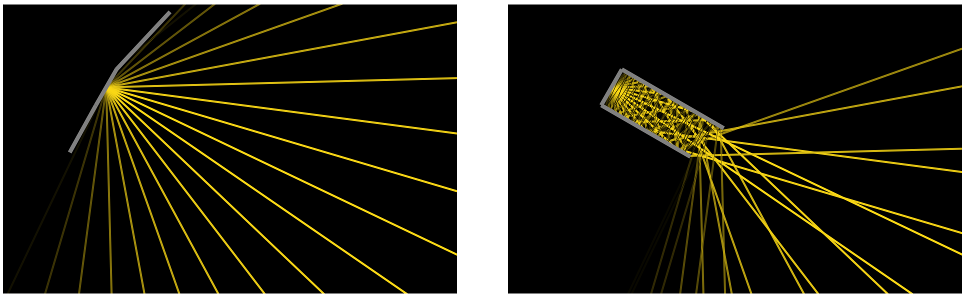

Figure 4.6 Optics efficiency - examples

$$obtrusive - light - el. = \frac{\sum_{ray \in road-intersections} intensity(ray)}{\sum_{ray \in rays-after-all-reflections} intensity(ray)} \quad (4.2)$$

Another important requirement for luminaire optics is elimination of obtrusive light. In our evaluation function we calculate what part of light is directed towards the road and we consider the rest to be obtrusive light. We sum the intensity of rays that intersect the road and divide it by total intensity of all rays from the device (4.2). In figure 4.7 we compare desirable and undesirable solutions. Ideally all of the light rays should intersect the road. We attempt to minimize the amount of light that will be directed elsewhere. The optical part that is displayed in the left image directs light rays very well, the amount of obtrusive light is less than 1%. In the other example more than 75% of the light intensity is directed outside of the road segment. When choosing a suitable prototype we attempt to minimize the amount of obtrusive light and we should definitely avoid individuals that direct any part of the light upwards.

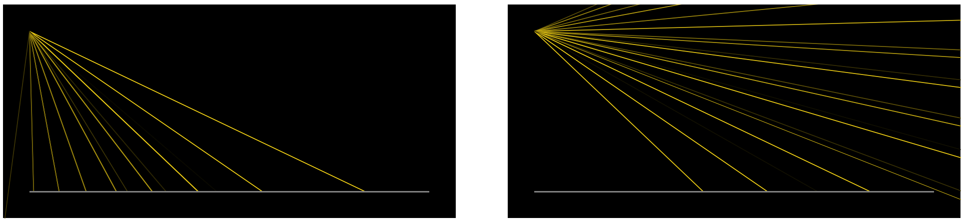

Figure 4.7 Obtrusive light elimination - examples

$$l. - uniformity = \frac{min_{sections}(\sum_{ray-intersecting-section} intensity(ray))}{max_{sections}(\sum_{ray-intersecting-section} intensity(ray))} \quad (4.3)$$

Third evaluation criterion in our experiments is longitudinal uniformity. It is calculated as the ratio of the lowest to the highest road surface luminance (4.3). We divide the road into a given number of segments and then for each sum the intensity of rays that intersect a given road segment. We decided to visualize the intensity of incident rays for each segment with red color. In examples in figure 4.8 there can be seen that the more intensity falls on a given section the brighter its color. The promising candidate on the left achieves longitudinal uniformity of 0.77. This is sufficient for all types of lighting classes from motorways to small regional roads. The example on the right has longitudinal uniformity 0 since there is one section with no incident rays at all.

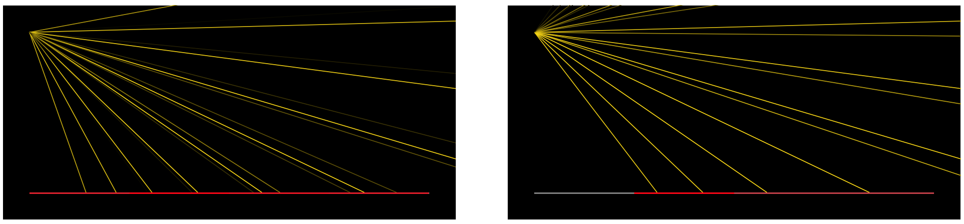

Figure 4.8 Longitudinal uniformity - examples

We can see that the best individual according to longitudinal uniformity criterion would perform poorly in the obtrusive light assessment. In addition we can assume that the most effective device would also generate a great amount of obtrusive light. Therefore we have to use multi-objective optimization to search for individuals that will be usable in practice.

4.3 Device Properties

Prior to delving into multi-objective optimization, we have to introduce technical parameters of the luminaire we will work with. We chose device Satheon L from manufacturer SATHEA VISION. In the device there are two rows of LEDs which are placed on laterally symmetrical bases with angle α of 60°. In figure 4.9 there is a photograph of a frame of the device as well as a cross section with dimensions relevant for our work.

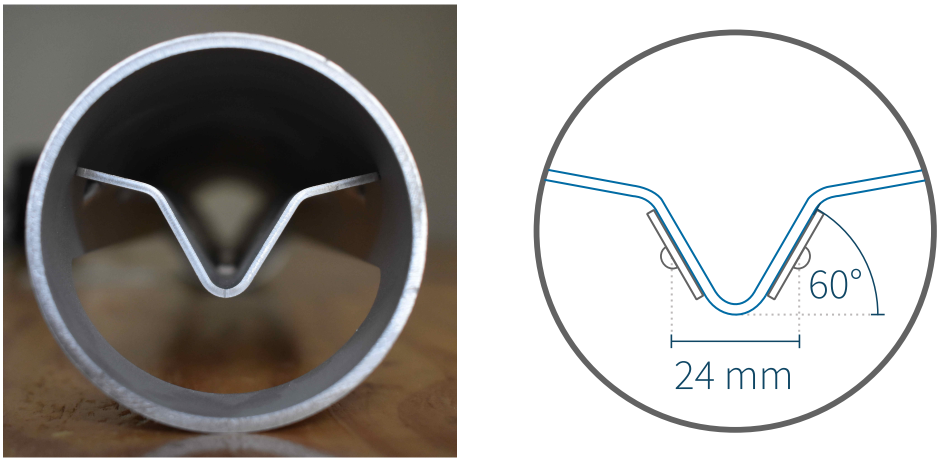

Figure 4.9 Base for LEDs

In our experiment we will evolve optimal reflective segments for one base. Then when evaluating individuals we will use several identical copies similarly to the technique used in section 2.1. Here, we will use two copies which are laterally symmetrical and placed a specified distance apart. For Satheon L the distance separating LEDs on one base from LEDs on the other base is approximately 24 mm. Computation with two mirrored LEDs will provide us with data about the ray directions along the road.

When optimizing the component for a perpendicular cross section, we have to examine the base itself. There is a module containing 16 LEDs mounted to each base. The distance between two LEDs that are placed next to each other is again 24 mm. Part of the module is displayed in figure 4.10. When evaluating individuals we use 16 identical copies of LED and adjacent reflective segments spaced 24 mm apart.

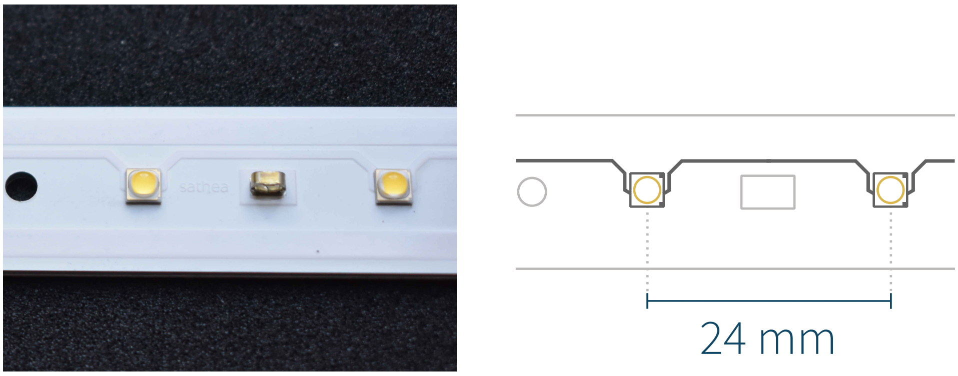

Figure 4.10 Module with LEDs

To search for a component that will be compliant with an existing device we have to set the parameters accordingly. For each of the two variants we set not only a number of LEDs but we also specified whether they are shifted or mirrored and what is the separating distance between them. Parameters for luminaire height and road coordinates originate in the most common street lighting scenario. We worked with a height of 6 metres and a road segment that is 30 metres long with the device placed in the middle. Regarding the width of the road we placed the start 3 metres behind the first LED and 6 metres ahead. This corresponds to a situation with a road of width of 6 metres where we want to illuminate also a 1.5 metre wide strip next to it on both sides. We used multi-objective optimization to search for the most suitable configurations of reflective segments.

4.4 Multi Objective Optimization

In multi objective optimization we used weighted sum method, which is described in subsection 1.5.1. We have three fitness functions, each generates a value in range between 0 and 1. Therefore all have the same magnitude which is convenient for this optimization method. We decided to maximize the utility value so we used *obtrusive light elimination*, *efficiency* and *longitudinal uniformity* fitness functions.

Benefits of usage of weighted sum method for this type of task include the versatility that comes from setting the weight for each criterion separately. We can exploit this and with one program we can find solutions to two different scenarios. With different parameter settings we can evolve individuals for both cross section and longitudinal section of the road.

First we optimized the reflector according to requirements for the longitudinal section. We set parameters for a given situation and prepared the optimization. We started with weight vector $w = [1, 1, 1]$ and attempted to evolve an optimal optical part for the selected device. After a few trial runs we decided to split the road into 9 sections, which should ensure sufficient uniformity results. With the basic weights setting the longitudinal uniformity criterion appeared to be the most troublesome. Solutions with high efficiency and strong obtrusive light elimination properties which received great overall score performed poorly in terms of longitudinal uniformity. This came as no surprise since we anticipated that illuminance uniformity will be the most tricky criterion.

We performed several runs and modified the weights in a few different ways. It is evident that the weight for longitudinal uniformity must be significantly greater than weight for efficiency. Vast majority of solutions that are initially generated or evolved over time reach high efficiency. Meanwhile achieving sufficient longitudinal uniformity is more complicated. We decided to use $w_{efficiency} = 1$ and $w_{longitudinal-un.} = 15$ to put more emphasis on the second criterion. For obtrusive light elimination we tested several options end ended with $w_{obtrusive-light-el.=4}$.

Over a course of a few runs of the algorithm we evolved a couple of individuals that got acceptable results. It means the efficiency was at least 80%, the longitudinal uniformity was at least 0.4 and only a small part of light rays was directed outside the desired area. However one problem kept occurring - a small part of the rays was directed upwards in some cases. This is a very undesirable situation which contributes to light pollution and should be avoided at all times. Therefore we decided to add one more objective to tackle this issue. We added a fitness function which calculates the number of upward directed rays and assigned a weight $w_{upwards} = -1$. Therefore for each ray that is directed upwards we penalize the aggregated fitness a lot. This should ensure that no solutions with this issue appear amongst best individuals.

In figure 4.11 there is the best solution from evolution run with 40 light rays for each LED, therefore there were 80 rays in total. We evolved a population of 8 individuals over 64 generations. We set a probability for all genetic operators to 0.4. The overview of parameters setting is in listing 1. Selected individual has efficiency of 99%, longitudinal uniformity 0.37 and amount of obtrusive light at 22% with zero rays directed upwards. We are aware that the value for longitudinal uniformity is slightly below the threshold we set earlier. Yet we decide to choose this solution to work with since we assume that it will perform well in real life application.

The left reflective segment is $11.33mm$ long and it forms an angle of $148°$ with a base. The right segment has length of $9.47mm$ and it forms an angle with the base of $113°$. Detail of the best individual is displayed in 4.12. We placed the cross section of the luminaire in the visualization to better illustrate the situation as a whole.

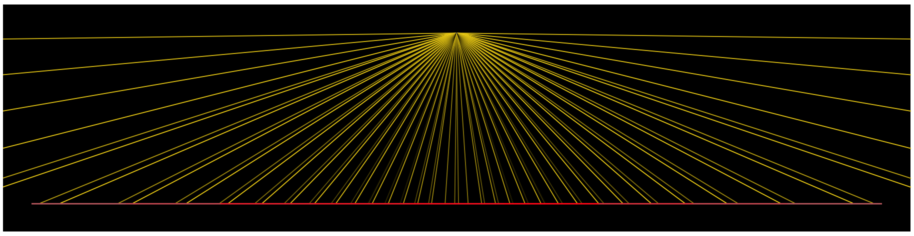

Figure 4.11 Road longitudinal section - evolved optics

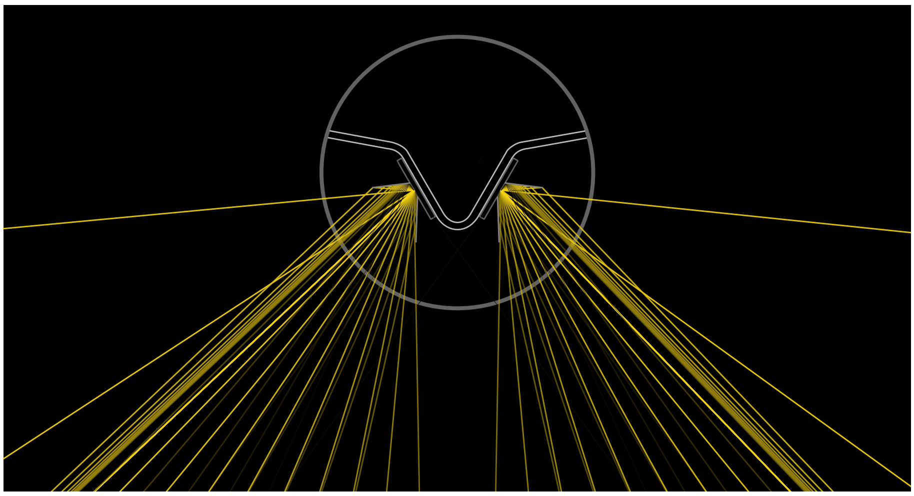

Figure 4.12 Road longitudinal section - detail of evolved optics

Listing 1 Parameter settings for longitudinal section


```
"lamp": {
    "number_of_LEDs": 2,
    "separating_distance": 24,
    "modification": "mirror",
    "number_of_rays": 40,
    "base_length": 4,
    "base_slope": 60,
    "configuration": "two connected",
    "two_connected": {
        "angle_lower_bound": 90,
        "angle_upper_bound": 180,
        "length_lower_bound": 1,
        "length_upper_bound": 3
    },
},
"road": {
    "start": -15000,
    "end": 15000,
    "depth": -6000,
    "sections": 9
},
"evolution": {
    "population_size": 8,
    "number_of_generations": 64,
    "operators": {
        "mutation": {
            "angle_mutation_prob": 0.4,
            "length_mutation_prob": 0.4,
        },
        "xover_prob": 0.4
    }
},
"evaluation": {
    "reflective_factor" : 0.98,
    "criterion": "weighted sum",
    "weights": [1,10,4,-1]
}
```

Afterwards we modified parameter settings for the program and again used weighted sum method, this time to search for the best solutions for the model of the cross section of the road. After some testing we chose weight setting as follows: $w_{efficiency} = 1$, $w_{longitudinal-un.} = 5$, $w_{obtrusive-light-el.} = 6$ and $w_{upwards} = -1$. This weight configuration reflects the requirements for this situation well enough. The efficiency of the optical part is usually not a problem. However longitudinal uniformity and obtrusive light elimination are more complex and thus require more emphasis in aggregated fitness. In this configuration it is a bit easier to create uniform illumination since the road width is smaller than the length of the road segment we worked with in the model of longitudinal section. We have to pay attention to the amount and direction of obtrusive light. We want to illuminate 1.5 metre wide strips on each side of the road since this area usually contains sidewalks. Apart from that we want to limit the amount of light that is directed outside of the road since it might fall on surrounding buildings and that is rather undesirable.

For the road cross section we used 16 LEDs, each modeled by 40 rays. The base angle was set to $0°$. We decided to split the road into 6 sections for uniformity calculations. With an appropriate street lighting model we continued with setting the evolution parameters. The probability for all genetic operators was set to 0.4. We evolved a population of 8 individuals over 64 generations. The overview of parameters that vary from previous settings are in listing 2.

We selected an individual with efficiency of 99% that reached longitudinal uniformity of 0.45 and generated obtrusive light of 8% of total emitted intensity from the device. In figure 4.13 there is visualization of the road cross section and a detail of one LED with two reflective segments. The left reflective segment is $6.95mm$ long and it forms an angle of $103°$ with a base. The right segment has length of $9.17mm$ and it forms an angle with the base of $139°$. In figure 4.14 there is an illustration of the evolved optics in the device.

We ran the program for both cross section and longitudinal section multiple times expecting it would converge to similar results every time. To our surprise we got several variants of reflective segment configuration that reached similar values for all fitness functions. When selecting an individual to be manufactured we attempted to choose a solution suitable for practical use.

Listing 2 Parameter settings for cross section

```
"lamp": {
    "number_of_LEDs": 16,
    "modification": "shift",
    "base_slope": 0,
},
"road": {
    "start": -3000,
    "end": 6000,
    "sections": 6
},
"evaluation": {
    "weights": [1,5,6,-1]
}
```

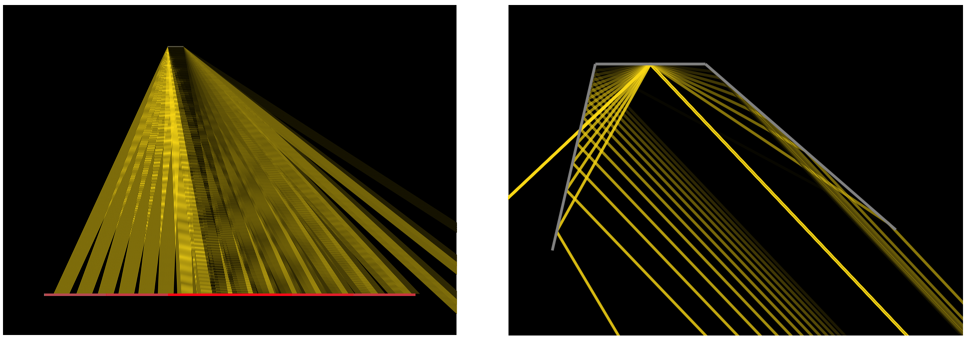

Figure 4.13 Road cross section - evolved optics

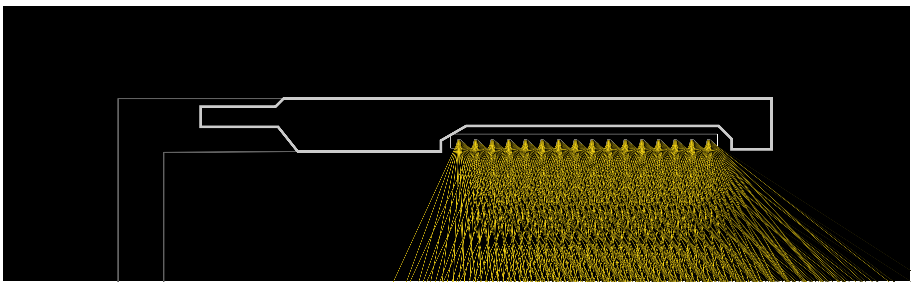

Figure 4.14 Luminaire with evolved optics

Chapter 5

Evolving New Luminaire

After optimizing an existing device we decided to use an evolutionary approach to generate completely new design. In this task we aim to generate an optical part for luminaire that can be used in parks, squares and other urban areas. We have some set of basic requirements the final device should meet. We also have some basic strategy about the types of LEDs the device should contain and their placement in the device. Still the algorithm has a lot of freedom to generate new and innovative optical parts. We intend to use the outcomes as a foundation for developing the overall design of a new device.

5.1 Requirements and Limitations

Unlike in the previous task where we had to direct all rays only on the road, in this case we want to design a luminaire which would distribute the same amount of light in all directions in the surrounding area.

Our model for this task is based on current trends in the area of urban fixtures. Although there are many different types of devices, they share some common properties such as rotational symmetry. Also this type of device is usually mounted directly on the pole and there is no need to use a bracket. We present two examples of fixtures that are being used nowadays. In figure 5.1 there are luminaires Clima 1518 (on the left) and Loto 3340 (on the right) both from the manufacturer Disano.

Figure 5.1 Luminaires for urban areas, manufacturer Disano Illuminazione

We intend to create a luminaire which will also have rotational symmetry. We will evolve only one section with one LED that can be afterwards copied multiple times to create the entire fixture. In our model we will work with LEDs placed 4 metres above the ground. We want to illuminate the area within 12 metres from the pole. We divided the road into 4 sections for uniformity calculations. This is the most common setting for illuminating urban areas. However the user can alter the parameters to develop devices for other scenarios.

5.2 Evolutionary Algorithm

We initiated the algorithm with a population of randomly generated individuals. Each individual consists of a set of reflective segments that are placed near the LED. Segments have various lengths and are randomly rotated in the space. Parameters for the number of segments, their length and distance from the diode can be set by the user. The initial base angle and parameters for base angle minimum and maximum can also be set. The representation of an individual is in figure 5.2.

Four types of mutations were implemented: segment shift, segment rotation, segment resizing and base tilt. Segment shift is done via adding one random value from range (-100, 100) to both ends of the segment either for x or y coordinate. This means that with a certain probability one reflective segment is shifted

Individual (Component) — *configuration with multiple reflective segments that are not connected to the base*

Base angle (int): the size of angle formed by base and horizontal line

Base length (int): the length of the base

Base (2D segment): calculated from base angle and length, midpoint is at point (0, 0)

Reflective segments (List[2D segment]): List of reflective segments

Figure 5.2 Structure of an individual - new device

up to 10 cm upwards, downwards or sideways. In segment rotation the chosen segment is rotated around its midpoint clockwise or counterclockwise for up to $30°$. In resizing mutation the segment can be shrunk or prolonged to up to twice the original length. In base tilt mutation the base angle is modified by adding a number from range (-10, 10). Again we check whether the angle is still within specified limits.

Another genetic operator that can be used is crossover. We take lists of reflective segments of two individuals and perform one point crossover. Probabilities for crossover and mutation can be set in program parameters as well as population size or number of generations.

Users can choose one of three evaluation criteria — efficiency, illuminance uniformity or obtrusive light elimination. We tested all three criteria separately to see what result the evolution would produce. It was evident that optimizing over one objective without taking into account the others can lead to quite strange results. For example, the most efficient individual did not direct any part of the rays on the road. Similarly when searching for solutions that illuminates the surrounding uniformly we evolved an individual with a fitness of 0.858. This value is enough to fulfill requirements for all types of roads. However only a small part of the light was actually directed towards the selected area. Hence these were clearly not valuable solutions at all. Therefore we used multi-objective optimization to search for ideal design.

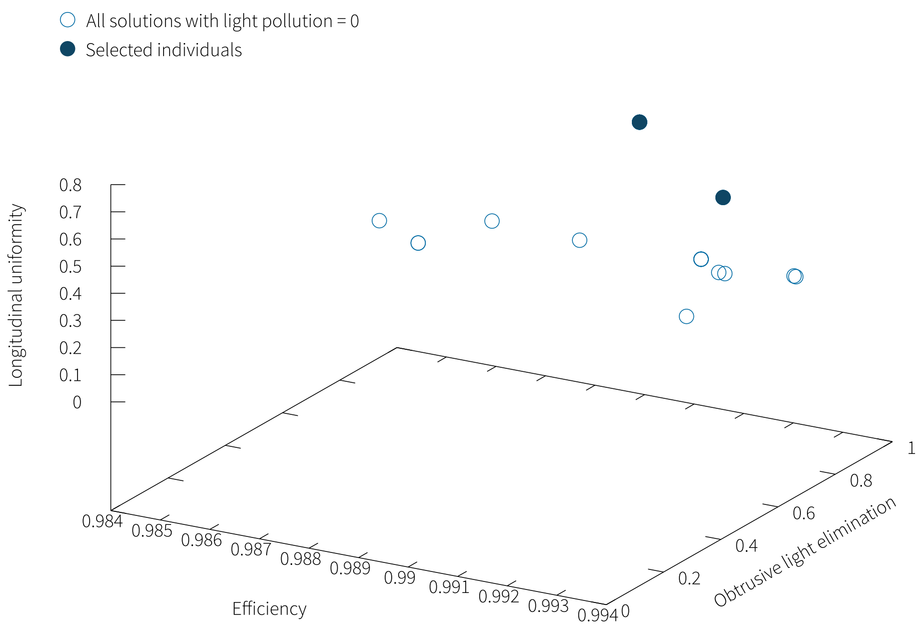

Figure 5.3 Visualization of a proposed device (1)

5.3 Multi Objective Optimization

We used NSGA II method to search for solutions that are suitable according to all three aforementioned criteria plus we added a demand for elimination of light pollution. We generated individuals with 6 reflective segments, set the initial base angle to $90°$ and set the minimum to $0°$ and maximum to $180°$. We set a probability for all genetic operators to 0.4 except for segment rotation which was set to 0.2. An overview of parameter settings in listing 3. We added a parameter for reflections timeout. In case a ray is reflected too many times, we terminate it. This should ensure that the program will not run indefinitely if we have an unfortunate configuration of reflective segments. Terminated rays influence the efficiency of the device. In addition if we have a ray that is directed back at the base it is also terminated.

We evolved a population of 16 individuals over 64 generations. Throughout the evolution we kept the most promising solutions in the so-called hall of fame. After the last generation we got 131 unique individuals. We selected a couple of solutions that performed well according to all given criteria. We examined the visualizations and chose two individuals most suitable for further work. In figure

Listing 3 Parameter settings for new luminaire design

```
"lamp": {
    "number_of_LEDs": 1,
    "number_of_rays": 20,
    "base_length": 40,
    "base_slope": 90,
    "multiple_free": {
        "no_of_reflective_segments": 6,
        "distance_limit": 400,
        "length_limit": 300,
        "base_angle_limit_min": 0,
        "base_angle_limit_max": 180
    }
},
"road": {
    "start": 0,
    "end": 12000,
    "depth": -4000,
    "sections": 4
},
"evolution": {
    "population_size": 8,
    "number_of_generations": 64,
    "operators": {
        "mutation": {
            "segment_shift_prob": 0.4,
            "segment_rotation_prob": 0.2,
            "segment_resizing_prob": 0.4,
            "tilt_base_prob": 0.4
        },
        "xover_prob": 0.4
    }
},
"evaluation": {
    "reflective_factor" : 0.98,
    "reflections_timeout": 20,
    "criterion": "nsgaii",
}
```

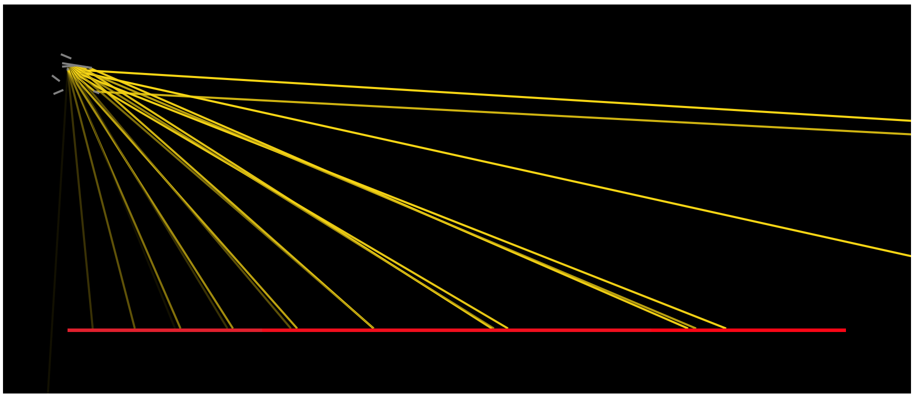

Figure 5.4 Visualization of a proposed device (1)

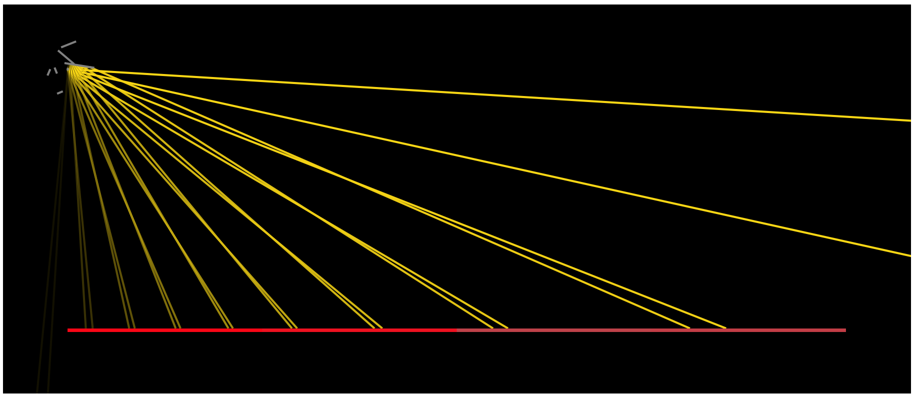

Figure 5.5 Visualization of a proposed device (2)

5.3 we display fitness for all solutions with light pollution value equal to 0. The two selected individuals are highlighted in the graph.

First one has an efficiency of 99%, illuminance uniformity of 0.78 and it directs 77% of the light intensity into the desired area while no rays are directed upwards. Second one has an efficiency of 99%, illuminance uniformity of 0.52 and it directs 83% of the light intensity into the desired area while no rays are directed upwards. The visualizations of the outcomes are in figures 5.4 and 5.5.

Chapter 6

Results and prototypes

6.1 Reflector for Existing Device

6.1.1 Results

We selected an individual with the following properties. We have a square base with a side length of 4 mm. There are four reflective segments, each attached to one side of the base as displayed in illustration 6.1. Each segment is marked by a letter from A, B, C or D. In table 6.1 there is an overview of dimensions and angles for individual reflective segments identified by the letters.

There are several possible ways to design the final shape of the reflector from the evolved data. The reflective segments can be rectangular with one dimension corresponding to the side length of the base and other is determined by the pro-

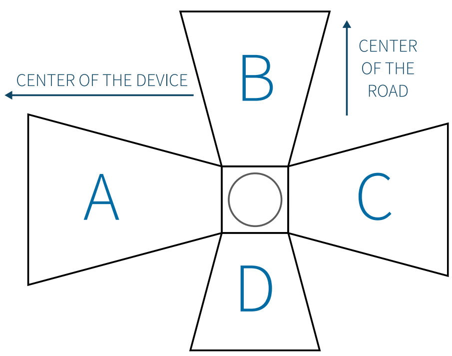

Figure 6.1 Illustration of reflective segments

Reflective segment	Length (mm)	Angle (°)
A	11.33	148
B	9.17	139
C	9.47	113
D	6.95	103

Table 6.1 Overview of reflective segments properties for selected individual

gram. Another option is to use trapezoids similarly to illustration in figure 6.1. Here the evolved dimensions determine the heights of the trapezoids. Third option is to use two long panels that span the entire length of the LED module and form reflective segments A and C for all 16 LEDs. Remaining segments B and D have rectangular shape as in the first described approach.

6.1.2 Manufacturing Prototype

In order to determine whether the evolved component is usable in practice we had to manufacture a prototype first. We decided to create a reflector that consists of two long panels that direct the light along the road for all 16 LEDs that are on one base. Additionally there are 32 small rectangular reflective segments which direct the light across the road. We started with creating a model from cardboard in scale 10:1 to see what the component would look like in three dimensions and to discover possible pitfalls of the design. At this point we also considered several means of mounting the reflector to the base with LEDs and few other practical aspects. We decided to keep the manufactured prototype as simple as possible in order not to introduce any other properties that were not evolved.

After deciding the practical aspects regarding the manufacturing process we created a model in Autodesk Inventor and prepared all necessary data for CNC machining. It is important to keep in mind that we had to create two laterally symmetrical versions to be able to assemble one device. We prepared a piece of silver coated aluminium sheet and affixed it to the CNC machine with an appropriate milling cutter secured in place. We ran the program and got cutouts for both bases as displayed in picture 6.2.

In the next phase we had to manufacture exact molds for creating the reflec-

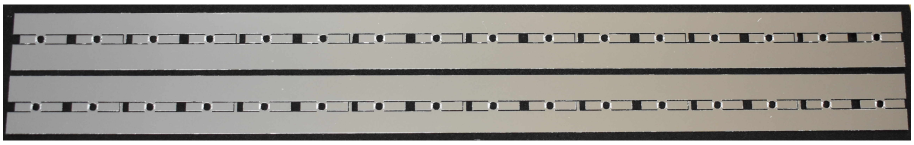

Figure 6.2 Laterally symmetrical cutouts

tors from the cutouts. Again we used Autodesk Inventor to create the models. We decided to use a 3D printer to create molds for the two long panels and a CNC machine to manufacture molds for individual reflective segments. Each form consists of two parts — die and punch. Photographs of both types of molds are in figure 6.3. On the left there is die for long panels and on the right there are both die and punch for smaller reflective segments.

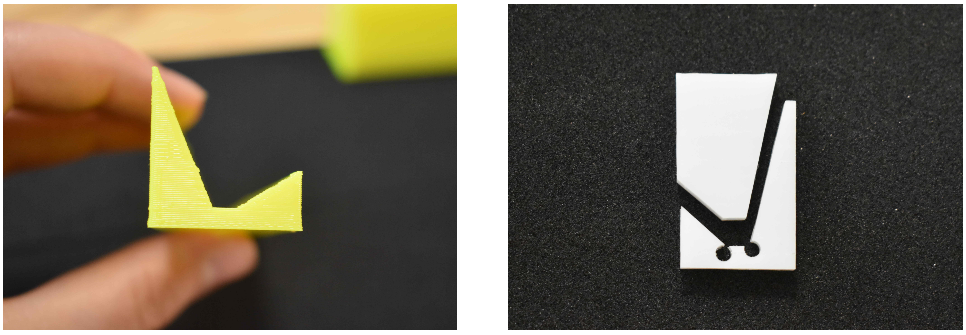

Figure 6.3 Molds for forming the reflector

First we used larger mold to bend the long panels into correct shape. Afterwards we shaped the pairs of smaller reflective segments using the other form as shown in figure 6.4. We are aware that our course of actions leads to inaccuracies in the shape of the reflectors. We designed the model of the molds with exact dimension and angles as we got from the problem solution. However when used to bend the metal sheet the outcome will not be accurate because of the properties of the material. In future work we might want to take this into consideration when evolving the shape of the optimal reflector.

Another problem emerged when we attempted to mount the reflector into the device itself. Part of our reflectors collided with bolts that are usually used to secure the LED module into the device. We improvised and attached all the components temporarily. This is sufficient for creating a prototype (figure 6.5) to

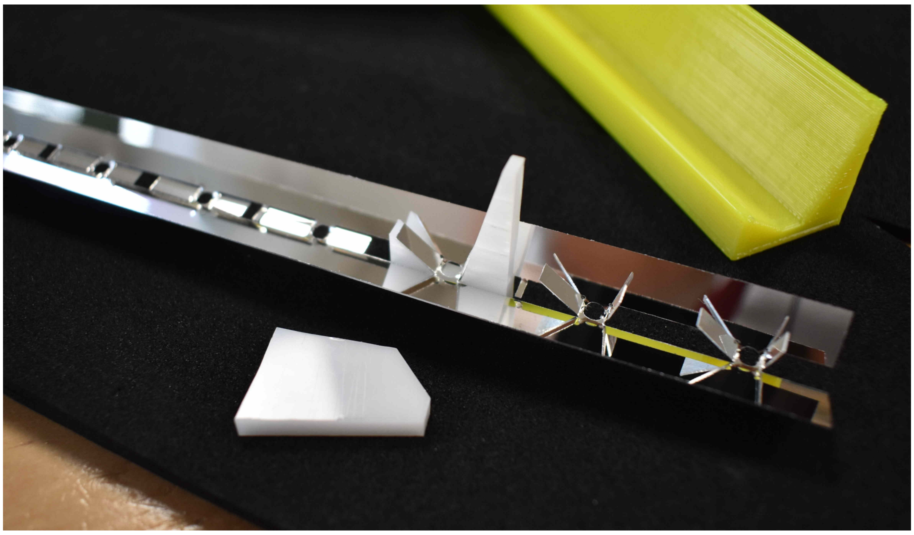

Figure 6.4 Using molds to shape reflectors

be measured, however for serial production we would need to modify the shape of the reflectors slightly.

6.1.3 Measuring Prototype

For measuring the results we used goniophotometer — device measuring the light intensity emitted from the luminaire in different angles. The apparatus we used rotates the luminaire along its longitudinal axis. Therefore it should record how well the light is distributed along the road. In figure 6.6 there is a photograph of the device affixed to the measuring equipment.

The outcomes are displayed in figure 6.7. The blue line represents the amount of light directed from the device into different angles. The yellow one portrays the reference curve of a standard luminaire. The difference in magnitudes is caused by using power supply with different outputs. We are primarily interested in the shape of the curve. We can see that directly below the device there is an unwanted peak followed by a shadow on both sides. This is not ideal and in future work we should focus more on the area below the luminaire. Apart from that the rest is satisfactory. We see that the outline of the lobes is smooth which suggests that the light will be distributed uniformly and there will be no other distinct peaks or shadows.

Figure 6.5 Reflectors mounted into device

We discussed the results with experts in the field of luminaire design and street lighting. They pointed out some problems caused by deficiencies in the manufacturing process. For example the reflector with two long panels and two small rectangles does not direct the light as well as the type with trapezoids would in practice. The overall evaluation of our results was positive, especially considering that this was the first prototype.

The problem of designing optics for an existing device is very complex. Finding a theoretically optimal solution is only a small part. The manufacturing process and subsequent use in practice bring a lot of additional demands for the shape of the reflector. We used results from optimization via evolutionary algorithms and created a prototype to test whether it is usable in practice. The measurement shows that there are some problems that need to be addressed before the device can be produced for practical use. There is a need for further analysis to say whether the problems are caused by deficiencies in manufacturing, if they originate in some simplification we made in our program or if it is a combination of the two.

Figure 6.6 Measuring the light intensity using goniophotometer

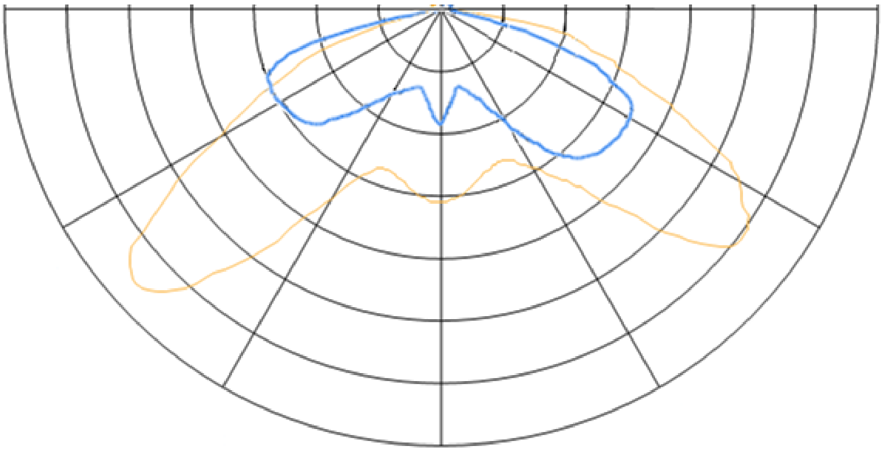

Figure 6.7 Light intensity from device (blue) vs. reference curve (yellow)

6.2 Novel Luminaire Designs

For novel luminaire design we used individuals evolved in section 5.3. Detail of the optical part of the first selected individual is in figure 6.8 on the left. On the right there is a version with redundant reflective segments removed. Segments that reflect any rays are left in place only slightly modified in order for the design proposal to be usable. These changes should not affect the outcome in any negative way. The same comparison of raw outcome and adapted version for the second selected individual is in figure 6.9.

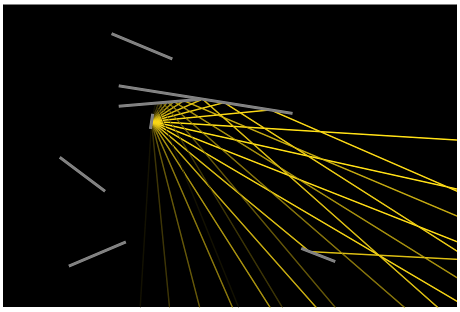 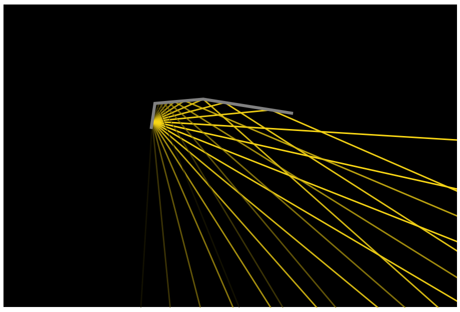

Figure 6.8 Detail of optics of new luminaire (1)

The exact specification of chosen solutions are in 6.10 and 6.11 . We sketched a cross section of the first luminaire (figure 6.12). The reflective segments are in grey color and the casing for the device is in black. We propose a luminaire

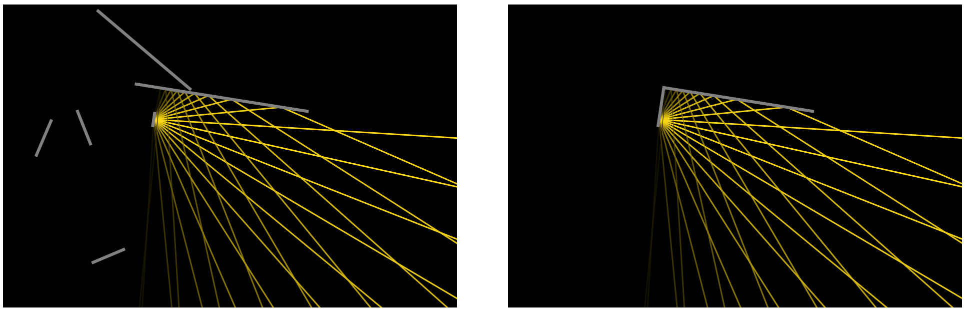

Figure 6.9 Detail of optics of new luminaire (2)

Device properties:

Base angle (°): 82

Reflective segments:

- start: (373, 21), end: (-87, 94)
- start: (55, 165), end: (-106, 232)
- start: (396, -336), end: (486, -371)
- start: (-87, 40), end: (127, 58)
- start: (-243, -95), end: (-123, -185)
- start: (-68, -319), end: (-219, -383)

Figure 6.10 Specification of solution for new luminaire (1)

structure composed of straight lines with rotational symmetry. There can be four or six LEDs in the final device as illustrated in 6.13.

In figure 6.14 there is a cross section of a luminaire design based on the second selected solution. We can see that both proposals consist of only a few straight segments. Therefore we assume that it would be feasible to manufacture them eventually. The only problem from our point of view is the size of the devices. The smaller one has the longest dimension of $838.3mm$ and that is just in the cross section. Once the device is manufactured the diameter will be even greater. The exact value depends on the selected configuration (four or six LEDs). The dimensions in the second proposal are even greater. We assume that depending on the demands of the manufacturer or the customer we could scale the dimensions down while keeping all the proportions. Hence the results should be similar while the size of the device would be modified.

Device properties:

Base angle (°): 82

Reflective segments:

- start: (410, 21), end: (-50, 94)
- start: (99, 78), end: (-150, 289)
- start: (-270, 0), end: (-312, -98)
- start: (129, 428), end: (-102, 336)
- start: (-203, 25), end: (-166, -68)
- start: (-76, -342), end: (-164, -379)

Figure 6.11 Specification of solution for new luminaire (2)

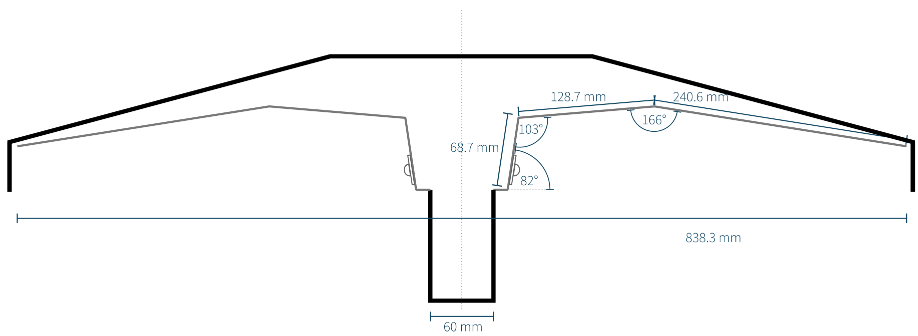

Figure 6.12 New luminaire cross section (1)

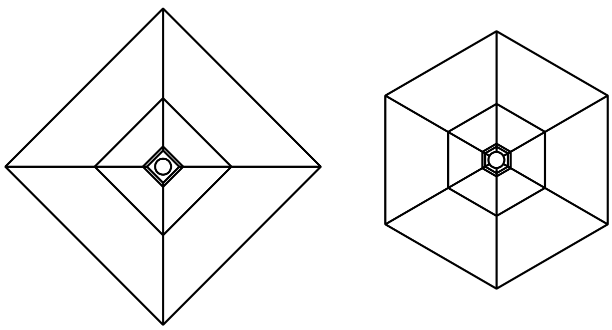

Figure 6.13 New luminaire - rotational symmetry

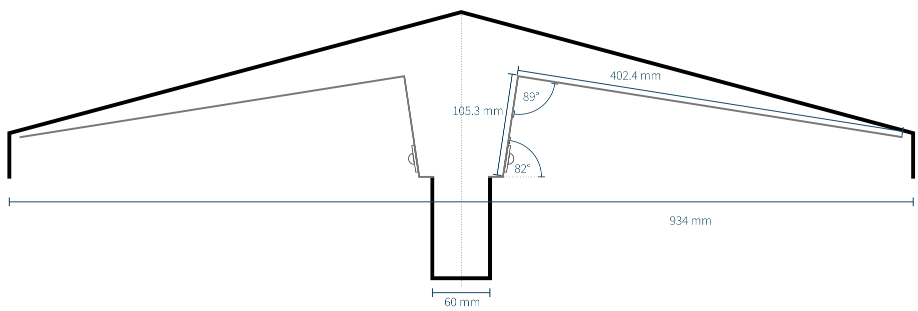

Figure 6.14 New luminaire cross section (2)

Chapter 7

Discussion on the Task of Evolutionary Design

The task of automated design of industrial parts via the use of evolutionary algorithms was examined several times in the past (see examples in chapter 2). In this chapter rather than describing technical aspects of our work, we will look on the topic from the perspective of applicability of our findings to similar tasks. We share our experience with evolving a specific component for an existing device and discuss our approach to several obstacles we encountered. Additionally we propose procedures to deal with the issues in general or possibly avoid them completely.

7.1 Task Requirements

Specifications for our task were given by experts from the field of street lighting. After some discussion and clarification of ambiguous points we arrived to a set of requirements that the ideal reflector for luminaires should fulfill. Initially the task assignment consisted of a set of sketches, few basic photometric formulas and some key concepts about luminaire optics design.

As we worked on the task many additional questions emerged. In some situations the answers we received contradicted the original specification and thus brought more and more confusion. Over the course of development of the program we had to simplify some sections while adding more functions elsewhere to create a more accurate model of the real situation. We continued with the work and eventually got to the phase of running the simulations and generating first results.

The lack of more formal specification became more and more apparent as we reached the final stages and began evaluating our results. It was difficult to assess the quality of evolved individuals since we did not have an exact set of criteria for ideal luminaire optics. We discussed the result with experts from a given field and eventually got to some values or ranges of values our solutions should meet. Based on that we modified weights for the multi-criteria algorithm and finally evolved individuals that not only met all necessary demands but performed quite well in terms of various optimization criteria.

We assume that a significant part of the problems originated in the fact that there are many different types of roads and the demands for optimal street lighting vary greatly. We suspect that there is no one perfect design for luminaire optics. Therefore we created a set of demands that are most common and attempted to evolve design for this situation. We hope that our proposed solutions will be as universal as possible.

If we were to do a similar type of automated design task again we would definitely ask for a more accurate assignment to start with. This applies to all possible fields of interest, not only street lighting. An exact set of demands the final item should meet is necessary as well as a specification of all criteria for optimization.

Regarding the problem of ambiguity that arises from having several subclasses of the problem we propose two possible strategies. First option is to develop a universal tool which will evolve an individual solution for each class based on given parameters. Second approach is based on aggregating the requirements to get only one set of demands which corresponds to the most common type of the problem.

7.2 Expectations and Outcomes

Other issues we encountered include the disparity between initial expectations for the work and its final outcomes. The results generated within the scope of this thesis fulfill given requirements however the findings are not particularly groundbreaking.

We assume that the source of problems emerges from the gap between fields of evolutionary algorithms and industrial components development. If the expert from some specific field has no experience with the area of evolutionary computation or multi-objective optimization, it is rather difficult to pass on all relevant information to the developer. When designing an evolutionary algorithm one must consider how to represent the individual, what genetic operators to use and how to evaluate the solutions. When there is not enough information available about the task, chances are that the developer will set up a representation for individuals that is actually unfit for the goal. Similarly unsuitable genetic operators or evaluation functions might be developed.

At the same time the task of designing a specific part is quite demanding even for experienced engineers with a great amount of domain-specific knowledge. Hence it is no surprise that it can be very challenging for an untrained individual to develop a program that encompasses all available design strategies and searches efficiently for best solutions.

In our work we spent a significant amount of time and energy on creating a model that features all necessary properties to evolve luminaire optics. This includes functions for computing ray reflection, longitudinal uniformity and much more. We gradually incorporated more and more functions to create a plausible model of the real world situation. Simultaneously we developed new genetic operators and fine tuned evaluation functions. We planned to experiment with a variety of scenarios both in a two-dimensional and a three-dimensional model.

After several months of work we still had a great amount of unrealized intentions ahead. It was not an easy task to find a balance between exploitation of existing strategies and involvement of unlimited search for novel ideas. At the same time we dealt with many requirements to enhance the model to be more realistic in terms of physics. Naturally we also encountered several problems that lead to compromises.

For example we worked on a three-dimensional model for the evolution to make the evaluation of individuals more realistic. After some time we decided to terminate this search path. Working with all three dimensions requires simulations with a large number of rays to get an evaluation of reasonable quality. Also it is much harder to visualize individuals and thus debugging is much more tricky. We decided to use two perpendicular cross sections instead. This is much less computationally demanding and it gives results which are sufficient for our scope of work.

Similarly when dealing with requirements for more and more accuracy we had to decide at some point to cease improving the environment since this is not a research in the field of optics or photometry. Keeping in mind what is actually the goal of automated design development is immensely important. There will always be another possibility how to enhance the program and potentially improve results. Eventually one must stop and focus on more practical aspects — manufacturing and testing an evolved component.

The step of creating a physical prototype is extremely important. It reveals whether it is actually possible to manufacture the component at all. Additionally it is one true key indicator whether the evolved design is usable for a given task or not. When a prototype is created it is important to measure its properties once it is incorporated into the device. Based on the outcomes we can alter the algorithm and work on the next version.

It is crucial to develop a program that is versatile. We might want to repeat several cycles of evolving and manufacturing prototypes with program modifications after each round. In case we want to expand the use of the program in the future to encompass more complicated scenarios we will appreciate if the program is well structured and easily modifiable. Also it can be used as a foundation or inspiration for future work with similar purpose.

If one wants to develop truly innovative components that will surpass the quality of existing solutions there are several key concepts to keep in mind. It is important to closely cooperate with the experts from a given domain. This starts with the clear and complete task assignment and continues throughout the development process up to manufacturing and measuring prototypes. It might be beneficial to introduce evolutionary algorithms and few examples of their usage to similar problems to collaborators from other fields. Hopefully this will lead to a more realistic idea about the potential and limitations of this method. When developing a tool for automated design of a particular component it is essential to balance the need for an exact model with other aspects such as the amount of necessary computations. It is always useful to develop a program that can be easily modified so that additional requirements can be implemented when needed.

Conclusion

Achieved Goals

Main goal of this thesis was to design a reflector for luminaires using evolutionary algorithms. First, we got acquainted with the technical standards and practical requirements for functional and efficient street lighting. We analyzed the problem and proposed a simplified model to work with. We developed a program that can be used to search for optimal shape of the optical part of luminaires for various scenarios.

We evolved a design of optics for an existing device. We manufactured a prototype and measured its properties. Afterwards we discussed the results with experts from the given domain. Although there were some deficiencies in the reflectors we created the overall assessment was positive.

Another goal was to evolve a design of a completely new luminaire. The focus was again on the optical part of the device. We used multi-objective optimization to search for novel designs of optics and utilize the outcomes to draw up proposals for two completely new designs.

Summary of Findings

We consider our work to have two main contributions. Firstly we evolved reflectors both for an existing device and for a completely new luminaire. The use of evolutionary algorithms for the design of the optical part is thus a feasible method which produces promising results. As for the existing device, we were able to create a prototype based solely on the evolved solution. The results from this prototype were rather impressive considering it was the first prototype generated by a completely new approach. This foundation definitely eliminates some expensive and time consuming development cycles and eventually can be used to create a reflector for serial production and widespread use.

Regarding the novel luminaire design it is not yet possible to tell whether it will be once manufactured. However the proposals we got from the evolved solutions are valuable for us. The main advantage is the fact that the design was not limited by common approaches of experts. The proposals are therefore new and unconventional while still fulfilling all technical requirements.

Second main contribution is the analysis of problems we encountered. We believe that this section is valuable for any future attempts to use evolutionary algorithms for design of an industrial or scientific component. We went over several problems we came across and presented possible solutions. We also discussed further improvements that can be applied in general, not only to our task.

Future Work

There are many possibilities on how to extend our work. In the future we intend to make the model three dimensional which will enable more complex computations of the impact of the reflector shape on the final outcome. We could also extend the possible shape of the reflector by adding for example parabolic segments.

It is equally important to take into account the manufacturing process. First of all we fabricate the reflector from one piece of silver coated aluminium sheet. This gives some limitations on the dimensions of the individual reflective segments that should be included in the boundaries of the program. Additionally there will always be inaccuracies and it should be incorporated into the evaluation functions in the program as well. Since the shape of the produced reflector is influenced by properties of chosen material, we could calculate the deformations specifically for its thickness and flexural properties and modify the computations accordingly. Another option is to alter the evaluation function to return results not only for one individual with exact properties but to average the outcomes over a neighborhood of similar solutions. This should ensure that the evolved individual will produce quality results when manufactured regardless of the small changes introduced when forming or handling the reflectors.

Apart from direct extensions of our work there are plenty other related tasks to focus on in the future. We believe that the attempts to use the automated design will become more and more frequent. As the trends in many areas are nowadays shifting towards the utilization of automation for more complicated tasks, this field should be no exception. We are aware that the task of designing a very specific component is immensely complex and consumes a great amount of time and cost. Not to mention it requires highly trained professionals. All of those reasons support the idea of automating at least some parts of the whole process.

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List of Figures

List of Abbreviations

CNC Computerised numerical control

CRI Color rendering index

EA(s) Evolutionary algorithm(s)

LED(s) Light emitting diode(s)

MOO Multi-objective optimization

NSGA-II Non-dominated Sorting Genetic Algorithm II

SVG Scalable Vector Graphics

Appendix A

Attachments

A.1 Digital attachments

We attach a folder with source codes of our program. It contains four sub-folders:

code - source codes and parameters file

docs - documentation

img - visualization of evolved solutions

stats - logs from the evolution run

Users can run the program in the folder **code** with command **python evolution.py**. The program loads parameters from file **parameters.json** and checks whether the values are valid. Start with information in **Readme.md**.

```
EvolvingComponents
    code
    docs
    img
    stats
    Readme.md
```